

Unusual Attitudes and the Aerodynamics of Maneuvering Flight



Author's Note to Flightlab Students

The collection of documents assembled here, under the general title “Unusual Attitudes and the Aerodynamics of Maneuvering Flight,” covers a lot of ground. That’s because unusual-attitude training is the perfect occasion for aerodynamics training, and in turn depends on aerodynamics training for success.

I don’t expect a pilot new to the subject to absorb everything here in one gulp. That’s not necessary; in fact, it would be beyond the call of duty for most—aspiring test pilots aside. But do give the contents a quick initial pass, if only to get the measure of what’s available and how it’s organized. Your flights will be more productive if you know where to go in the texts for additional background.

Before we fly together, I suggest that you read the section called “Axes and Derivatives.” This will introduce you to the concept of the velocity vector and to the basic aircraft response modes. If you pick up a head of steam, go on to read “Two-Dimensional Aerodynamics.” This is mostly about how pressure patterns form over the surface of a wing during the generation of lift, and begins to suggest how changes in those patterns, visible to us through our wing tufts, affect control.

If you catch any typos, or statements that you think are either unclear or simply preposterous, please let me know. Thanks.

Bill Crawford

Unusual Attitudes and the Aerodynamics of Maneuvering Flight

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Contents

Flightlab's Upset Recovery and Basic Aerobatics Program

(Introduction to unusual-attitude and aerobatic training)

Maneuvers and Flight Notes

(Describes training maneuvers and associated aerodynamics)

Flightlab Ground School Texts:

(More on aerodynamics: This background material is useful for pilots who want to prepare for the course beforehand, and for follow-up reading.)

1. Axes and Derivatives

(Descriptive concepts, vectors, moments, cause and effect)

2. Two-Dimensional Aerodynamics

(Lift and stall fundamentals: pressure, boundary layer, circulation)

3. Three-Dimensional Aerodynamics

(How wing planform affects stall behavior)

4. Lateral-Directional Stability

(Sideslips, yaw/roll coupling, straight and swept-wing dihedral effect, Dutch roll)

5. Longitudinal Static Stability

(Aircraft in trim, pitch control forces in 1-g flight)

6. Longitudinal Maneuvering Stability

(Pulling g)

7. Longitudinal Dynamic Stability

(Oscillations in pitch)

8. Maneuvering Loads, High-G Maneuvers

(V-n diagram, corner speed, radial g)

9. Rolling Dynamics

(Roll performance, adverse yaw, coordination)

Contents

10. Spins

(History, spin phases, momentum effects, recovery)

11. Some Differences Between Prop Trainers and Passenger Jets

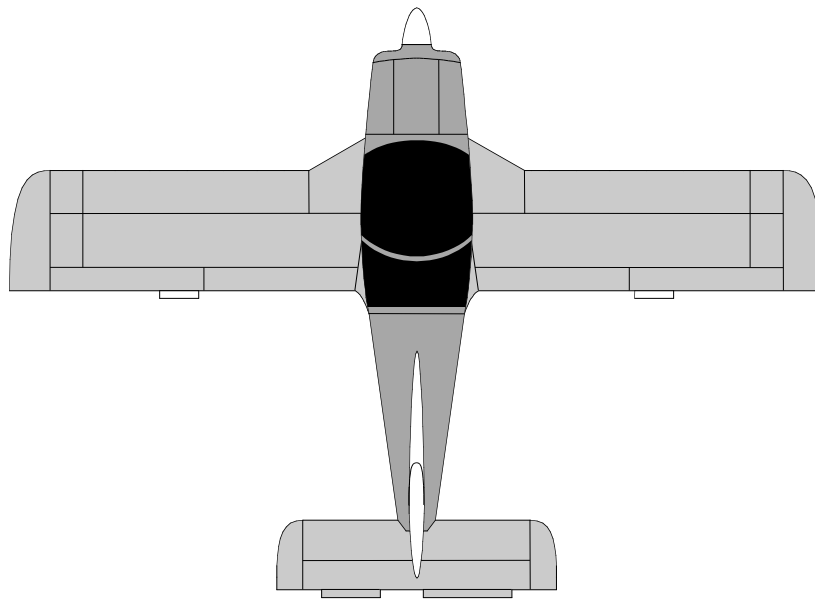
(Differences in control and response)

12. Vortex Wake Turbulence

(Vortex flow field/aircraft interaction)

13. A Selective Summary of Certification Requirements

(What the regulations say about aircraft stability and control)



Flightlab's Upset Recovery and Basic Aerobatics Program

Understanding the Aerodynamics of Maneuvering Flight

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Summary

Flightlab's Upset Recovery and Basic Aerobatics Program provides intensive ground school and flight training in aerobatics and unusual-attitude/upset recovery for flight crews, flight instructors, and individual pilots of all experience levels. Our ground school features a comprehensive but nonmathematical review of aerodynamics—taught using digital wind tunnels and flight-dynamics software designed for analysis and comparison of aircraft response. In the air, we use actual engineering flight-test procedures to demonstrate upset aerodynamics, and training disciplines from competition aerobatics to teach attitude perception and recovery skills. Because flying different aircraft reinforces the ability to adapt recovery techniques learned in one cockpit to another, students compare the stability and unusual-attitude characteristics of two aerobatic aircraft: a SIAI Marchetti SF260 and a Zlin 242L.

Course duration is typically three days, but can be extended over a longer period. Total flight time is approximately four hours. Students receive a detailed training record for insurance and employment purposes, and extensive ground school notes. The course can also include a complex/high-performance checkout and Biennial Flight Review.

Pilots will gain:

- A significantly increased understanding of maneuvering aerodynamics.
- The ability to recognize and track aircraft motion paths and energy transitions during unusual attitudes.
- Inverted-flight experience under real g forces in a true dynamic environment.
- Control skills necessary to recover from unusual attitudes and energy states.
- Strategies for dealing with flight characteristics following control failures.
- Enhanced confidence and safety.

Ground School Topics

Pilots can choose among a variety of ground school sessions and subjects, including:

The Aerodynamics of Lift and Control:

- Angle of attack and pressure patterns.
- Boundary layer and separation.
- Wing planform: Stall pattern and vortex effects.

Aircraft Dynamics and Upset Recovery:

- Aircraft axes and derivatives.
- The nature of stability and control.
- The aircraft's natural modes.
- Lateral/directional coupling.
- Roll dynamics.
- Recovery procedures.
- Flying qualities: Differences between prop trainers and passenger jets.
- Limitations on the use of rudders for large aircraft.
- FAR certification requirements.
- Simulator alpha/beta envelopes.

Spin Dynamics:

- Departure, incipient phase, steady state, recovery.
- Inertial and aerodynamic moments.
- Aircraft mass distribution and recovery techniques.

Upset Causes:

- NASA vortex studies and encounter dynamics.

Basic Aerobatic Maneuvers and Techniques

Flightlab's Upset Recovery and Basic Aerobatics Program

Introduction

Welcome to the program. The following pages describe our training goals, and provide the introduction to the Maneuvers and Flight Notes you and your instructor will use during your flights and briefings.

We developed our training program over many hours of flying with test pilots from NASA's Langley Research Center, the Empire Test Pilot School (U.K.), and the National Test Pilot School (U.S.A.), with fighter pilots and military instructors, and with International Aerobatic Club competition pilots, including members of the United States Aerobatic Team. Each discipline brought its own perspective. At NASA, we flew with experts on aircraft wake vortices to explore training methods based on recent studies of vortex encounters. We talked to experts about the limitations in using simulators for upset training. We worked on ways to help pilots safely translate the skills learned in straight-wing aerobatic aircraft to swept-wing transports.

Our program is unique in combining the aerobatic competitor's and military pilot's emphasis on attitude awareness and maneuvering airmanship with the test pilot's knowledge of aircraft dynamics. And we've introduced to aviation training the use of flight-test methods as cockpit teaching tools.

To gain a sense of where you're headed, take a look at the Maneuvers and Flight Notes before we fly. Review as much of our text material as you can, but don't be concerned if you can't get through everything, or intimidated when things get technical. We'll cover the essentials in our aerodynamics presentations. Aerobatics and unusual-attitude training both require and provide the ideal time for aerodynamics training. Our program is designed to help you understand the aerodynamics of upset and wide-envelope maneuvering, and to lay the groundwork for future study in general. You'll be on the right track if you ask lots of questions and then follow up on the reading when the course is over.

Our job is to answer those questions and to make the flying informative, appropriately challenging, and—this is important—enjoyable. Elevated anxiety shuts down the learning process.

Your job breaks down into three closely linked tasks: ***We want you to increase your***

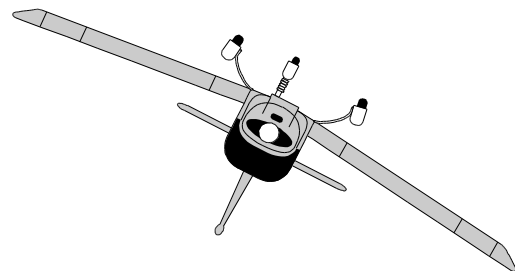
understanding of maneuvering and departure aerodynamics, become familiar with the stimulus environment generated by unusual attitudes, and develop the control skills necessary for recovery.

During your flights, the instructor will read out the checklist for each maneuver, then guide you through the steps, demonstrating first when necessary. We follow a consistent maneuver format, with each pilot receiving the same core training necessary for crew coordination and for developing a CRM approach to unusual attitudes. Beyond these basics, we'll adapt to your background and skills. The flights will be an opportunity to practice assertive stick-and-rudder flying—the kind not possible in most daily operations but fundamental in emergencies.

You'll begin the first flight by observing the classical *free response* modes around the aircraft's axes, and the aerodynamics of high angle of attack (high α , pronounced "alpha,") and high sideslip (or high β , pronounced "beta"). The flight also includes the first set of 360-degree rolls. During this and later flights you'll learn to recognize and recover from an increasingly challenging range of unusual attitudes, both with full controls and during simulated control failures. You will also begin to fly basic, controlled aerobatic maneuvers.

Each maneuver set in the program builds on the previous ones, so we want to try to fly them in order, weather (and stomach) permitting. But we'll adjust the sequence to your rate of physiological adaptation. If you have doubts about motion sickness, a cautious start and a night's sleep between the first and second flights can be surprisingly helpful.

If your motion tolerance is low, we'll emphasize aerodynamics in your flight program and go a little lighter on unusual attitudes.



Flightlab's Upset Recovery and Basic Aerobatics Program

Because you might be reading this while still deciding whether to take an unusual-attitude program, the following contains some points worth considering, as well as a general description of what to expect in our program.

Our Training Aircraft

Your flights will be divided between a Zlin 242L and a Marchetti SF260. Both are Lycoming-powered, with FAA Airworthiness Certificates in the Utility-Aerobatic Category, and built to satisfy military training requirements. Because the aircraft have tricycle gear and don't require tailwheel experience, students can do all the flying. The flight instrumentation allows unusual-attitude practice in simulated IMC, and the low wings allow tufting for airflow visualization. The aircraft are responsive and aerobatic. The Zlin is capable of outside maneuvers (including outside loops), plus tail slides and sustained inverted flight. The SF260 is less stable than the Zlin, and requires a more developed piloting technique.

We chose these aircraft partly because they demonstrate different levels of aerodynamic coupling in yaw and roll.¹ Yaw/roll coupling is a key to understanding the dynamics of unusual attitudes. Yaw/roll couple is typical of the general and especially the swept-wing fleet, but largely absent in aerobatic aircraft certified under the lateral stability exemption of FAR Part 23.177(c). Our aircraft also have flaps, which allow us to analyze changes in span loading and downwash. While our aircraft can't achieve the rapid roll and pitch rates possible in such aircraft as the Extra or Pitts, those rates are in fact undesirable. Moderate rates, more pronounced coupling, and higher stability margins and control forces are far better for unusual-attitude training and aerodynamics demonstration. Plus our cockpit environments are much more comfortable!

In addition to being more fun, flying different aircraft as part of your unusual-attitude training allows you to make comparisons that illustrate the variables behind aerodynamic behavior. It reinforces your ability to adapt to those variables and transfer recovery techniques learned in one cockpit to another. ***Confidence in the ability to adapt what you've learned is crucial to reaction***

¹ In a coupled response, rotation around one axis causes rotation around another. Aircraft can have both aerodynamic and inertial couples.

time, and thus essential in a future upset emergency in your own aircraft.

What's an Unusual Attitude?

Some pilots prefer the term "unusual attitude," others prefer "upset." We use them interchangeably. Here's the definition of aircraft "upset" from the *Airplane Upset Recovery Training Aid* (or AURTA, first released in 1998 and developed jointly by government agencies and an industry-wide group of airlines, aircraft manufacturers, and training providers). The AURTA (page 1.1) definition takes the aircraft as the starting point:

"Airplane upset is defined as an airplane in flight unintentionally exceeding the parameters normally expected in line operations or training.

While specific values may vary among airplane models, the following unintentional conditions generally describe an airplane upset:

- *Pitch attitude greater than 25 deg, nose up.*
- *Pitch attitude greater than 10 deg, nose down.*
- *Bank angle greater than 45 deg.*
- *Within the above parameters, but flying at airspeeds inappropriate for the conditions."*

The attitudes given above do set appropriate limits for most aircraft and operations, but they're very narrow in terms of the possible attitudes a pilot can experience. This reflects an observation made by many professional pilots: after the maneuvering lessons of primary training and perhaps time spent as a flight instructor, as hours and aircraft size increase, maneuvering opportunities tend to diminish and proficiency tends to atrophy. There can be an inverse or at least no positive relationship between flight hours and wide-envelope maneuvering ability. In the absence of in-flight training, aggressive maneuvering ultimately becomes a simulator exercise, with the limitations that simulation implies.

While we take the AURTA definition as a start, we expand it in our program to underscore the aerodynamics behind upsets. Here's an addition:

In an unusual- attitude situation there's also typically an "unusual" relationship going on (or

Flightlab's Upset Recovery and Basic Aerobatics Program

about to start going on) around the aircraft's axes. It's unusual in the sense that the opposing moments around those axes—which in a trimmed airplane normally find balance and keep things roughly straight and level—start to shift in ways that produce divergent results.

The above gets into technicalities and will take some explaining! Don't worry; you'll get a handle on it during our flights and ground-school briefings, as the examples unfold.

We should also expand the AURTA definition in terms of situational awareness: *It's fair to call an unusual attitude anything that a pilot can't immediately recognize: that is, whenever there's a loss of correspondence between what the aircraft is doing and what the pilot perceives.* The disconnection can be essentially cognitive, where a pilot just can't figure out what he's seeing, or take the form of spatial disorientation provoked by the vestibular system, where he can't believe what he's seeing because of conflicting motion cues. The resulting loss of "sense security" can produce panic in even the most experienced pilot.

Choosing an Instructor

There are no FAA regulations specifically governing curriculum or special instructor qualifications for unusual-attitude training. While there are guidelines, like the *Airplane Upset Recovery Training Aid*,² it's up to the training provider to define the tasks and training style in a manner that leads to an effective program. For safety, all instructors should be *current* in advanced aerobatics well beyond the maneuvering needs of the program itself.

Instructors in aerobatic or unusual-attitude programs typically have backgrounds in civilian competition aerobatics or are former fighter pilots. While both backgrounds can produce highly qualified instructors, remember that military and civilian aerobatic training and flying techniques are not always the same. The same laws of nature and aerodynamics apply, but, because of differences in mission and machinery, those laws are frequently invoked in different ways.

² The *Training Aid* was itself a product of debate. See "Airbus Industrie Presentation at 10th Performance and Operations Conference." www.nts.gov/events/2001/AA587/exhibits/240005.pdf

As a result, civilian aerobatic and military pilots can develop different skill sets and ways of thinking about aircraft maneuvering. Not surprisingly, each tends to *teach as they've learned*, sometimes inappropriately. Early in the development of airline unusual-attitude programs, for example, former fighter pilots—whose generation of swept-wing fighters relied on the rudder pedals for lateral control at high α —encouraged far more aggressive use of the rudder than airliner manufacturers thought safe. This led to what many regarded as "negative training," a situation in which the pilot was less safe after the training than before. Yet an aerobatic instructor with a competition background would have been just as likely to make the same training mistake regarding rudder use, although for different reasons. Don't let yourself be too impressed by an instructor's credentials—even the most veteran instructor has a point of view limited by his or her own training and maneuvering experience.

One way to counteract this is by introducing a wider, more integrated point of view—the test pilot's. By virtue of the job, test pilots have the techniques necessary to evaluate aircraft characteristics, and the experience to know how those characteristics can vary. Our ground school contains elements of the actual training a test pilot receives. Our flight program begins with basic "flying qualities" test procedures that reveal the fundamental mechanics of aircraft behavior—and builds from there.

Wide-Envelope Aerodynamics

Whether you receive instruction in flight or in a simulator, in any form of unusual-attitude training you're going to find yourself placed in upset attitudes (often while your eyes are first closed) from which you'll be expected to recover using the proper control movements. We'll do the same, but build to it in steps. First, we'll use our flight-test tools to illustrate the aerodynamics learned in ground school. *We'll examine the nature of stability and the conditions that lead to departure* by flying the aircraft carefully through the boundaries of the normal attitude envelope (but *well within* speed, recovery, and g-limits) while analyzing its behavior in both controlled and "free" response. This means flying at combinations of high angle of attack and high sideslip (α and β) where coupled behaviors can

Flightlab's Upset Recovery and Basic Aerobatics Program

predominate, and at attitudes where the aircraft's inherently convergent, back-to-normal stability characteristics start producing undamped, divergent responses. It also means flying at energy states where you'll first need to reestablish dynamic pressure and reattach airflow before control can return. We'll emphasize that the underlying aerodynamic conditions—and not merely the aircraft's attitude—determine the inputs necessary to regain control.

As a result of this demonstration approach you'll gain a better understanding of aircraft dynamics, and of the circumstances that actually produce unusual attitudes, than you would if we began our work by placing you in already-developed attitudes and then just coached you through textbook recoveries. To start, we'll tuft the wing to see how airflow, and thus control effectiveness, changes as the aircraft enters and recovers from stalls.

As an additional way of understanding aircraft characteristics, we can also review the flying qualities mandated by FAR certification requirements.

Accidents

Many of the training tasks in our program are drawn from both recent and historically typical unusual-attitude accidents. Some examples are essentially aerodynamic in provocation, like vortex encounters, stalls, and spins. Other accidents stem from mechanical or control system failures. Although the engineering causes of system failures might be specific to aircraft type, there's usually an accompanying aerodynamics lesson that's applicable in general. That's why, for example, we'll have you examine the aerodynamics of rudder hardovers—the bane of the Boeing 737—even if you think it could never happen on your aircraft.

When we practice intentional unusual attitudes, briefed and prepared, it's easy to forget how unintentional attitudes often happen. Sudden catastrophes aside, they evolve. They're often the culmination of a chain of events that typically starts while the aircraft is still under normal control. Problems appear, the workload goes up, the pilot enters an overload state and fails to monitor attitude, and a departure from the normal envelope begins. Pilots who've experienced the alarming physical sensations of spatial

disorientation can almost always look back and trace the bad *decisions* that set the seeds.

The National Transportation Safety Board's website www.nts.gov contains statistics on loss of control accidents, updates on current investigations, and detailed final reports.

Simulators for Upset Training?

Kinesthesia is the term for the sensation of the body's position, weight, and movement, as conveyed through our muscles, tendons, and joints. Both the vestibular (inner ear) and kinesthetic systems are components of *proprioception*, the general term (although usage varies) for all the non-visual systems involved in providing information on the orientation and movement of the body.

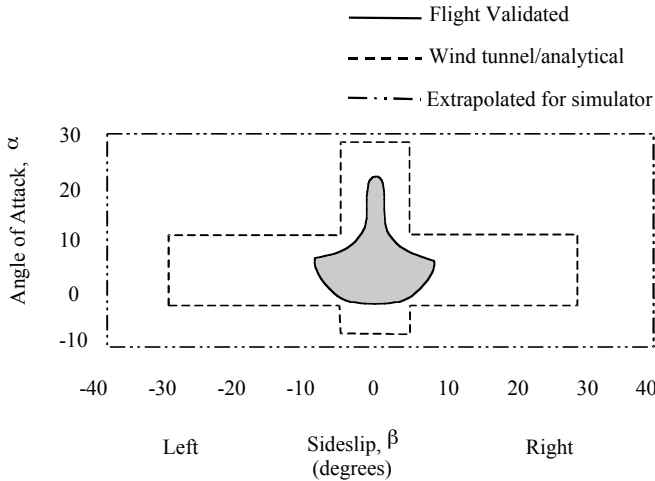
The proprioception of aerobatic flight involves sustained rotation and sustained g forces. But even the best six-degree-of-freedom simulator can only supply momentary cues. You won't feel a continuous 2 g during a simulated 60-degree banked turn, for example.

When a simulator can't provide a reasonably seamless motion environment in which to learn, and toward which to adapt, simulator based unusual-attitude training is limited to drills and procedures. The simulator can't provide equivalent *experience*, as it can in other flight regimes and emergencies involving less extreme motion. And if the simulator gives a false impression of how vision and proprioception match, it may actually lay the groundwork for even greater confusion during unusual attitudes in flight, when visual cues are combined with more challenging proprioceptive inputs than the simulator's motions allowed.

In addition to their limited ability to produce the physical sensations of aerobatic flight, the computers that drive simulators have flight model limitations. Both civilian and military aircraft are flight tested for their intended use, with some additional level of control abuse. Manufacturers of non-aerobatic aircraft are not required to develop actual extreme-attitude flight-test data. It would often be unsafe. As an example, the illustration shows the extent of the 737 flaps-up, flight-validated envelope. Note how combinations of high sideslip and high angle of attack are

737 Flaps Up Alpha/Beta Envelope

Adapted from AURTA, App. 3-D.



avoided. Behavior in these flight regimes simply isn't *known*. According to AURTA, App.3-D.1:

"From an aerodynamic standpoint, the regimes of flight that are usually not fully validated with flight data are the stall region and the region of high angle of attack with high sideslip angle where there may be separated airflow over the wing or empennage surfaces. While numerous approaches to stall or stalls are flown on each model (available test data are normally matched on the simulator), the flight controls are not fully exercised during an approach to stall or during a full stall, because of safety concerns. Also, roll and yaw rates and sideslip angle are carefully controlled during stall maneuvers to be near zero: therefore, validation of derivatives involving these terms in the stall region is not possible. Training maneuvers [in the simulator] in this regime of flight must be carefully tailored to ensure that the combination of angle of attack and sideslip angle reached during the maneuver does not exceed the range of validated data or analytical/extrapolated data supported by the airplane manufacturer."

It's worth noting that this doesn't preclude simulated rolling maneuvers at bank angles and attitudes outside flight-test parameters, but within α/β limits. Again from AURTA:

"Values of pitch, roll, and heading angles, however, do not directly affect the aerodynamic characteristics of the airplane or the validity of the simulator training as long as angle of attack and sideslip angles do not exceed the values supported by the airplane manufacturer. For example, the aerodynamic characteristics of the upset experienced during a 360-deg. roll maneuver will be correctly replicated if the maneuver is conducted without exceeding the valid range of angle of attack and sideslip."

You can see that limitations in the flight model beyond certain α/β values should be taken into account when simulators are used to re-create and study upset accidents. The same caution is necessary when simulators are used to *develop* unusual-attitude recovery techniques—a somewhat abused practice in the past. Be suspicious of simulation at high α and β , especially beyond stall.

But also put the limitations of a non-validated flight model into perspective. An aerobatic aircraft isn't going to "model" precisely the kind of aircraft the AURTA is concerned with, either. In-flight unusual-attitude training is illustrative. It can take you into, and show you how to get out of, all sorts of territory. It produces true sensations. Yet it can only provide for the transfer of general principles and fundamental skills.

Unusual-Attitude versus Aerobatic Training

In typical aerobatics courses you'll learn to fly a standard set of maneuvers: roll, loop, hammerhead, Cuban-eight, Immelman, spin, etc. It's valuable training and worth encouraging, but not always the best approach for a pilot whose first concern might be to learn unusual-attitude aerodynamics and recovery skills for use in non-aerobatic aircraft.

One problem is that aerobatic training focusing on perfecting standard maneuvers tends to be inherently aircraft-biased in the way muscle memories are developed. Although the basic aerobatic techniques aren't appreciably different between aircraft, if you want to keep your instructor happy, and get the maneuvers right, you'll have to match your control inputs to the characteristics of the trainer you fly. In a very responsive aerobatic aircraft, such as an Extra or a Pitts, a little bit of input will produce a lot of

Flightlab's Upset Recovery and Basic Aerobatics Program

maneuvering. You'll learn a light touch—otherwise you'll have a rough ride.

Unfortunately, those light control forces (which include the initial breakout force necessary to deflect controls from neutral) can lead a pilot to an unrealistic set of motor skills and response expectations if applied to less nimble, non-aerobatic aircraft in unusual-attitude situations. There a light touch might take a long time getting noticed.

Another drawback to standard aerobatic training is that the maneuvers, properly taught and flown, don't present all of the control issues that an unusual attitude program really needs to address. Although the *attitudes* may be new to the pilot, if the aerobatic maneuvers have been entered correctly the aircraft will be in an *energy state* well within the envelope of positive and immediate control. The pilot will have seen only part of the problem.

As a matter of fact, you have to fly aerobatic maneuvers badly in order to take them to the regions of the attitude/energy envelope where they start to provide the most complete training opportunities for unusual-attitude recovery. In a standard aerobatics course, a good instructor will set up bad maneuvers for just that reason. Even so, the experience may still be somewhat off the mark as unusual-attitude training, because the attitude emergencies a student will face in cross-country flying won't originate from a botched hammerhead or a sloppy Immelmann, but typically from such things as turbulence, ice, wake encounter, or systems and control failures.

We've created a maneuver sequence that addresses the aerodynamics of attitude, energy, and basic upset response more completely than a typical spin-loop-roll aerobatics course, using aircraft chosen to relate as well as possible to the general fleet. You'll start with stability and control demonstrations adapted from flight test procedures, begin to develop unusual attitude recovery skills, and then move on to the classic aerobatic maneuvers.

Wide-Envelope Attitude Awareness

You're going to be in for trouble in an upset situation unless you can visually track rapid and complex changes in aircraft attitude. Tracking information can come to you in three ways: by

looking at the scene out the window, looking at the attitude and performance instruments in the cockpit, and by scanning inside and out. In VFR, this all happens within a wide-angle visual field that can develop rapid *peripheral rotations* that profoundly affect perception of the scene. In IFR, the angle narrows and potentially helpful peripheral cues are missing. And all of this occurs while your body is contending with abrupt and perhaps contradictory vestibular stimulation.

This environment is confusing at first. The perceptual skills that prevent it from remaining a blur take practice to develop. The forces are disconcerting and the usual references can disappear. Experience shows that the best way to enter it is in increments that provide a gradual exposure to increasingly unfamiliar aircraft attitudes and motions, while maintaining a comfortable sense of aircraft control. In addition to building understanding, the aerodynamics observations we'll be making in the first flight are designed to help you relax and develop confidence in the aircraft, while gaining the tracking ability necessary for more complex maneuvers later on.

As our maneuvering increases, you'll become more familiar with the aircraft's attitude cues and typical motion paths. You'll build a mental image, or model, of the aircraft's motions, as if visualizing the aircraft from outside. You'll also begin to acquire what aviation physiologists call ***earth-stationary perception***: You'll start to gain *the perceptual ability to fix the plane of the earth and horizon in place* during unusual attitudes, just as you do in normal ones, and you'll begin to experience and anticipate the motion of the aircraft against that stationary reference. The ability to imagine aircraft motion correctly in three axes supports the ability to perceive attitude in earth-stationary terms, since the internal model acts as a bridge during intervals when horizon reference is temporarily lost.

Although this learning occurs in VFR, you'll find that it applies to instrument interpretation in IFR, as well. Unusual-attitude instrument indications are easier to decipher when you can associate them with dynamics you've already seen outside. Interpretation can be very difficult otherwise. We'll start you on outside references, and then bring your focus inside.

Flightlab's Upset Recovery and Basic Aerobatics Program

Control Skills

Mantras: Because we want you to develop core response habits based on earth-stationary perception, we don't rely heavily on mantras, meaning memorized control sequences or control inputs remembered through acronyms. Mantras for guiding the hands and feet are fine—as long as they're acted out in phase with the aircraft's attitude. The trouble comes when a pilot loses or lacks earth-stationary visual tracking, applies sequenced inputs out of phase with the maneuvering requirements, and then becomes confused when the aircraft responds unexpectedly. Confused pilots often freeze. Aerobatics instructors see this all the time.

Also, in some cases maneuvers are actually easier to master if the necessary control motions are learned out of sequence. The flexibility necessary for this in training makes mantras inappropriate, and often irrelevant once the student catches on. This is the case in learning to roll an aircraft with integrated rudder and elevator inputs. (See "Slow Roll Flight Dynamics" in the Maneuvers and Flight Notes.)

We think mantras can be helpful, but as ways to summarize and seal the control skills you've learned, not as a primary training technique.

Airline training for unusual attitudes often relies on standardized "flow response" or "rule-based" performance.³ The pilot learns to interpret flight instruments in the sequence necessary to determine aircraft attitude and perform the right control inputs. Pilots are trained to recognize the situation, confirm it, and then take the prescribed steps. This approach is based on instrument flying and suits the airline and FAA preference for uniform procedures. If the pilot follows the procedure correctly, he or she is considered trained.

Our program is different. We strive for "skill-based" performance and will encourage you to *fly in direct response to the visual cues*, mediated as little as possible by mental checklists designed to tell you what to do with your hands and feet. Direct response is how experienced aerobatic pilots fly. This approach isn't meant to replace procedural flying where procedures are necessary.

³ Human factors experts distinguish between skill-based, essentially automatic performance, and more cognitive, if-then, rule-based performance.

The skills gained should make upset "procedures" easier, because you'll be able to take in attitude information more efficiently.

That said, a case where talking yourself through a memorized control sequence can work best, as both a learning and a survival technique, is during a spin recovery—especially once a spin develops and the wrong sequence can delay or prevent recovery.

The Debate over Spin Training

The then CAA (now FAA) removed the spin requirement from the private pilot flight test in 1949, but the arguments over spin training never let up. There were even Congressional hearings, in 1980, in which the Subcommittee on Investigations and Oversight of the House Committee on Science and Technology, clearly wowed by a witness list of famous test pilots, recommended that spin training be restored—a recommendation the FAA did not follow.

Under FAR Part 61, an applicant for a private pilot certificate is required to receive only ground instruction in "stall awareness, spin entry, spins, and spin recovery techniques." A candidate for flight instructor must demonstrate ground "instructional proficiency" in the same areas, and receive actual spin flight instruction. The flight instructor requirements can be satisfied with a logbook endorsement from a current CFI after just one spin-training flight.

The result is often a new instructor who speaks from limited direct experience.⁴ Unfortunately, he'll be speaking to his eventual students about flying's most complex dynamic event—an event that can quickly deteriorate to the point where training restricted to ground instruction, however informed the instructor might be, won't prove much help. Pilots learn spins through their hands, feet, and eyes. Not only do they have to learn the correct recovery response, they have to filter out the impulsive and incorrect. That's not a ground-based academic task.

Over the years, some authorities have argued that stall avoidance training is the real answer to spin

⁴ Patrick R. Veillette, *Re-Examination of Stall/Spin Prevention Training*, Transportation Research Record, No. 1379, National Research Council, Transportation Research Board, 1993.

Flightlab's Upset Recovery and Basic Aerobatics Program

accidents. They cite as evidence the accidents that occur during spin training itself, and the statistics that show that most fatal stall/spins happen during takeoffs and landings (or during buzz jobs), at altitudes too low for recovery in the first place.⁵ Their argument ignores the fact that only spin accidents get recorded, while there's no way of knowing how many people spin training has actually saved at recoverable altitudes, *or prevented from making mistakes* at low altitude by virtue of a better understanding of how things can go wrong. It's also a self-fulfilling prophecy: If you avoid spin training because you think recoveries from developed spins are statistically unlikely below standard traffic pattern altitude, as the Air Safety Foundation has asserted, you probably won't have the skill to recover from an initial spin departure, either.⁶ Yet, with training, recovery from the initial wing drop that signals the beginning of autorotation is possible in many light aircraft, at least above 500 feet. So the question for the individual pilot becomes: Do you resign yourself to statistical outcomes—or do you try to beat them through training that takes you beyond stall avoidance and into actual spin departures and recoveries?

Some aircraft put up a good barrier between stall and spin. Stick shakers and pushers on turboprops and jets make it difficult to get into the territory necessary for a spin. Modern wing, empennage, and aileron designs make inadvertent spins less likely than in the old J-3 Cubs, Cessna 120/140s, and Aeroncas in which civilian spin instruction was once given. It was their departure characteristics that the classic, stall/spin-training scenarios were designed to reflect. Although their stall behaviors were often gentle, they had significant adverse aileron yaw and powerful elevators and rudders—a combination that affords plenty of pro-spin opportunity if a pilot misapplies the controls. The ease with which these aircraft (and many other pre- and World-War-II trainers and especially fighters) could spin if mishandled made spin training necessary. Later generations of aircraft were harder to provoke. Making them that way was part of the reasoning behind the removal of the private pilot spin requirement. As long as spins were required, manufacturers had to produce trainers that were easy to spin. Without the

requirement, more spin-resistant designs became marketable.

In our training program we'll concentrate first on post-stall departures and incipient spin entries, where aerodynamic moments predominate and emergency recoveries should occur. When you're comfortable, the training moves to spins in which the aerodynamic and inertial moments are approaching balance, and incorrect control movements can delay recovery. You'll find that the stick forces necessary for recovery tend to increase as a spin develops, and spin rate can temporarily increase after recovery inputs. These are essential points to demonstrate, because their misinterpretation can cause a pilot to panic and misuse controls.

It's important to note that practice spins at safe altitudes, while necessary for learning spin dynamics and recoveries, don't recreate the mental state in which many spin accidents are likely to occur. Spins particularly happen down low, when an anxious pilot attempts to increase a turn rate while fighting a growing sink rate. Prime examples are turn-backs due to engine failure on takeoff, and skidding turns when low and tight on base to final. Pilots who claim they'd never mishandle an aircraft in this way simply don't realize how powerful the impulse becomes when the ground starts rising and there's unfriendly terrain ahead. In fact, spins aren't just fatal at low altitude: low altitude literally provokes departure if a pilot responds to the unexpected ground threat with visceral but inappropriate control movements. For the untrained pilot, the visceral response—stick back, opposite aileron—is pro-spin. If spin training up high fails to accomplish a safer outcome down low, it's a good bet that the instructor failed to point out that spin training is also crash training! It's certainly better to crash under control in a more or less level attitude than in the sudden-stop, nose-in-the-dirt vertical attitude of a low-altitude spin departure.

Also remember that the differences between aerobatic and non-aerobatic aircraft can be substantial. The FAR Part 23 one-turn spin recovery requirement for normal category certification can produce a much less predictable aircraft than one certified under the six-turn requirement for aerobatics and spin-approved utility. Part 23 twins and large aircraft certified under Part 25 have no spin recovery requirements at all. Consequently, it's dangerous to venture far-reaching predictions about the spin behavior of a

⁵ Especially Leighton Collins, *Air Facts*, vol. 36, June 1973, pp. 80-96.

⁶ www.aopa.org/asf/ntsb/stall_spin.html

Flightlab's Upset Recovery and Basic Aerobatics Program

non-aerobatic aircraft based on one's experience in well-mannered aerobatic trainers alone. Our ground school takes this into account.

But the good news is that spin departures are essentially alike. Aircraft have different susceptibilities, but they go into spins or post-stall gyrations for the same underlying reason: failure of lateral/directional stability at stalling angle of attack. As a result, learning to enter into and recover from spins in any one aircraft gives you the basic lessons needed to keep them from happening in most others. By opening your eyes to both spin causes and consequences, spin training can build more ingrained and technically proficient stall avoidance. That's of course the foundation on which the argument for spin training ultimately rests: Spin training should make emergency spin recoveries unnecessary. The training doesn't have to be hair-raising and the airmanship benefits, once you've experienced them, are too genuine to ignore—a big chunk of mystery and vulnerability will be gone.

Maneuvers and Flight Notes

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For Training Purposes Only

General Briefing

Anxiety!!!

If you've never flown aerobatics (or have had some bad experiences in the past), anxiety is natural. Sometimes people are anxious about safety, sometimes about how well they'll respond when the instructor places the aircraft in an upset condition. Anxiety disappears as you learn to control the aircraft. We won't take you by surprise (well, not immediately). We'll teach you how to follow events so that surprises become manageable.

Even so, there may be times when you feel that too much is happening too fast. That's not entirely bad: it shows that you're pushing the boundaries of your previous training. As you gain practice you'll find that the aircraft's motions become easier to follow and tracking the horizon becomes less difficult. Your comfort level then quickly rises.

But if you feel confused or unsafe at any time, let us know.

Airsick?

The same goes if you begin to feel airsick. You probably don't learn well with your head in a bag, so *don't hesitate*. Let us know immediately so that we can modify the program and flight schedule for your comfort. If you're new to aerobatics, you'll discover that airsickness has nothing to do with the previous number of trouble-free hours in your flying career. Resistance—or “habituation,” depending on your theory—usually arrives, but it takes time.

Most of our maneuver sets call for repetitions, but we can easily stretch those out over several flights, if you prefer. That's easier on the instructor, as well. If you're concerned about airsickness, a good resistance-building technique is to fly somewhat aggressive lazy-eights (which you might remember from the Commercial Flight Test) in a light aircraft a few days before you fly with us. Lazy-eights supply the pitching and rolling motions and variations in g force your body must adjust to. But stop at the first

feelings of discomfort. Becoming sick does not help you adapt faster.

Don't fly aerobatics on an empty stomach. Eat! You look thin! Drink plenty of water, especially when the outside temperature is high. Dehydration reduces g tolerance.

Research done with persons subject to motion sickness suggests what you've perhaps already observed: People who report that they've recovered from feelings of nausea can remain highly sensitized to vestibular disturbance for hours afterwards. That's why those airsick passengers who announce with relief that they're now feeling much better often spontaneously re-erupt as you start to maneuver into the traffic pattern. The temporary disappearance of symptoms doesn't necessarily mean the battle is over.

What to Read: Ground School Texts

The texts you'll receive (or download) along with the Maneuvers and Flight Notes cover a wide range of subjects, giving background material you can go into, more or less deeply, according to your interests. Our program is best for pilots who not only want to gain aerobatic and upset recovery skills but who also have a broader curiosity about the principles of aircraft response. Skills can be learned quickly, but satisfying curiosity takes time—because, ideally, curiosity grows. (And the subject of airplanes is vast.) You may find it helpful to read at least the ground school selections “Axes and Derivatives” and “Two-Dimensional Aerodynamics” before the first flight—don't worry if you don't have a technical background; they're not as nerdy as they sound. *Treat the ground school texts as a long-term resource, not a short-term burden.*

What to Think About

Think about searching out the basic relationships that determine aircraft behavior. At very least, you need to examine two areas. The two ground

Maneuvers and Flight Notes

school selections mentioned above provide an introduction.

You need to *understand how an aircraft responds to its own velocity vector, and to its lift vector*. If you know where the velocity vector is pointed (relative to the aircraft's fixed axes), and where the lift vector is pointed (relative to the horizon), you know how a stable aircraft is likely to behave. This is the core of our presentation of stability and control.

You also need to *understand the nature of the pressure patterns over the surface of the wing*: how those patterns originate and how they migrate as angle of attack changes. This is especially important as the aircraft approaches the stall, because pressure patterns determine the availability of control.

Where to Look

Unusual-attitude training should take both outside and inside attitude references into account. Aerobatic pilots look outside first. We fly in reference to the real horizon, not the artificial one. Of course, that's because we fly aerobatics only in VFR conditions; but even if we have an aerobatic-friendly attitude indicator, the real horizon provides much better information.

Unlike aerobatic pilots, many IFR pilots tend to look inside first, even in good weather. If control of aircraft attitude is a reflexive, heads-in activity for you, you may need to reacquaint yourself with the information out the window. Partly because of the essential role peripheral visual cues play in spatial awareness, that's where the information is best during unusual attitudes. Physiological correlation between what your body feels and what your eyes see also happens much faster when you're looking outside. Then begin to connect what you've learned about aircraft behavior from looking out with the symbolic attitude information available within the cockpit. You'll find that the symbolic information—which unfortunately lacks the peripheral cues we primarily rely on to perceive our motion within the world—becomes easier to interpret when you can associate it with attitudes and flight behaviors you've already seen outside.

One of the drawbacks of simulator training programs for unusual attitudes is that this

valuable building block, outside/inside-learning process may not occur with sufficient repetition for the benefits to sink in. Pilots might demonstrate maneuvering proficiency in specific, directed tasks, but still have limited attitude awareness.

Rudder Use

We want you to experience and understand the effects of rudder deflection on aircraft response at high angles of attack. While the same basic aerodynamic principles apply in swept-wing aircraft as in our straight-wing propeller-driven trainers, in practice large aircraft and swept-wing dynamics are different, and more limited rudder use is recommended. On matters concerning rudders, search the Internet for *Boeing Commercial Airplane Group Flight Operations Bulletin*, May 13, 2002. Also *Airbus FCOM Bulletin, Use of Rudders on Transport Category Airplanes*, March 2002.

Standard Procedures

- Clear the airspace before each maneuver.
- Acknowledge transfer of control.
- Don't hesitate to apply your own CRM procedures and call-outs as you think appropriate to the safety of the flight.
- Don't fret about your mistakes. Mistakes are your best source of information. Bracket your responses until you zero-in on the correct procedure.

Maneuvers and Flight Notes

Maneuver Sets and Lesson Plan

Because certain maneuvers use up motion tolerance more rapidly than others, and personal tolerance varies, your maneuver sequence might be different than the standard schedule. You'll also repeat some maneuvers when you fly the second aircraft.

The core lesson is upset recovery, but we teach much more than recovery procedures, as you'll see when you begin reading. The Flight Notes below each maneuver description cover fundamental aerodynamic principles. Together with the ground school presentations and supporting texts, they describe aircraft characteristics you'll observe and techniques you'll learn. They attempt to expand your frame of reference with examples drawn from different aircraft types. They're part narrative, part explanation, and sometimes a warning.

The information in the Flight Notes is obviously more than an instructor could give during a flight, and much more than a student could be expected to take in. Chances are we won't have time to cover every detail, nor will every detail apply to your type of flying. *Don't let the material overwhelm you.* Familiarize yourself with the relevant Flight Notes before each sortie, as you think best. When you review the notes after the flight, you'll find them much easier to absorb, because you can connect them with what you've just done. The ground school texts reinforce the Flight Notes and add further information.

We use ***boldface italics*** to emphasize important concepts. (**Boldface** in the procedure description reminds instructors of points to emphasize in setting up and carrying out maneuvers.)

Here's how the maneuvers break down into general categories:

Natural Aircraft Stability Modes, Yaw/Roll Couple:

1. Longitudinal & Directional Stability, Spiral Divergence, Phugoid

2. Steady-Heading Sideslip: Dihedral Effect & Roll Control

High Angle of Attack (Alpha):

3. Stall: Separation & Planform Flow (Wing tuft observation)
4. Accelerated Stalls: G Loads & Buffet Boundary, Maneuvering Stability
5. Nose High Full Stalls & Rolling Recoveries
6. Roll Authority: Adverse Yaw & Angle of Attack, Lateral Divergence
7. Flap-Induced Non-convergent Phugoid

Roll Dynamics:

8. Nose-Level Aileron Roll: Rolling Flight Dynamics, Free Response
9. Slow Roll Flight Dynamics: Controlled Response
10. Sustained Inverted Flight
11. Inverted Recoveries
12. Rudder Roll: Yaw to Roll Coupling

Refinements and Aerodynamics:

13. Rudder & Aileron Hardovers
14. Lateral/Directional Effects of Flaps
15. Dutch Roll Characteristics
16. CRM Issues: Pilot Flying/Pilot Monitoring
17. Primary Control Failures

High-Alpha/Beta Departures:

18. Spins

Additional Basic Aerobatic Maneuvers:

Loop, Cuban Eight, Immelman, Hammerhead, Slow Roll, Point Roll

Maneuvers and Flight Notes

First Flight	Second Flight	Third Flight
<p>1. Longitudinal & Directional Stability, Spiral Divergence, Phugoid</p> <p>2. Steady-Heading Sideslip: Dihedral Effect & Roll Control</p> <p>3. Stall: Separation & Planform Flow (Wing tuft observation)</p> <p>4. Accelerated Stalls: G Loads & Buffet Boundary, Maneuvering Stability</p> <p>5. Nose High Full Stalls & Rolling Recoveries</p> <p>6. Roll Authority: Adverse Yaw & Angle of Attack, Lateral Divergence</p> <p>7. Flap-Induced Non-convergent Phugoid</p> <p>8. Nose-Level Aileron Roll: Rolling Flight Dynamics, Free Response</p> <p>Possible:</p> <p>9. Slow Roll Flight Dynamics: Controlled Response</p> <p>On Return:</p> <p>17. Primary Control Failures</p>	<p>9. Slow Roll Flight Dynamics: Controlled Response</p> <p>10. Sustained Inverted Flight</p> <p>11. Inverted Recoveries</p> <p>12. Rudder Roll: Yaw to Roll Coupling</p> <p>13. Rudder & Aileron Hardovers</p> <p>14. Lateral Effects of Flaps</p> <p>15. Dutch Roll Characteristics</p> <p>Possible:</p> <p>19. Spins</p> <p>Basic Aerobatic Maneuvers</p> <p>On Return:</p> <p>17. Primary Control Failures</p>	<p>Review Maneuver Sets 9-12</p> <p>16. CRM Issues: Pilot Flying/Pilot-Not-Flying</p> <p>18. Spins</p> <p>Basic Aerobatic Maneuvers</p> <p>On Return:</p> <p>17. Primary Control Failures (as necessary)</p> <p>Fourth Flight</p> <p>Review and additional aerobatic maneuvers to be determined.</p>

These maneuvers are for training purposes in appropriate aircraft only. Follow the procedures and obey the restrictions listed in your pilot's operating handbook or aircraft flight manual.

Trimming for Airspeed in Level Flight

We usually trim an aircraft in climb for V_Y , best rate of climb, or perhaps a bit faster to preserve the view over the nose and to keep engine temperatures from rising. In descending from altitude for landing, we might trim for a comfortable descent rate. In the pattern we trim for pattern speed based on habitual power settings, and then for our landing reference speed.

But we usually don't trim for a particular airspeed in cruise. Instead, we level off at a certain altitude, accelerate a little while nudging the trim forward, and then pull back the power to cruise setting. Last, we final-trim to zero out the control force necessary to maintain level flight. Then we take the airspeed we get.

Sometimes in flight-testing, or in our program, you'll want to start a maneuver from a specific, trimmed, level-flight airspeed. Here's what you do:

- Bring the aircraft to the required altitude
- Set the power to the approximate value dictated by experience. Of course, don't chase airspeed with large power changes. Just get close.
- Use pitch control to bring the aircraft to the desired airspeed.
- While holding airspeed constant, use power to center the VSI at zero climb/descent rate.
- Trim out the control force.

Note that pitch controls airspeed, power controls the aircraft's flight path angle relative to the horizon.

1. Longitudinal & Directional Stability, Spiral Divergence, Phugoid

Flight Condition: Upright, free response in roll/pitch/yaw.

Lesson: Aircraft behavior when disturbed from equilibrium flight.

Procedures:

Longitudinal Stability: Stick force, Phugoid

Static stability: On the climb to the practice area, trim for V_Y . Observe longitudinal (pitch axis) stick forces needed to fly at airspeeds greater than or less than trim. Assess force gradient. Look for characteristics due to friction.

Simulate the effect on longitudinal stability of moving center of gravity aft: Trim, pitch up to fly 10 knots slower than trim, hold speed while instructor slowly trims nose up. Note how stick force decreases (simulating a decrease in stability), disappears (simulating neutral stability), and then reverses (simulating static instability).

Dynamic stability: Use pitch up and stick release to demonstrate phugoid. Observe period, amplitude, damping.

Directional Stability:

Low cruise power, airspeed white arc.

Enter flat turn with rudder, while keeping wings level with aileron. Observe build up of pedal forces to full deflection.

Quickly return pedals and ailerons to neutral; observe overshoots and damping.

Look for characteristics due to friction.

Lateral Stability: Spiral Mode

Power and trim for low cruise.

Enter a 10-degree bank angle, return controls to neutral and observe response in roll. Note appearance of phugoid. Repeat bank with additional 10-degree increments until onset of spiral departure.

Look for asymmetries by repeating to the opposite side.

Allow spiral mode to develop as consistent with comfort and safety.

Roll wings level; release controls; observe recovery phugoid.

Reduce entry airspeed and observe the increase in roll amplitude versus time.

Knife-edge recovery:

Low cruise power, airspeed white arc.

Roll knife-edge.

Immediately release controls and observe response.

Flight Notes

We'll start by exploring how an aircraft's inherent stability determines its *free response* when disturbed from equilibrium. Free response is what happens when the pilot stays out of the control loop. It's easier to understand the sources of an aircraft's complex, self-generated motions when you can break them down into simpler, free response "modes" around each axis. Usually, a moment generated around one axis produces some form of response around another. From the standpoint of unusual-attitude training, if you understand and can anticipate an aircraft's "basic moves," managing the control loop properly to maintain or to re-establish control becomes closer to second nature.

In aircraft with basic cable-and-pushrod reversible controls, like our trainers, free response can depend on whether the stick and rudder pedals are held fixed or literally left free so that the control surfaces are allowed to streamline themselves to changes in airflow. Irreversible, hydraulically powered controls are always effectively fixed. See FAR Parts 23 & 25.171-181 for stability requirements.

Longitudinal Static and Dynamic Stability

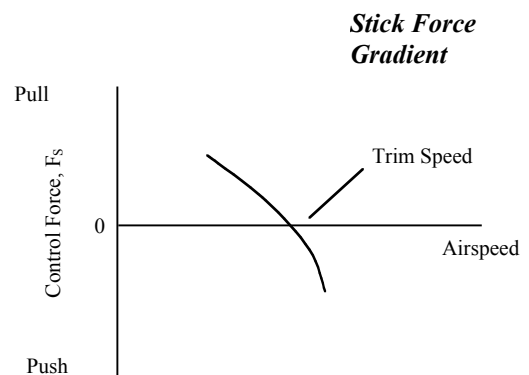
- We'll use some maneuvers borrowed from flight test procedures to look at basic aircraft characteristics. We're going to adapt the procedures to our own purposes, take a general approach, have fun, and not worry about always doing things with the real precision that's required to gain accurate data points in actual flight test. A rough narrative follows.

- Here's the deal on longitudinal static stability, as required by Part 23.173: "... with the airplane trimmed ... the characteristics of the elevator control forces and the friction within the control system must be as follows: (a) A pull must be required to obtain and maintain speeds below the specified trim speed and a push required to obtain and maintain speeds above the specified trim speed."

- On the way to the practice area we'll observe the Part 23.173 requirement. We'll trim the aircraft and then observe the stick forces necessary to fly at slower and faster airspeeds (a.k.a. angles of attack) without retrimming. When we release the force, the nose initially pitches toward the trim angle of attack. This initial tendency is what we mean by positive *static* stability (*static* refers to the initial tendency, *dynamic* refers to the tendency over time). The more force we have to apply to deviate from trim, the greater the stability. We can increase static stability (and thus the stick

forces needed to deviate from trim) by moving the center of gravity forward. We decrease stability (and decrease the forces) by moving it aft. We can fake the effect using trim, as described in the Procedures, above.

- You'll observe that the push force required to hold the aircraft 10 knots, say, faster than trim is noticeably greater than the pull force needed to hold it 10 knots slower. That's because the dynamic pressure generated by the airflow you're holding against is a function of velocity squared, V^2 . The illustration below suggests how stick forces vary with speed. The force is zero at trim speed.



Maneuvers and Flight Notes

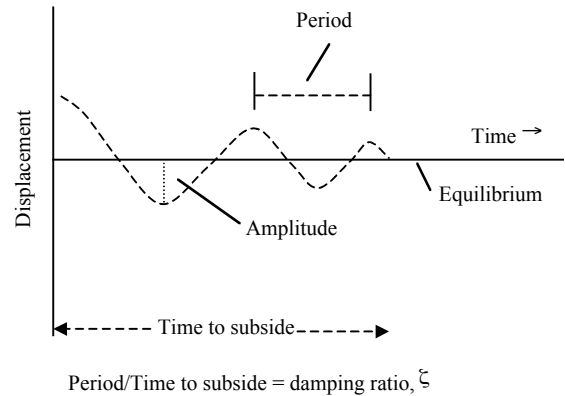
•**Phugoid:** Next, we'll pitch up about 45 degrees or more, slow down and nibble at the stall, then return the stick to its trim position and let go.

(This is a more aggressive entry than actually required to provoke a phugoid, but it's a good attention-getter during unusual-attitude training.)

The nose will start down, again indicating positive *static* stability, but then go below the horizon. Velocity will increase past trim speed, and the nose will begin to rise. Although the aircraft's attitude varies, its angle of attack remains essentially constant. The aircraft will pitch up, slow, pitch down again, speed up, and then repeat this up-and-down phugoid cycle a number of times. It will gradually converge back to its original trimmed state. (Had we simply let go of the stick instead of carefully returning it to the original trimmed position, control system friction might have produced a different elevator angle and a different trim. That, in turn, could superimpose a climb or a dive over the phugoid motion.) Your instructor will point out that the amplitude of each pitch excursion from level decreases (indicating positive damping and thus positive *dynamic* stability) while the period (time to complete one cycle) remains constant at a given trim speed. The period is quite long, so the phugoid is also referred to as the 'long period' mode—and the faster you fly the longer the period. Damping in the phugoid comes from the combined effects of thrust change and drag change as the aircraft alternately decelerates and accelerates as it climbs and descends.

•You'll need right rudder at the top of the phugoid to counter the slipstream and p-factor and keep the nose from yawing, and maybe some left rudder at the bottom. You might need aileron to keep wings-level, as well—but don't contaminate the phugoid with inadvertent elevator inputs.

Positive Longitudinal Dynamic Stability



Directional Stability

•**Flat Turn:** The next maneuver is the basic flight test for static directional (z-axis) stability. When you depress and hold a rudder pedal, causing the nose to yaw along the horizon, you generate a sideslip angle, β . Sideslip creates a side force and an opposing moment. Notice the increased pedal force necessary as rudder deflection increases. For certification purposes, rudder pedal force may begin to grow less rapidly as deflection increases, but must not reverse, and increased rudder deflection must produce increased angles of sideslip. The rudder must not have a tendency to float to and lock in the fully deflected position due to a decrease in aircraft directional stability at high sideslip angles as the fin begins to stall. If it did, the aircraft would stay in the sideslip even with feet off the pedals. (Things could be dicey if the pedal force needed to return a big rudder exceeded the pilot's strength. Many well-known aircraft had rudder lock problems during their early careers, including the DC-3 and the early Boeing 707, and the B-24 Liberator bomber.)

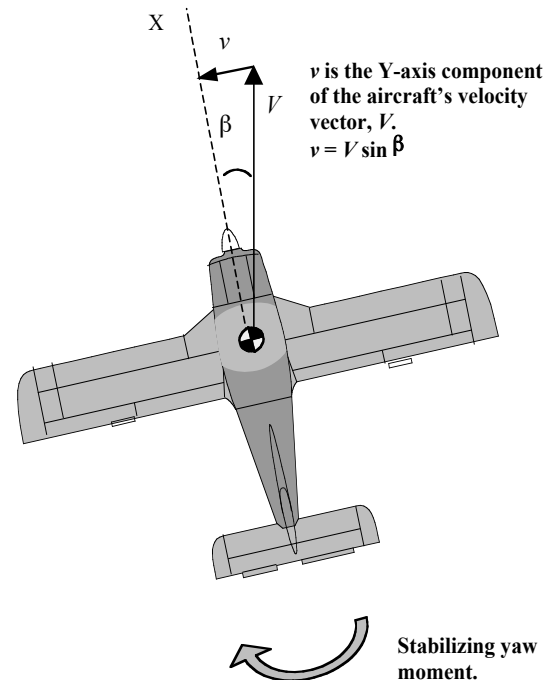
•A given rudder deflection produces a given sideslip angle, but the force required rises with the square of airspeed. So we won't have to work as hard if we pull the power back to keep the speed down.

•When you release or quickly center the pedals, the now unopposed side force causes the aircraft to yaw (weathervane) into the relative wind. In our jargon, *the directionally stable aircraft yaws its plane of symmetry back into alignment with the velocity vector*. This initial tendency demonstrates positive *static* directional stability. We've entered a dynamic state, as well. Momentum takes the nose past center, which generates an opposing side force that pushes it back the other way. The nose keeps overshooting, but the amplitude of the divergence decreases each time. This time history indicates positive *dynamic* directional stability. You might notice an increase in damping when you return the rudders positively to neutral and hold them fixed, instead of letting them float free. However, this behavior also depends on the amount of friction in the rudder control circuit.

• Notice that the aircraft tries to roll in the direction of the deflected rudder, and that you have to apply opposite aileron to keep the wings level. This is caused by a combination of dihedral effect (an aircraft's tendency to roll away from a sideslip angle, β , a response we'll examine presently), and roll due to yaw rate—in which one wing moves faster than the other and produces more lift. An aircraft with reduced directional stability may yaw faster in response to rudder deflection than will a more stable type, and go to a higher β , and consequently need more opposite aileron. (You'll see a difference between the Zlin and the SF 260 in this regard.)

•Finally, note that when you apply aileron against the roll, you're also applying an additional "pro-rudder" yaw moment, this time caused by the adverse yaw that occurs when the into-the-turn aileron goes down. (There're other moments in the mix we won't worry about.)

Directional Stability



Spiral Mode

- When you enter a shallow bank and positively return the controls back to neutral (so that unintended deflections or control system friction don't taint the result) the aircraft should slowly start to roll level after a few moments. The aircraft's velocity vector (for a definition, see ground school text "Axes and Derivatives") has a component of motion (sideslip) toward the low wing, which leads to a wings-level rolling moment due to dihedral effect—a response referred to as lateral stability. The aircraft's lateral stability provides positive spiral stability. Sideslip also produces a yawing tendency, but dihedral effect predominates at smaller bank angles.

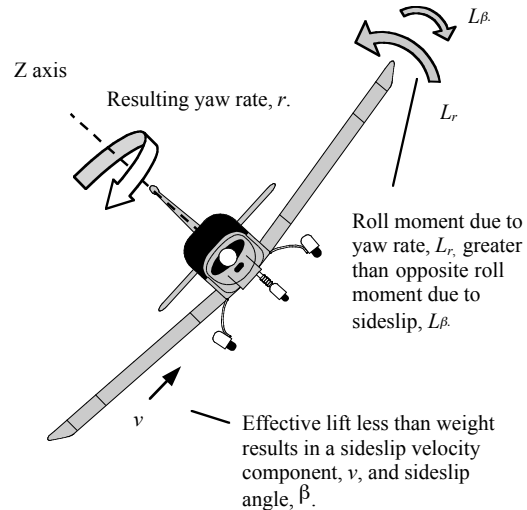
- The outside wing in the turn is moving faster than the inside wing—that's a yaw rate. As you add bank increments you'll find a point—if the atmosphere's not too turbulent—where bank angle remains constant (neutral spiral stability). The rolling moments produced by dihedral effect and roll due to yaw rate are now equal and opposite. (Again, there're other moments in the mix, but their contribution is minor.)

- At some point the aircraft will likely begin a banked phugoid, just like the phugoids we've observed, but tipped on its side. The aircraft will bring its nose up and down as it turns. Hands off, the aircraft retains a constant angle of attack, according to trim, regardless of pitch attitude or bank angle.

- When we raise the bank angle further, but don't increase lift by adding back stick, the aircraft slips increasingly toward the low wing. The yaw rate builds due to the greater side force against the tail. Directional (z-axis) stability causes the nose to weathervane earthward in a descending arc. Now roll due to yaw rate predominates over the opposite rolling moments, and sends the aircraft into the unstable spiral mode

- Test pilots typically place an aircraft in a given bank angle, center the ailerons (or bank the aircraft with rudder while holding the ailerons fixed), and then time the interval required to reach half the bank angle for the spirally stable condition, or double the bank angle for the unstable. It's important that control surfaces are

Sideslip Becomes a Spiral Dive When Dihedral Effect \times Yaw Damping < Directional Stability \times Roll Due to Yaw Rate



positively centered during these tests, because any residual deflection caused by control system friction can create an apparent difference in spiral characteristics. (Friction confuses the picture when you're trying to figure out how an aircraft behaves. Friction in the elevator system makes you think longitudinal stability is different than it is; friction in the ailerons that prevents them from returning to center automatically when released gives you a roll rate that shouldn't be there. Normally, you'd accommodate to such things without really being aware of the extra control input—but here we're paying attention!)

- The coefficient of roll moment due to yaw rate, C_{lr} , goes up with coefficient of lift, C_L , so it's more pronounced at low speeds, where α and coefficient of lift are high. And for a given bank angle, yaw rate goes up as airspeed goes down. So you'll double your spiral bank angle more quickly at lower entry speeds.

- Finally, note that the ball stays essentially centered during a spiral departure. That's directional stability doing its job, unto the last.

Phugoid Again

•**Recover from spiral dives by first rolling the wings level with the horizon.** Now we're back in the more familiar wings-level phugoid. Notice how the aircraft's positive *static* longitudinal (y-axis) stability initially brings the nose back to level flight. You'd normally push to suppress the phugoid as the nose comes level with the horizon, but we'll again allow the aircraft to go past level and progress through the first cycles of the phugoid mode.

•Again, you'll need right rudder at the top of the phugoid to counteract the slipstream and p-factor and keep the nose from yawing, and some left rudder at the bottom. Jets and counter-rotating twins don't have this problem.

•An aircraft's longitudinal stability comes from its tendency to maintain a trimmed angle of attack. As you ride through it, the attitudes, altitudes, and airspeeds change, but ***in a phugoid the angle of attack, α , remains basically constant.*** The attitude excursions of our constant- α phugoid remind us again that an aircraft's angle of attack and its attitude are two different things. When displaced, aircraft return to their trimmed attitude and airspeed by virtue of maintaining their trim angle of attack throughout a cycle of phugoid motions. In essence, pilots keep *altitude* pegged by keeping ahead of the phugoid and damping its cycle themselves. A power change provokes a phugoid, unless the pilot intervenes to smooth out the transition.

•We'll experience an increased g load as airspeed exceeds trim speed at the bottom of the phugoid. At a constant angle of attack, lift goes up as the square of the increase in airspeed. If we trim for 100 knots in level flight (1 g) and manage things so as to reach 200 knots (which we won't!), airspeed will be doubled and load factor will hit a theoretical 4 g. If we accelerate to 140 knots, that's a 1.4 increase in speed. $1.4^2 = 2$; thus a load factor of 2 g. (The actual factor can be affected by the mass balance of the elevator, or the presence of springs or bob weights.) We'll experience less than 1 g over the top.

•The phugoid shows us how a trimmed, longitudinally stable aircraft normally maintains its speed if left to its own devices. After a disturbance, it puts its nose up or down, trading between kinetic and potential energy, until it eventually oscillates its way back to trim speed (or to its trim speed band if control friction is evident). But the trade becomes solely potential to kinetic when a bank degenerates into a spiral and, as we've seen, the bank angle becomes too steep for the phugoid to overcome. Think of a spiral departure as a "failed" phugoid, in which the nose can't get back up to the horizon because the lift vector is tilted too far over.

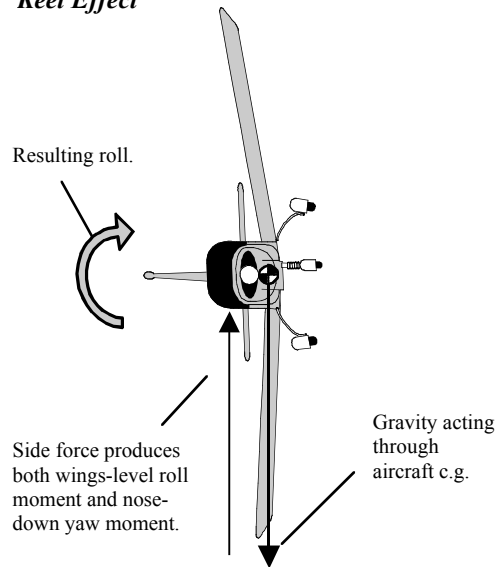
•What if an aircraft trimmed for cruise rolls inverted for some reason and the befuddled pilot just lets go? Left unattended, the inverted aircraft will pursue its trim by dropping its nose and "reverse-phugoiding" itself around in a rapidly accelerating back half of a loop (a "split-s"). Speed will rise until the structure maybe quits, or the dirt arrives. Inverted, hands-off survival prospects improve in the unlikely situation that the aircraft is at altitude but trimmed for slow flight. Trimmed for 70 knots with power for level flight, and then rolled inverted while the nose is allowed to fall, the Zlin will pull a 4-g split-s, hands-off on its trim state alone, using up some 1,300 feet of altitude. Then it will playfully zoom right back up into a normal but initially high-amplitude phugoid.

Knife-edge Free Response

•After you've observed spiral characteristics, and learned to expect divergence following a high bank angle, knife-edge behavior might surprise you. Starting at knife-edge with the nose on the horizon, when the controls are released an aircraft with positive dihedral effect will generally roll upright and pitch nose-down (and then eventually pitch up into a phugoid if you don't touch the elevator). The roll response has been associated with the amount of "keel" area above the aircraft's c.g. Acting at different locations and in opposite directions, aerodynamic side force and gravity produce a roll couple. This wings-leveling couple, added to that generated by dihedral effect, overcomes the opposing spiral tendencies caused by directional stability and roll due to yaw rate.

•If you enter knife-edge flight, or even just a steep bank angle, in a nose-high attitude, however, spiral tendencies will often dominate. It's fun to examine this by flying aggressive lazy-eights (linked wingovers) and observing

Keel Effect



which moments win out when you let go of the stick and/or rudder at various points. Note the phugoid embedded in the maneuver as the aircraft climbs and descends.

2. Steady-Heading Sideslip: Dihedral Effect & Roll Control

Flight Condition: Upright, crossed controls, high β .

Lesson: Lateral behavior during sideslips.

Procedures:

Power for speed in the white arc.

Apply simultaneous aileron and opposite rudder to rudder stop.

Aileron as necessary to maintain steady heading with no yaw rate.

Maintain approximate trim speed. Aircraft will descend.

Hold rudder/ **release stick**.

Repeat in opposite direction.

Hold stick/ **release rudder**. Observe sequence of yaw and roll.

Hold sideslip. Pitch up and down to demonstrate y-wind-axis pitch/roll couple.

Possible Maneuver: Hold the sideslip and demonstrate “over the top” spin entry, with immediate, **controls neutral** recovery.

Flight Notes

A directionally and laterally stable aircraft yaws toward but rolls away from its velocity vector when the vector is off the plane of symmetry. Those characteristics are the “basic moves” of directional and lateral behavior. In our steady-heading sideslips, we’ll apply cross-controls—rudder in one direction and aileron in the other—causing the aircraft to fly with its velocity vector displaced from symmetry. The control forces necessary to prevent the aircraft from yawing and rolling in response to that displacement are the reflection of its inherent stability. They tend to change with angle of attack, especially in the buffet boundary, where aileron effectiveness often deteriorates and the rudder takes on increasing importance for lateral control. In that regime, a pilot often displaces the velocity vector on purpose, to assist roll control. (He may not know that’s what he’s doing, but nevertheless...)

Pilots of flapless (usually aerobatic) aircraft are accustomed to using sideslips to control the descent to landing. It’s how they show off in front of the aircraft waiting at the hold line. If you rely on flaps for descent, you may be rusty on aggressive cross-control slips. A little practice with them will improve your ability to respond to control system failures. You counter the rolling moment generated by an uncommanded rudder or aileron deflection by entering an opposing sideslip, modifying the sideslip as necessary for turns.

•Test pilots use steady-heading sideslips to evaluate an aircraft’s lateral stability. That means its tendency to roll away from the direction of a sideslip—in other words, to *roll away from the*

direction the velocity vector is pointed when the velocity vector is not on the plane of symmetry. (The mechanics of lateral stability, or dihedral effect, are explained in more detail in the ground

Maneuvers and Flight Notes

school text “Lateral-Directional Stability.”)

Steady-heading sideslips are also used to assess directional stability and rudder effectiveness by measuring the rudder deflection and pedal force needed to produce a given sideslip angle, β .

They can also be used to evaluate control harmony and to set up the conditions for observing Dutch roll. Wing-low crosswind landings are steady-heading sideslips, so an aircraft’s behavior in sideslips can limit crosswind capability.

- Pressing the rudder and yawing the aircraft creates a sideslip angle between the aircraft’s velocity vector and its x-axis plane of symmetry, as illustrated to the right, below. This in turn produces a rolling moment due to dihedral effect. We’ll evaluate the strength of this *yaw/roll couple* at various sideslip angles by observing the aileron deflection needed to counteract the roll and fly the aircraft at a constant, steady heading, although sideways and wing-low.

- You’ll enter a steady-heading sideslip by applying crossed controls: deflecting the rudder while adding opposite aileron to keep the aircraft from turning. Notice how the forces and deflections increase as you move the controls toward the stops. Under FAR 23.177(d), “the aileron and rudder control movements and forces must increase steadily, but not necessarily in constant proportion, as the angle of sideslip is increased up to the maximum appropriate to the type of airplane... the aileron and rudder control movements and forces must not reverse as the angle of sideslip is increased.”

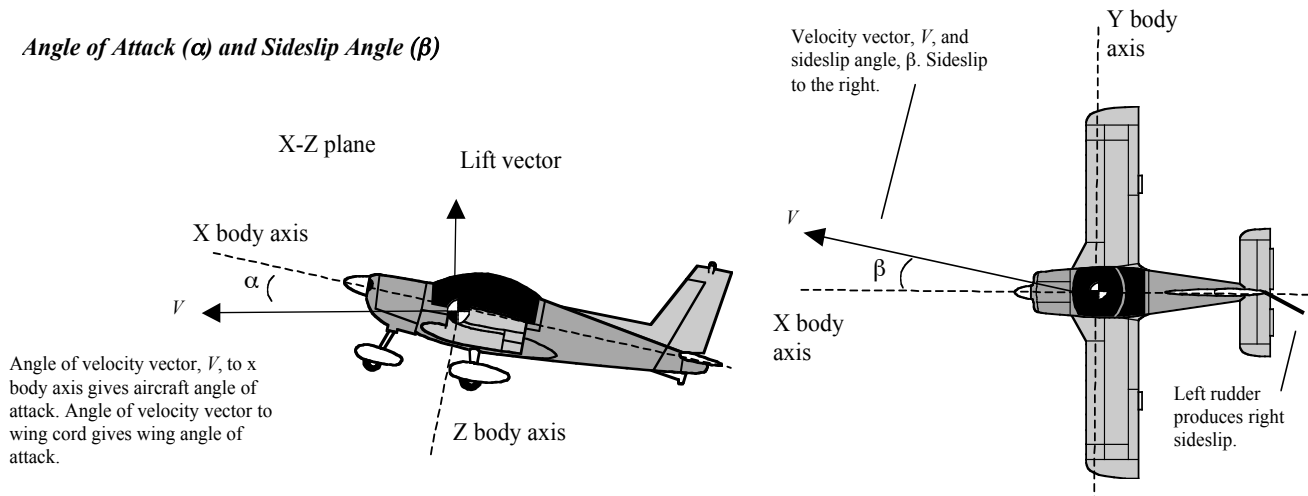
- Do you notice any differences sideslipping to the left or right, possibly caused by p-factor or slipstream?

- Dihedral effect can depend on aircraft configuration. It can diminish with flap extension. This is important in connection with rudder hard-overs, because flaps lower “crossover” speed, as you’ll see later.

- When you release the *stick* while holding rudder, the low wing rises due to dihedral effect *and* to roll due to yaw rate. Dihedral effect, strongest at first, decreases as the sideslip angle goes to zero. Roll due to yaw rate, weak at first, increases as the yaw rate rises; then suddenly disappears when the yaw damps out. The capacity to raise a wing with rudder alone, in case ailerons fail, is a certification requirement for non-aerobatic aircraft, and this stick release is a standard flight-test procedure.

- Aerobatic aircraft without much dihedral effect (such as the Great Lakes, or the Yak-52) often tend not to roll toward level but to pitch down at stick release. An aircraft’s *pitching moment due to sideslip* may be nose-up or down, minimal or pronounced, different left or right—depending on how propeller slipstream, fuselage wake, and the downwash generated by the wing and flaps affect the horizontal stabilizer. The combination of longitudinal (pitch) and lateral (roll) forces you find yourself holding helps you anticipate how aggressively the aircraft will respond on release. The Zlin is a great trainer in this respect.

Angle of Attack (α) and Sideslip Angle (β)



Maneuvers and Flight Notes

When the stick is released in a sideslip to the left (right rudder down, left aileron), the Zlin can aggressively pitch-up and roll right, the combined motions leading to a sudden increase in the angle of attack of the right wingtip, and a possible tip stall. Much fun!

- Swept-wing aircraft can build up large rolling moments during sideslips, and mishandling can put even a large aircraft on its back. Sideslip angles are generally restricted to around 15 degrees during flight test for transport aircraft. FAR 23.177(d) says that a “Rapid entry into, and recovery from, a maximum sideslip considered appropriate for the airplane must not result in uncontrollable flight characteristics.” “Rapid” is a key word here, since a slow entry to and recovery from a sideslip keeps the aircraft’s angular momentum under control.

- Things get a little complicated now, and we apologize. Notice that when you first release the *rudder*, while holding aileron deflection constant, the aircraft doesn’t respond to the ailerons and immediately start rolling. Watch how the nose yaws and reduces the sideslip *before* the roll begins. The vertical stabilizer’s center of lift is above the aircraft’s center of gravity. As a result, the rudder deflection in a steady-heading sideslip actually produces an added roll moment in the same direction as the ailerons. (See Figure 17 in the ground school text “Lateral-Directional Stability.”) Releasing just the rudder eliminates this rolling moment contribution, but replaces it briefly by a rolling moment due to yaw rate as the aircraft straightens out. (Did you get that?) The important point is that only after the aircraft’s directional stability substantially eliminates the sideslip will the ailerons start to dominate and the aircraft roll. This really is less confusing with a hand-held model for demonstration, or in the aircraft where you can see things unfold.

- Our trick of holding the ailerons in place while releasing the rudder allows us to keep the roll moment due to aileron deflection fixed. We can then observe the yaw as the aircraft’s directional stability realigns the nose with the velocity vector. We can observe the ramp-up in roll response and properly attribute it to the vanishing sideslip. This gives us a way to use a

steady-heading sideslip to demonstrate the relationship between sideslip and aileron effectiveness. A sideslip can either work for a roll rate, or against it. For a given aileron deflection, ***in an aircraft with dihedral effect, roll rate goes down when rolling into a sideslip*** (right stick, right velocity vector, say, as in the sideslip seen from above, illustrated on the previous page). Such an “adverse” sideslip could typically happen in an aircraft with adverse yaw and not enough coordinated rudder deflection when beginning the roll. On the other hand, stomping on the rudder too hard while rolling with aileron will skid the airplane and demonstrate that ***a proverse sideslip, opposite the direction of applied aileron, increases roll rate***—in addition to sliding your butt across the seat. That stomp could be a useful trick for accelerating roll response in an emergency, but in swept-wing aircraft could lead to a severe Dutch roll oscillation. The fundamental relationship between sideslip angle (angle of the velocity vector versus plane of symmetry) and *roll rate* is something many pilots never really get—maybe because instructors think that the rudder affects only yaw. But in a laterally stable aircraft, yaw just about always provokes a rolling moment.

- Roll couple for a given sideslip angle, β , and aircraft configuration varies in direct proportion to the coefficient of lift, C_L .*** That’s certainly the case with swept-wing aircraft, and at least apparently the case with straight-wing, although not to the same degree. (See ground school text “Lateral-Directional Stability.”)

- Roll due to yaw rate also varies directly with C_L ,*** as noted when we observed the spiral mode. When we fly steady-heading sideslips, we try to isolate dihedral effect by keeping the heading steady and eliminating yaw rate. But there’s always a yaw rate when we enter and leave the maneuver, and of course sideslips and yaw rates occur together in turbulence. Their individual contributions at a given moment can be difficult to sort out.

- You can think of the deflected rudder (or an existing sideslip) as setting the direction and initial rolling tendency, and of the elevator as modulating the rate through its control of C_L .

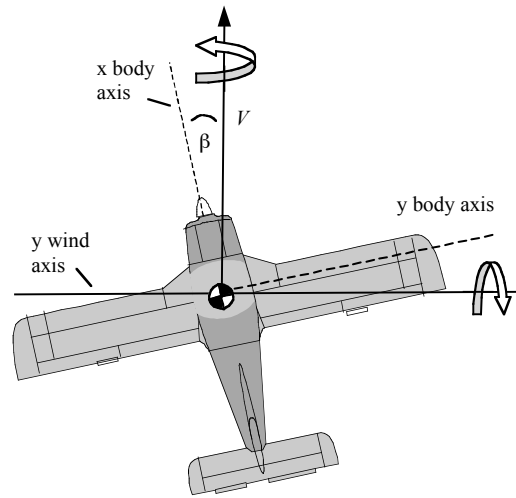
This is easy to remember, because *when you raise C_L by pulling back on the stick, toward the rudder, roll moment produced through dihedral effect and roll due to yaw rate increases. When you lower C_L by pushing, the contribution decreases.* This relationship holds for both straight and especially for swept wings, although the mechanisms and some details are different, as the ground school illustrates. It also works upside-down; as long as you have positive g. You will see this when we do rudder rolls.

•Or, if you prefer a more visceral terminology, put it this way: *Hauling back and “loading” an aircraft increases yaw/roll couple; “unloading” decreases it.* And that’s not all unloading does, as we’ll note more than once. Imagine that you’re operating at an angle of attack high enough to reduce aileron effectiveness through airflow separation, and high enough to disrupt flow over the tail such that yaw-axis stability is reduced and a sideslip develops. Putting the stick forward and unloading will reattach the flow, bringing the ailerons back while also reducing the sideslip-generated roll couple by reducing coefficient of lift, C_L . (Examples might be during an *immediate* recovery from an initial stall/spin departure—developed spins are handled with rudder first—or during a recovery from a rudder hardover.)

• With a swept wing, the dihedral effect derived specifically from sweep actually disappears at zero C_L . A sideslip then no longer produces a rolling moment, unless the wing also has geometrical dihedral (tips higher than roots), which does work at zero C_L . (Again, see ground school text “Lateral-Directional Stability.”)

•**Wind-Axis:** In this maneuver set we pushed and pulled on the on the stick while sideslipping. We watched the motion of the nose relative to the horizon, and discovered that the aircraft was pitching about its y wind axis, not its y body axis. Because of the displacement of the y wind axis from the body axis, a pitching moment also produces a rolling moment, as described in the illustration to the right. This geometrical effect works in the same direction as the C_L effect described above. In other words, pulling will geometrically produce a rolling moment opposite the velocity vector; pushing will produce a

Aircraft Pitch Around Y Wind Axis



The y wind axis remains perpendicular to and moves with the velocity vector, V . The aircraft pitches around the y wind axis. Geometrically, this also produces a roll. So in a sideslip to the right, as above, pulling the control back causes a roll to the left; pushing forward causes a roll to the right.

rolling moment toward the vector. This is another effect that’s tough to visualize, but if you spend a few minutes fiddling with a small aircraft model you just might have a revelation.

Maneuvers and Flight Notes

•Steady-Heading Sideslip Spin Departure:

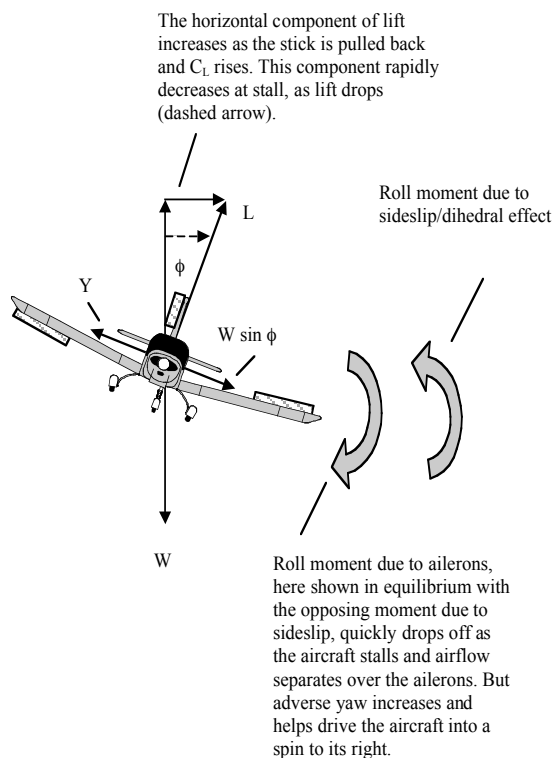
More confusing stuff, sorry again: Here's what happens when we stall the aircraft during a steady-heading sideslip, by holding crossed rudder and aileron while increasing aft stick. In a steady-heading sideslip to the aircraft's left, as illustrated here, right rudder is deflected; ailerons are left. The horizontal component of lift created by the bank angle pulls the aircraft to its left and thus generates a nose-left aerodynamic force against the tail. We counter the resulting left yaw moment with right rudder to maintain our steady heading. At the stall, as lift goes down so does its horizontal component and the resulting yawing moment to the left. This allows the rightward yaw moment generated by right rudder to

dominate. If we hold control positions the aircraft yaws and rolls to the right in an "over the top" entry into a spin.

- Going over the top is the most congenial way for the aircraft to behave, because the wings first roll toward level and there's more time for recovery. Bringing the stick forward and neutralizing the other controls should keep the aircraft from entering a spin. Opposite rudder might also help. Remember that aircraft always depart toward the deflected rudder (opposite the displaced velocity vector). So you won't break toward the low wing in a sideslip—it just feels like you might because that's the direction in which you're sliding off your seat.

- Note that in a side-slipping spin departure to the aircraft's right, for illustration, the left aileron we originally hold to maintain a steady heading, and then for demonstration keep in at the stall, doesn't arrest the rightward roll off. There's too much airflow separation by that point for the ailerons to generate much opposite roll. But the down aileron still produces lots of adverse yaw, which pulls the right wing back and encourages a spin entry.

Steady-heading Sideslip Spin Departure



3. Stall: Separation & Planform Flow (Wing tuft observation)

Flight Condition: Upright, power-off 1 g stall, high α .

Lesson: Stall anatomy.

Procedures:

Clearing turns.

Power idle.

Trim for 1.5 times anticipated stall speed.

1-knot-per-second deceleration below 70 knots.

Note buffet onset airspeed and stall speed.

Full stall before power-off recovery.

Power as required for recovery and climb.

Repeat with 5-knot-per-second deceleration below 70 knots.

Stalls while watching the wing tufts.

Provoke secondary stall in recovery.

Repeat with flaps. (Is there a difference in “break?”)

Flight Notes

We’ll cover boundary layers, adverse pressure gradients, and wing planform effects in the ground school and supporting texts. Then, as an accomplished aerodynamicist, you’ll be able to interpret the sometimes-surprising motions of the wing tufts and the accompanying separation of the airflow from the wing as α rises or the aircraft’s configuration changes. FAR Parts 23 & 25.201-207 cover stall requirements.

- On the way to the practice area, note the turbulence in the boundary layer as shown by the movement of the wing tufts. Note the increased movement as the turbulent layer thickens downstream.

- Don’t make our stalls a minimum-altitude-loss, flight-check-style exercise. Give yourself time to observe the full aerodynamic progression. Play around. But remember: ***This is not procedure training. Follow the recovery techniques in your aircraft’s AFM or POH.***

- For FAR Part 23 and 25 certification, stall speeds are determined for the aircraft configured for the highest stall speed likely to be seen in service. In part, this means at maximum takeoff weight and forward center of gravity limit, trim set for 1.5 anticipated stall speed, and using an airspeed deceleration rate of 1 knot-per-second starting at least 10 knots above stall. We’ll try to maintain this deceleration rate for later comparison to a 5 knot-per-second deceleration entry. Up to a point, increasing the deceleration

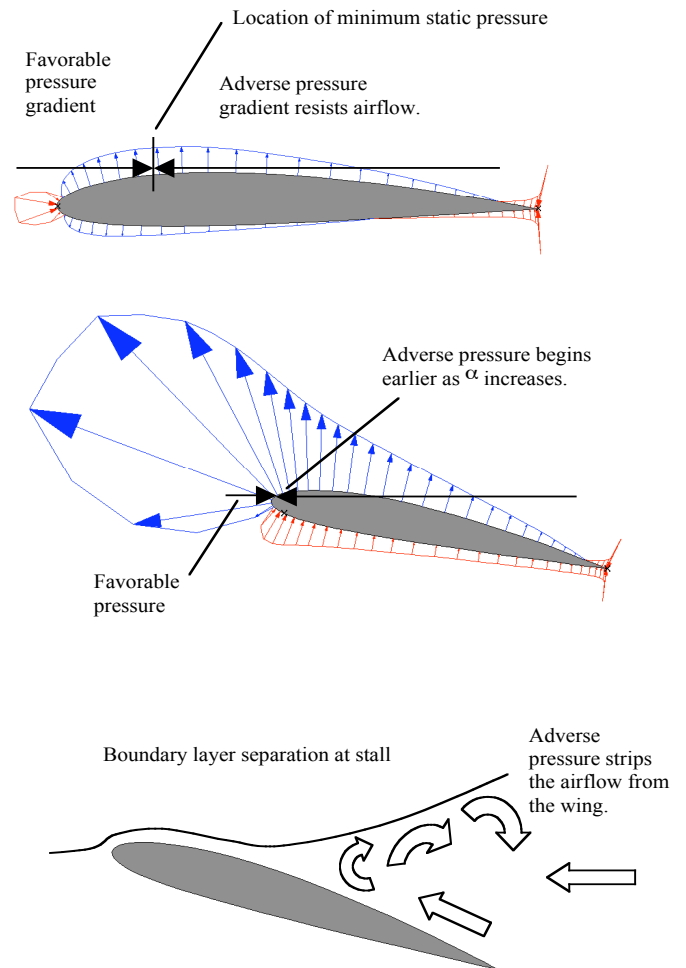
Maneuvers and Flight Notes

rate beyond 1 knot-per-second usually drives down the stall speed, but then the load factor starts to rise and stall speed increases. The decrease in stall speed that comes with a somewhat increased deceleration occurs because of the delay in pressure redistribution as α rises. This delays separation and allows the wing to function briefly at a higher angle of attack and coefficient of lift than normal, a phenomenon called *dynamic lift* to differentiate it from the lift conditions at static angles of attack measured in a wind tunnel. Lift normally creates a downwash over the horizontal stabilizer, and thus a nose-up pitching moment. The nose pitches down when the downwash disappears at the stall. Dynamic lift delays this to a higher angle of attack.

- It's important that a rapid deceleration produced by a high pitch rate doesn't compromise control authority. That's not an issue with our aircraft, but can be with large aircraft in which pitching momentum can carry and momentarily hold the aircraft past stall angle of attack, with insufficient airflow available for positive control. On the other hand, a deceleration rate below 1 knot-per-second may not produce maximum α .

- Watch the tufts. The trainer has the root-first stall progression typical of its wing shape. In contrast, swept wings naturally stall first at the tips. They're coerced to behave more in a root-first manner by the use of stall fences, vortilons, vortex generators, and changes in airfoil from root to tip.

- Notice the definite relationship between airflow separation at the wing root, as evidenced by the tufts, and the buffet onset in our training aircraft. Do you feel the buffet in the airframe, mostly in the stick (as in the L-39 jet trainer), or in both? In our aircraft the buffet provides plenty of aerodynamic stall warning. Compare this to a T-tail design where the turbulent flow largely passes beneath the stabilizer and stall warning has to be augmented by a mechanical stick shaker, or to planform designs where the wing root separation happens too late to provide much aerodynamic warning. In the MiG-15, for example, there's no real buffet—the stick gets light and lateral control goes to mush.



- You might want to do a couple of stalls with the instructor assisting in directional control while you concentrate on the wing and play the stick to modulate the full tuft stall progression from root to tip. If you've done the relevant ground school, visualize and manipulate the adverse pressure gradient in the chordwise direction, and the change in local coefficient of lift in the spanwise direction. Note the change in airflow over their surfaces (as shown by the tufts) when the flaps or ailerons go down. When the flaps go down, note the vortex that forms on the outboard tip. Acting on the tail, the increased downwash from this vortex causes the pitch-up that follows flap deployment.

- The secondary stall we provoked on purpose, by pulling too hard on recovery, reminds us of

Maneuvers and Flight Notes

the absence of positive (nose-up) pitch authority at maximum lift coefficient, $C_{L_{max}}$, regardless of aircraft attitude. ***We can run out of elevator (and aileron!) authority in any attitude when there's no angle of attack in reserve.*** The absence of positive pitch authority, in the form of an “uncontrollable downward pitching moment” is one of the ways the FAA defines a stall for certification purposes under FAR Part 23.201(b). We'll revisit this loss of pitch authority when we fly loops, and during the pull-up recovering from spins.

- Part 23.201(d) states, “During the entry into and the recovery from the [stall] maneuver, it must be possible to prevent more than 15 degrees of roll or yaw by the normal use of the controls.” In coordinated flight, our trainers tend to stall straight ahead, without dropping a wing—at least not initially. If you hold the stick back during the stall oscillation, a wing may drop. Many aircraft, like the sultry Siai Marchetti SF260, will announce a stall more by a wing drop than by a nose-down pitch-break (also called a g-break). Some airfoil and planform arrangements can be demanding, no matter how carefully the pilot keeps the ball centered. A venerable T-6 Texan or SNJ will generally drop to the right. The right wing stalls first, reportedly, because it's set at a higher incidence. Our ground school video of a T-6 wing shows how the stall pattern leads to early flow separation in the aileron region. Our video of the Giles G-200 aerobatic aircraft shows a rapid trailing-to-leading-edge stall, which gives

no buffet warning, and in this particular aircraft produces a sudden drop to the left.

- Stall separation can also begin at the leading edge, and aircraft with leading-edge stalls typically misbehave. The stall break, perhaps caused by the sudden bursting of the laminar separation bubble, is abrupt and usually happens asymmetrically due to physical differences between the leading-edge spans. A wing drop is likely. On various Lear models, if the leading edge has been removed for repair, a test pilot will come out from the factory to do a stall test before the aircraft goes back in service.

- Even if meant to be, aircraft often aren't aerodynamically symmetrical in behavior. In practice, manufacturing tolerances simply aren't that tight; and a life of airborne adventure takes its toll. The PA-38 Piper Tomahawk became a particular offender when the production aircraft were built with fewer wing ribs than the prototype used for certification tests. This allowed the wing skins to deform—or “oilcan”—under changing air loads. Unfortunately, the performance of its GA(W)-1 wing is very sensitive to airfoil profile. The deformations led to rapid and unpredictable wing drop at stall. Prompt, proper recovery inputs were necessary. The Tomahawk has about twice the stall/spin accident rate per flight hours as the Cessna 150/152.

4. Accelerated Stall: G Loads & Buffet Boundary, Maneuvering Stability

Flight Condition: Banked, high α .

Lesson: Flight behavior under turning loads.

Procedures:

Power low cruise.

Trim.

Using instrument or outside reference, roll to bank angle specified by instructor.

Keep the ball centered with rudder.

Apply stick-back pressure to buffet, reducing power or increasing bank angle as necessary.

Note buffet speed, stall speed, buffet margin as compared to 1-g stall.

Repeat at higher bank angles. Note **exponential** rise in buffet speeds and stick force.

Explore aileron effectiveness in buffet by rocking wings 15 degrees left and right.

Flight Notes

Earlier, we increased the airspeed deceleration rate to lower the “book” stall speed. Here we use load factor to raise it.

- Stall speed goes up by the square root of the load factor, n . ($n = \text{Lift/Weight}$).
- Induced drag goes up by the square of the load factor.
- Thus whenever you raise the load factor (pull “g”), stall speed and drag also rise. You can’t feel the latter two directly; you have to learn the association. The increasing stick force is one cue that the numbers are ascending. The force driving you into your seat is another.
- Of course, hangar wisdom holds that a wing’s *stalling angle of attack remains constant* for a given configuration (high-lift devices in or out). That’s a small fiction, but also a profound working “truth” because it emphasizes angle of

attack as the essential stall determinant, not just a number on the airspeed dial—a number that itself changes with weight and load factor for a given configuration. If you want to be picky, stalling angle of attack depends on Reynolds Number, which is the ratio between inertia forces and viscous forces in the boundary layer on the surface of the wing. For a given airfoil, stall angle of attack rises with Reynolds Number.

- Notice the increased buffet intensity in the accelerated stalls compared to those at 1 g. There’s more energy in the turbulent airflow shed by the wing at this higher buffet speed (the inboard wing tufts tend to capitulate and blow off after repeated accelerated stalls), and more energy in the surrounding free stream flow.

Pitch Damping

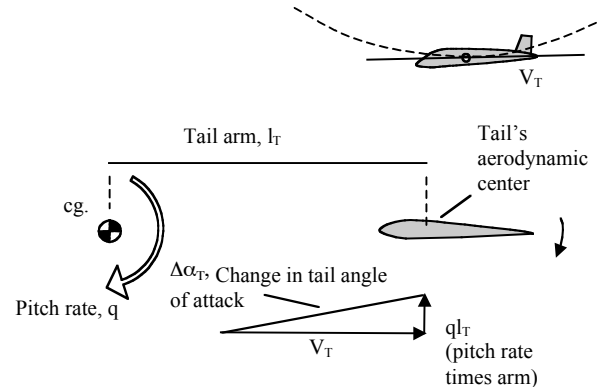
- At higher g, does the buffet margin change compared to a 1-g stall? The comparison should be made at the same knots-per-second airspeed deceleration rate to be valid. Often stall warning varies inversely with knots-per-second, more rapid entry producing less warning. A rapid entry is probably typical of pilot technique in an accelerated stall.

- The accelerated stall and the 1-g stall both occur at the same angle of attack, but the accelerated stall requires a heftier pull. The aircraft exhibits an increase in pitch stability as the g load rises (meaning a stronger tendency to return to trim speed, which is the tendency you're pulling so hard against). That's because the angular velocity of the tail, caused by the pitch rate in the turn, produces a change in tail angle of attack, as illustrated to the right, and thus an opposing damping moment. Increasing the g load means increasing the pitch rate, and ups the damping. The additional elevator deflection needed to overcome more damping requires more force. This effect leads to what's called *maneuvering stability* (which we cover in the ground school text "Longitudinal Maneuvering Stability"). Damping is a function of air density, and goes down as you climb.

- The geometry is such that, for a given g, an aircraft has a higher pitch rate (thus higher damping) in a turn than it does in a wings-level pull up. As a result, you'll pull harder in a 2-g turn than in a 2-g pull up, for example.

- At a given density altitude, in aircraft with reversible control systems, like ours, the necessary stick-force-per-g is independent of airspeed (although Mach effects may increase forces at higher speeds). In other words, the force required to pull a given g doesn't increase with airspeed, as you might naturally think. (Of course, it's a bit more complicated. See ground school text "Longitudinal Maneuvering Stability.")

- The table farther on shows how load factor increases exponentially with bank angle in a constant-altitude turn. It follows that stick forces



also increase exponentially, rather than uniformly, with bank angle. A pilot banking into a steep turn has to increase his pull force at a faster and faster rate. Stick force rises slowly at lesser bank angles. Past 40 degrees or so, the increasing force gradient starts becoming more apparent. There's a surprising difference in the force necessary for a 55-degree versus a 60-degree bank. Steep turns might get a little easier (maybe) once you figure this out.

- Notice the instant transformation in control authority at recovery due to the increased airspeed in the accelerated stall. Watch the wing tufts to see how quickly the airflow reattaches when you release some aft pressure. The damping you generate in the turn pushes the nose right down. At 2 g's there's a 40 percent increase in stall speed. Because dynamic pressure goes up as the square of the airspeed increase, that means double the dynamic pressure ($1.4^2 = 2$) available for flight control compared to a recovery from a stall near 1 g. More dynamic pressure means more control response for a given deflection. You can recover from an accelerated stall while the wing is still loaded (pulling more than 1 g). You only have to release enough g to get the stall speed back down.

Maneuvers and Flight Notes

•But releasing g may not always be equivalent to releasing your aft pressure on the stick. In some aircraft (often former military) you may have to push to expedite things. You may find that the gradient of stick force rises more slowly as g increases, as it does in the L-39 jet trainer because of the bungee cord “boost” within the elevator circuit. Or the aircraft may have an aft c.g., which increases maneuverability at the expense of stability, and thus reduces the tendency to pitch the nose down when aft pressure is released. Early swept-wing fighters had a tendency to stall at the tips first. Because of the sweep, a loss of lift at the tips shifted the center of lift forward and caused the aircraft to pitch nose-up and “dig in” during accelerated stalls.

•The higher dynamic pressure while maneuvering can lead to higher rolling moments if the wings stall asymmetrically. Any wing-dropping obstreperousness an aircraft might hint at during 1-g stalls can intensify at the higher airspeeds of an accelerated stall. Our rectangular-wing trainers stall root-first, and resist roll-off if flown in a coordinated, ball-centered manner. But accelerated stalls in other aircraft can be defined more by a wing drop than by a pitch break or a stolid, straight-ahead mush.

•As the load factor increases, the stall speed starts coming up to meet your airspeed. At the same time, if you didn’t or can’t increase power (“thrust-limited”), your airspeed starts heading down because of the increased induced drag. Eventually, if you pull hard enough, the two speeds converge. If an aircraft is thrust-limited, test pilots will perform descending, *wind-up turns* to explore its behavior at higher g, by turning altitude into the increasing airspeed necessary to attain increasing g levels.

•***Because stall speed rises in a turn, your calibrated airspeed above 1-g stall dictates your bank-angle maneuvering envelope. The closer you are to the 1-g (wings-level) stall speed in a given configuration, the less aggressively you can bank and turn an aircraft while keeping out of buffet and maintaining altitude.*** You can certainly enter a steep bank without stalling while flying slowly, since *stall speed is not*

Deg. bank	Load factor required for constant-altitude turn	Stall speed factor increase over 1-g V_s	60 kt stall times increase
30°	1.15	1.07	64.3
35°	1.22	1.10	66.3
40°	1.30	1.14	68.4
45°	1.41	1.19	71.2
50°	1.55	1.24	74.7
55°	1.74	1.32	79.1
60°	2.00	1.41	84.8
65°	2.37	1.54	92.4
70°	2.92	1.71	102.5
75°	3.86	1.96	117.9
80°	5.76	2.40	144

directly related to bank angle. Stall speed depends on load factor—in this case on the load factor required to make a turn happen at a given bank angle without altitude loss. ***For a constant-altitude turn, load factor goes up exponentially with bank angle***, as the table illustrates. You can’t generate the necessary load factor unless you’re going fast enough for your bank angle. If you’re too slow, but nevertheless try to arrest a descent by hauling back on the stick, you’ll stall. Level the wings first. If you have excess airspeed, you can haul back and turn *and* climb. The relationship between airspeed, attainable load factor, and turning performance is discussed in the ground school text “Maneuvering Loads, High-G Maneuvers.”

•Pilots have it drilled into them that an aircraft can stall at any attitude. Stall speed is also independent of attitude. At a given weight and configuration, an aircraft pulling two g, for

Maneuvers and Flight Notes

example, has the same stall speed regardless of its attitude relative to the horizon.

- An aircraft constantly rolls toward the outside of a climbing turn. It constantly rolls toward the inside of a descending turn. (You're right. This is difficult to visualize.) The rolling motion creates a difference in angle of attack between the wings, with the down-going wing operating at a higher angle of attack. As a result, climbing aircraft tend to roll *away* from the direction of the turn at stall break. This is favorable because it decreases the bank angle. When descending, they tend to roll *into* the direction of the turn at stall break. But propeller effects, rigging, and poor coordination can gum this up. Watch where the skid/slip ball is and see what happens.

- Prop-induced gyroscopic precession can affect control forces in turns. Precession creates a moment that's always parallel to the axis of the turn—the axis typically being perpendicular to the horizon. On aircraft with clockwise-rotating propellers, as seen from the cockpit, precession pulls the nose to the dirt in a turn to the right, and to the sky in a turn to the left. If the forces generated are large enough (heavy prop, high rpm, high turn rate, long moment arm from prop to aircraft c.g.) more up-elevator will be needed

when turning to the right. And the rudder becomes more involved as the bank angle increases and precession moves closer into alignment with the aircraft's y axis. Greater rudder deflection may then be needed for coordination. The WW-I pursuits equipped with rotary engines (engine and prop turned together) were famous for their gyroscopic behaviors—quick turning to the left but awkward and vulnerable to the right. If the nose pitched down gyroscopically in a right turn, the pilot could spin out trying to counter with opposite rudder and up elevator.

- Finally, notice the greater rudder force necessary to stop or reverse a steep turn, compared to the coordinating rudder force necessary when beginning the turn. One reason is the higher angle of attack in the turn and thus the greater adverse yaw accompanying aileron deflection. Also, the aircraft has picked up angular momentum, which the rudder has to help oppose. So more rudder deflection is required for coordination coming out.

Maneuvers and Flight Notes

Stick-force-per-g test procedure: wind-up turn.

Fly the test at a constant, trimmed airspeed. Airspeed variations introduce additional forces, as described in the ground school “Longitudinal Maneuvering Stability.” At a constant airspeed and power setting, you will descend during the maneuver as bank angle increases.

Establish trim speed in level flight at test altitude. Record pressure altitude, temperature, and power setting.

Climb with increased power to 1,000 above test altitude. Reset trim power.

Bank as required to obtain desired load while descending as necessary to remain at trim speed.

If equipped, measure stick force when airspeed and g-meter readings stabilize. Establishing a stable state, even briefly, isn’t always easy— it takes practice, especially as bank angle increases! If you’re not equipped for measuring, a subjective assessment of stick force and gradient is still a useful exercise.

If the aircraft does not have a g-meter, use bank angles to establish approximate load factors. As 60° approaches, you might find it easier to control airspeed with your feet: for example, top rudder if speed exceeds trim.

Trim speed:

Pressure altitude:

Temp:

Power setting:

Bank angle	30° 1.15-g	45° 1.41-g	60° 2-g
Actual g-meter reading			
Stick force			

5. Nose-High Full Stalls, Lateral Control Loss & Rolling Recoveries

Flight Condition: Wings level, high α , nose-high, limited lateral control.

Lesson: Exposure to nose-high attitudes, limited visual references, lateral control loss.

Procedures:

Full Stall: Nose-High Pitch Break

25"/2,500 rpm.

Clearing turns.

Pitch up + 60 degrees (use wingtip reference).

Power idle.

Hold wings-level attitude as possible, keeping the ball centered with rudder.

Allow **full stall with stick held back.**

Pitch up + 60 degrees.

Hold necessary power, with **stick back, aileron neutral** and **feet off the rudder pedals.**

Allow a yaw rate to develop (aircraft will yaw left due to prop effects).

Observe lateral control divergence.

Recover aileron effectiveness with nose down pitch input.

Recover aileron effectiveness with opposite rudder.

Rolling Recovery from Nose High

Recover nose-below-the-horizon.

Recover nose-to-the- horizon.

Flight Notes

Nose-high recoveries are practiced in simulators as a standard element in upset training. The *Airplane Upset Recovery Training Aid* gives a procedure based on a push—followed by a roll, as required to get the nose back down. We'll explore the dynamics of recoveries done badly. We want you to lose lateral control, see why, and see what it takes to get it back.

- The first maneuver gets you familiar with nose-high attitudes and pitch breaks. The pitch break (or g-break) in a 1-g nose-high stall is much more pronounced than in the 1-g stalls done from close to normal pitch attitudes. The aircraft rapidly sinks and the nose will swing well below the horizon before it's possible to recover a

flyable angle of attack. The initial nose-up attitude will block the horizon ahead and force you to use the wingtips for roll, pitch, and yaw reference. (The attitude indicator will be off, unless we forget.) Don't just stare at one wingtip. We have two! Compare them.

Maneuvers and Flight Notes

- We want you to experience lateral control divergence and loss of *roll damping*. We set this up by holding a nose-high attitude with power on, stick back, feet off the rudders, and ailerons initially neutral. We let the aircraft's natural tendencies in this configuration take over. P-factor and slipstream will yaw the aircraft to the left. We'll try to recover from the resulting coupled roll with ailerons alone (stick still held back). Lateral control will be lost.

- Notice that, while you can retain some aileron effectiveness into a stall buffet and break, ***at high α , aileron effectiveness disappears if the airplane starts to yaw opposite the direction of intended roll***, as we let it do above. Instead of rolling the aircraft as we intend, the ailerons generate more adverse yaw than lift, which simply makes things worse. Once the stick goes forward, however, or the pilot uses rudder to stop the yaw, the ailerons regain authority.

- The Airplane Upset Recovery Training Aid recommends recovery from a nose-high attitude with a push, followed by a roll if necessary (2.6.3.2-5)***. Pushing starts the nose in the right direction and unloads the wing so that the aircraft accelerates and the ailerons retain effectiveness. Rolling tilts the lift vector and allows the aircraft's z-axis directional stability to assist in bringing the nose down. Confining the roll to less than approximately 60 degrees keeps the wing lift vector above the horizon and makes pitch control easier in the recovery back to level flight. During the time it takes to roll the lift vector back to vertical, the buildup in angular momentum in a heavy aircraft can carry the nose unnecessarily below the horizon if the initial bank angle is too steep.

- In a delayed rolling recovery, if you hold the nose in the buffet and apply ailerons, you won't have much roll authority. The reduced roll control at low airspeeds and high angles of attack can increase the difficulty of a rolling recovery from a nose-high attitude. This underscores the need to push and unload the airplane if the ailerons aren't working.

- The "nose below horizon" and "nose to the horizon" rolling recoveries demonstrate the problem of flight path control at high angles of attack. Because nose-up authority disappears at high α , stopping the nose on the horizon is difficult without encountering a buffet.

- In a jet, power application in a nose-high recovery will depend on the aircraft's thrust line and the resulting pitching moment when power is applied. Aircraft with engines mounted on pylons below the wings can pitch up in a manner possibly difficult to control when thrust is increased at low airspeed. In addition, a jet has to accelerate and build up speed before control surfaces regain authority. With a prop, horizontal and vertical stabilizers start to regain authority once the slipstream returns. But ailerons still require airspeed. In an extreme case, if you slam the power forward on a go-around in a P-51 or similar warbird while flying slowly, the torque effect can be more than the ailerons can handle.

6. Roll Authority: Adverse Yaw & Angle of Attack, Lateral Divergence

Flight Condition: Upright, power-off 1g stall, high α , varying β , pro-spin.

Lesson: Lateral/directional control at increasing α .

Procedures:

Spin recovery briefing as required.

Power idle.

1-knot-per-second deceleration below 70 knots.

Instructor demonstrates initial task.

Sample **aileron** authority: Decelerate toward stall while rolling 15 degrees left and right **at a constant roll rate**. Alternate between rudder free and coordinated rudder as necessary to hold nose on point.

- Note:
1. Change in aileron deflection needed to maintain roll rate.
 2. Change in aileron forces.
 3. Increase in adverse yaw.
 4. Contribution of coordinated rudder to roll rate.
 5. Lowest speed for aileron authority.

Continue rolling inputs through stall break. **At wing drop, hold opposite aileron.** Observe aileron reversal. Hold aileron deflection and **recover using forward stick** to demonstrate return of aileron authority. Instructor will demonstrate if required.

Sample **rudder** authority: (Instructor demonstrates initial task.) Establish **constant rate** left/right yaw tempo sufficient to assess rudder authority during stall entry.

- Note:
1. Change in required rudder deflection.
 2. Change in rudder forces.
 3. Lowest speed for rudder authority.

Observe lowest speed for lateral control using coordinated aileron and rudder.

Flight Notes

In the previous maneuver set we observed the loss of aileron effectiveness during delayed nose-high rolling recoveries. In this set we'll continue to examine changes in lateral control. We won't intentionally spin the aircraft at this point in the program, but the aircraft will be bopping around pretty aggressively, with the velocity vector wagging left and right, and these are potential spin entries (high angle of attack plus sideslip and yaw rate). Just **centering the rudder and ailerons and releasing aft pressure is enough for recovery from an incipient spin departure in our aircraft.** (As the spin develops, however, recovery technique becomes more critical, for reasons we'll cover in spin training.). That said—don't be timid. Challenge the aircraft to the point where lateral control is lost, and then get it back.

Maneuvers and Flight Notes

The subject of this maneuver set is mostly the rudder. Rudder-induced sideslips can accelerate a rolling maneuver and contribute to maximum-performance upset recoveries. Proper rudder use is essential for coordination at high α : but misuse of the rudder at high α can also cause spin departure, or severe yaw/roll oscillation (Dutch roll), especially in swept-wing aircraft. Following the November 12, 2001 vertical stabilizer failure and crash of American Airlines Flight 587, an Airbus A300-605R, attention has focused on the structural loads generated on a vertical stabilizer when the rudder is deflected to opposite sides in rapid succession. Rapid rudder reversals, even below maneuvering speed, V_A , and even with rudder limiters, can result in loads in excess of certification requirements. FAR Part 25.351 rudder and fin load requirements are based on the demonstration of a sudden full rudder deflection (either to the stop or until a specified pedal force is reached) at speeds between V_{MC} and V_D (design dive speed) in non-accelerated flight. This is followed by a stabilized sideslip angle, and then the sudden return of the rudder to *neutral*, not to a deflection in the opposite direction.

The American Flight 587 accident also raised fears that unusual-attitude training that overemphasizes rudder can in fact provoke an upset if a pilot overreacts with rudder to an otherwise non-critical event, or uses it at the wrong time. Although we'll demonstrate the effects of rudder and sideslip on rolling moments as α increases, for all the reasons above we won't define the rudder as the primary high- α roll control, especially not for swept-wing transport aircraft (historical jet fighters are a separate issue). ***Reduce the angle of attack if necessary to regain lateral authority, and use ailerons or spoilers for unusual-attitude roll recoveries, along with the rudder required for coordination, not roll acceleration.*** This is consistent with both Boeing and Airbus philosophy, but can be applied to any aircraft. Aggressive rudder use is an important part of aerobatic training, and of course aerobatic training is the basis of unusual-attitude training. But aggressive rudder use doesn't always carry over—partly because of concern the rudder will be used at the wrong moment and partly because, even with an experienced aerobatic pilot at the controls, the dynamics following a nominally correct aerobatic input may be different in a swept-wing aircraft than in a straight-wing trainer.

- In the golden days, when tail-wheel aircraft with lots of adverse yaw were standard, and pilots could still be seen wearing jodhpurs, flight instructors often had students perform back and forth rolls-on-point, which instructors in jeans today often mistakenly call “Dutch rolls.” (In a real Dutch roll the nose wanders.) The idea was to wake up the feet for directional control during takeoffs and landings, and especially to teach the rudder coordination necessary to counteract adverse yaw. This maneuver set is similar, but the dynamics are more complex and revealing because we roll the aircraft while simultaneously increasing its angle of attack (and thus its coefficient of lift, C_L).

- Pay attention to how control authority deteriorates: You'll need to increase your control deflections to maintain rolling and yawing moments as airspeed (dynamic pressure) diminishes. The down aileron will begin producing proportionally less roll control and more induced drag as the angle of attack rises (induced drag increases directly as the *square* of

lift), and therefore more adverse yaw. You'll see the result in the movement of the nose. Keeping the nose on point with rudder will demonstrate how ***the rudder becomes increasingly necessary for directional control when using ailerons for roll control at higher angles of attack, and then increasingly dominant for roll control as the ailerons lose authority and roll damping begins to disappear.***

- Rudder-induced roll control doesn't decline as much as aileron control typically does, because the yaw/roll couple that the rudder provokes goes up in proportion to coefficient of lift. Aileron authority, however, goes down as airspeed diminishes and as flow separation begins to affect the outboard wing sections.

- Ultimately, at aircraft stalling angle of attack the ailerons can (legally, see below) begin to “reverse” (not to be confused with wing twisting, “aeroelastic reversal”). This happens when adverse yaw begins to dominate, and the opposing roll moment the yaw produces (through

Maneuvers and Flight Notes

sideslip and yaw rate) overcomes the roll moment generated by the ailerons. The airplane then rolls toward the *down* aileron. This is called *lateral control divergence*. Its natural prey is an airplane with lots of adverse yaw and lots of dihedral effect, when flown at high angle of attack by pilots who don't use their feet to keep yaw under control (and thus the velocity vector on the plane of symmetry).

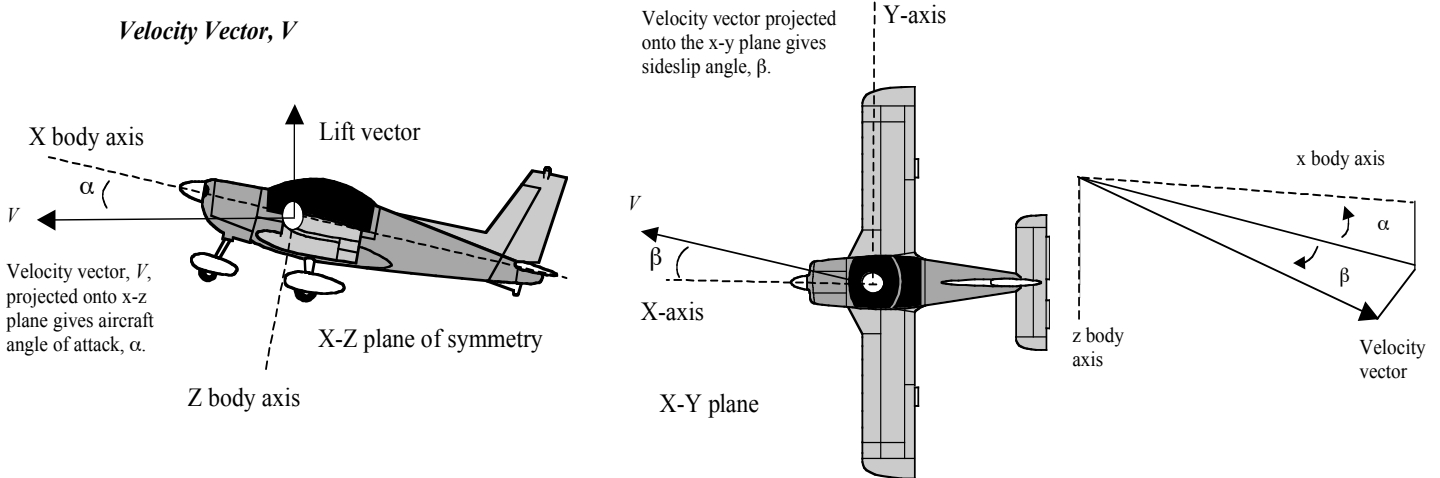
- Adverse yaw goes down and aileron effectiveness returns when you apply forward pressure to reduce α : ***Push to recover aileron effectiveness***. As in the nose-high stalls done earlier, you'll see how quickly a "reversed" aileron regains its appropriate authority once the nose comes down.

- After the flight, compare the trainer's stall behavior to the requirements in FAR Part 23.201-203 (for aircraft under 12,500 pounds) and to the requirements for transport certification under FAR Part 25.201-203. (See the Summary of Certification Requirements.) The wording is different, but 23.201(a) and 25.203(a) say the same thing. According to the latter: "It must be possible to produce and to correct roll and yaw by unreversed use of the aileron and rudder controls, *up to the time the airplane is stalled*." [Italics ours] Did we demonstrate capabilities at stall α beyond those explicitly required?

- We've demonstrated the continuing authority of rudder, compared to aileron, for roll control in the high- α region of the envelope. Nevertheless, in general, ***don't rely on the rudder for primary roll authority at high α , if you can avoid it***. The best course is to push the stick forward and cause normal control authority to return. Certification requirements assume a pilot will do just that. We don't want our demonstrations to turn into what the airlines call *negative learning*, so remember: These lateral and directional control exercises are not procedure training. ***Recover roll control at high α by pushing to reattach airflow and to restore aileron effectiveness as required. Use coordinated, ball-centered rudder to enhance roll rate by checking adverse yaw***. This is correct for any aircraft, but particularly so for swept-wing—in which yaw/roll couple is more pronounced than for straight-wing aircraft and the gyrations of the real Dutch roll are more severe, and in which the high- α/β corners of the envelope may not have been explored during flight test because operational encounter was never intended.

Maneuvers and Flight Notes

The illustration below puts things in velocity vector terms.



A directionally stable aircraft yaws in the direction the velocity vector is pointed, returning the vector to the x-z plane of symmetry as it does. A laterally stable aircraft rolls away from the velocity vector when the vector becomes displaced from the plane of symmetry. In the illustration, the second aircraft wants to yaw right but roll left.

As an aircraft slows, and angle of attack and thus adverse yaw increase, aileron deflection will increasingly shift the velocity vector off the plane of symmetry, unless the pilot uses “coordinated” rudder deflection to counter the yaw. If present, P-factor and slipstream will also increase, tending to shift the velocity vector to the right unless the pilot compensates with right rudder.

So as speed goes down, the tendency of the velocity vector to wander goes up. The resulting rolling moments away from the velocity vector increase with β , and also increase with angle of attack.

Rolling an aircraft with rudder is a matter of pointing the velocity vector to generate a rolling moment in the desired direction. The dangers of aggressive rudder use at high angle of attack are that the aircraft enters a spin, or enters a Dutch roll oscillation the pilot inadvertently reinforces while trying to correct.

7. Flap-Induced Phugoid

Flight Condition: Longitudinally unstable, varying lateral/directional control.

Lesson: Downwash/horizontal stabilizer interaction, control practice.

Procedures:

Speed for white arc in level flight.

Student's hands in "prayer" position (palms facing inward but not touching stick, **rudder/aileron control only**).

Instructor lowers flaps approximately 15 degrees.

Student maintains directional and lateral control. **No pitch input.**

Instructor manipulates flaps as required, monitors flaps-extended speed.

Observe the effect of lowering the landing gear.

Flight Notes

A dynamically stable phugoid motion is convergent. We can produce a non-convergent phugoid by lowering the flaps, but we don't retrim. The flaps increase the downwash angle over the horizontal stabilizer and, with the stick free, the nose pitches up in response. As the wing roots stall and the downwash disappears, the nose pitches down. When lift then returns, the downwash reappears, driving the nose back up for the next stall. Your job, during this stall-and-recovery roller coaster, is to keep the aircraft under directional and lateral control, using aileron and rudder only.

- The center of lift moves rearward along the wing chord when you lower the flaps. This produces a nose-down pitch moment. (The drag you create below the aircraft's center of gravity also contributes.) But watch the tufts when the flaps go down and note the vortices that form around the flaps' outboard tips. These vortices increase the angle of the downwash affecting the horizontal stabilizer. This down flow produces a nose-up pitch moment. The pitch-up from the downwash on the stabilizer is greater than the pitch-down from the rearward shift in lift. As a result, the aircraft pitches up at flap deployment.

- Anytime you (or a gust) raise the angle of attack of a wing you also increase the downwash angle. Typically, the downwash angle changes more rapidly with AOA when the flaps are deployed. Because the change in downwash

angle reinforces rather than opposes a change in wing angle of attack, flaps generally reduce longitudinal (pitch axis) stability. One reason for T-tails is to raise the stabilizer out of the area of downwash (and propwash) influence.

- As the aircraft stalls and recovers, you'll experience changes in lateral and directional control, already familiar from earlier nose-high maneuvers. Propeller and slipstream effects will be more pronounced, however, because of the need to maintain power to keep the maneuver going.

8. Nose-Level Aileron Roll: Rolling Flight Dynamics, Free Response

Flight Condition: Knife-edge & inverted, free yaw/pitch response.

Lesson: Free response behavior in rolling flight, attitude familiarization.

Procedures:

Check: Seat belt, cockpit, instruments, altitude, outside.

About 23¹/₂, 300 rpm.

From **level** flight with **elevator and rudder neutral** throughout.

360-degree roll with **full aileron**.

Recover from dive (instructor notes g's pulled in recovery).

If motion sickness is not a concern, repeat the same as above but use **partial aileron deflection** to decrease roll rate and allow the nose to fall farther below the horizon.

Flight Notes

We teach you to roll an aircraft through 360 degrees before we tackle emergency upset roll scenarios. This is less demanding on your motion tolerance at the start of training because the flying is smoother and you remain in control. You'll begin by observing how the aircraft responds in pitch and yaw to changes in bank angle during a 360-degree rolling maneuver. Then you'll learn to control that response.

- You'll end up losing altitude, with the nose well below the horizon at the completion of these introductory rolls. They're not the way an experienced aerobatic pilot rolls an aircraft—but we start with this ailerons-only, nose-in-level-flight technique to demonstrate the airmanship problems that an actual unusual-attitude rolling departure would involve. You'll gain more sophisticated, aerobatic control inputs as we fly.

- Because the aircraft rolls, pitches, and yaws in a relatively extreme manner with respect to the horizon, pilots new to aerobatics usually have a difficult time tracking attitude. In the second roll, with reduced aileron, the horizon will certainly disappear behind the nose as the aircraft rolls through inverted. At this point untrained pilots have the famous tendency to release aileron and pull into a split-s. Don't worry. This you will never do!

- The aircraft's free-response directional and longitudinal stability characteristics are designed for upright flight. They produce nose-down moments (with respect to the horizon) during a roll. Directional stability drives the nose down at each knife-edge, and longitudinal stability does the same at inverted. The more stable the aircraft, the more adverse the result.

- Notice the important relationship between roll rate and pitch attitude at roll completion. ***The slower the roll rate the steeper the final pitch-down attitude.*** The aircraft's free response has more time to bring the nose down. Larger passenger aircraft roll far more slowly than aerobatic trainers. As a result, a badly executed maneuver for a trainer might actually simulate a best-case controlled-response outcome for a less

Maneuvers and Flight Notes

responsive aircraft. So, **keep the roll going at the highest possible rate.**

- While we want you to understand the importance of holding full aileron deflection to achieve maximum-rate recoveries, the idea of keeping the roll going needs qualification when we think about vortex encounters, and for the sake of primacy we should state it right off. By the time a pilot reacts to a vortex with opposite aileron the aircraft probably has already been tossed to a different part of the paired vortex flow field (and/or the individual vortex has snaked around to a different part of the aircraft) and the imposed rolling moment has changed. The compilation of NASA vortex encounter videos you'll see in ground school will demonstrate how an aircraft is dispelled from a vortex core. You'll see why you shouldn't assume that even a violent initial roll acceleration caused by a vortex encounter is handled best by keeping the vortex-induced roll going through 360 degrees. That being said, note that The National Test Pilot School, in Mojave, California, does recommend using the aircraft's existing rolling momentum, if advantageous, and continuing a roll once past 160 degrees.

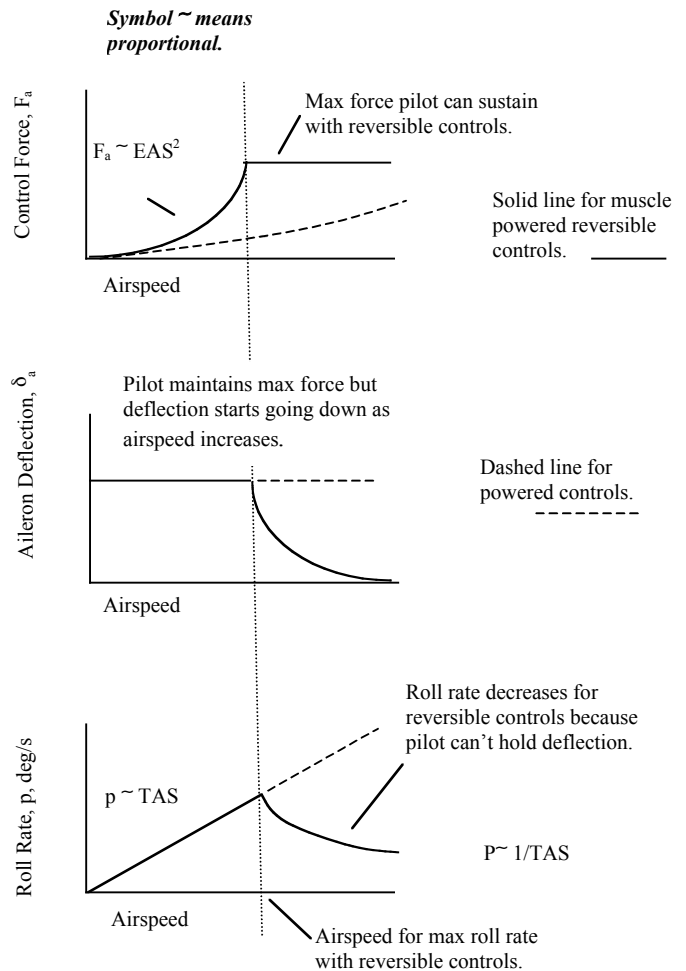
- For a given control deflection, **roll rate varies directly with airspeed.** In aircraft with reversible controls, like our trainers, for a given deflection, **aileron stick force goes up as the square of airspeed.** Assuming no aeroelastic reversal, you'll roll faster when flying faster, although you'll have to push the ailerons harder and harder, and eventually will come to a point where the stick force is too much to handle and roll rate starts back down. The problem for us is at the low-speed end, where low roll rates going into the maneuver permit the nose more leisure to fall below the horizon if the pilot allows, and rolling recoveries back to upright take more time.

- A recovery at higher g after a partial-deflection roll allows you to experience sensations typically past the minimum 2.5-g positive limit load allowable for an aircraft certified under FAR Part 25.337(b). (Unfortunately a 360-degree roll followed by high g can trigger motion sickness in some, so let's be cautious.) For aerobatic

certification, which we operate under, FAR Part 23.337(a)(3) requires a positive limit load of 6 g.

- Remember that for a given g load the radius of a turn (or of a pull-up at the completion of a roll, as is the case here) at any instant varies directly with the square of the true airspeed. Double the speed means four times the altitude consumed. A recovery in a piston aerobatic trainer's low-air-speed/high-g envelope consumes much less altitude than recovery in a jet operating at higher speeds and lower limit loads.

Roll Rates Depend on Airspeed and Control System Design



9. Slow Roll Flight Dynamics: Controlled Response

Flight Condition: Knife-edge & inverted, controlled yaw/pitch response.

Lesson: Control in rolling flight.

Procedures:

Task: Complete the roll with the nose on or near the horizon, not in a dive.

Check: Seat belt, cockpit, instruments, altitude, outside.

Roll 1: 25°/2,500 rpm.

Airspeed at instructor's discretion.

Raise the nose 20-30 degrees.

Release aft pressure/ rudder neutral.

Full aileron.

Roll 2: Raise the nose as instructor directs.

Top rudder at second knife-edge.

Roll 3: Raise the nose as instructor directs.

Forward pressure at inverted.

Top rudder at second knife-edge.

Roll 4: Raise the nose as instructor directs.

Top rudder at first knife-edge.

Forward pressure inverted.

Top rudder at second knife-edge.

Roll 5: Roll in the **opposite** direction.

Flight Notes

There're three standard aerobatic rolls (and one weird one). The first exercise in this sequence is an *aileron roll*, so named because the ailerons do all the work. The next exercises introduce the *slow roll*—an aerobatic competition maneuver that uses help from rudder and elevator to keep the center of gravity of the aircraft moving in a straight line (as opposed to the climb and descent of the aileron roll). Slow rolls give you the tools to handle roll emergencies with minimum altitude loss. The third standard roll is the *barrel roll*, which is actually a combination loop/roll that takes a path through the sky as if the aircraft were following the outline of a barrel laid on its side. The idea behind the barrel roll is to keep the aircraft at positive g for the sake of fuel flow and lubrication if it lacks inverted systems. It also keeps the occupants more confidently in their seats and permits the trick of pouring coffee from thermos to mug while upside down. We won't do barrel rolls as part of your standard training sequence (although we can toss some in) but the *rudder roll* (the weird one), which we will do, is fairly similar.

Maneuvers and Flight Notes

Learning to slow roll is actually easier—and the exercise is more informative—when you take it as a problem to be solved by experimentation, and not as a textbook set of sequenced control inputs. Then, to make it easier still, you learn the rudder and elevator skills in reverse.

- In Roll 1, raising the nose high enough at the beginning of the maneuver and then rolling fast enough solves the procedure task by default. Start high and the nose simply falls through to meet the horizon at the end. (Of course, this doesn't represent a typical *nose-down* unusual-attitude scenario.)

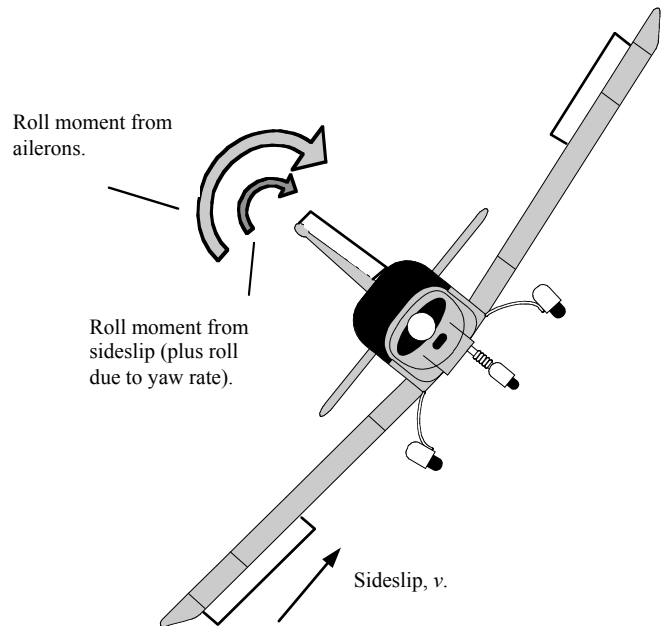
- In Roll 2, the *rudder helps hold the nose up at the second knife-edge*. The resulting sideslip can accelerate the roll rate through dihedral effect and roll due to yaw rate. Your instructor will make sure you experience this acceleration, because—with certain reservations—it's an important emergency skill. As you gain experience, you'll learn to amplify the effect by aft pressure on the stick. (The ultimate amplification becomes a snap roll, an aerobatic rather than emergency maneuver. Aerobatic pilots, especially competition pilots, actually avoid accelerating aileron rolls with rudder and elevator, since it leads to a sloppy-looking and physically unpleasant maneuver. But fighter pilots have used snapping roll entries since the First World War to quickly reverse direction and shake an attacker from their tail, especially at low speeds where aircraft usually snap roll faster than aileron roll.)

- Roll 3 uses *forward pressure at inverted to keep the nose up*. Remember that the necessary stick pressure and movement is much less in an aerobatic trainer, and the response much greater, than in an aircraft with more longitudinal stability.

- Roll 4 begins to approximate the technique used in competition slow rolls: *initial top rudder at the first knife-edge*, transitioning to forward elevator and back to the opposite top rudder at the second knife-edge. This produces a constant nose up (with respect to the horizon) yawing/pitching/yawing moment throughout the roll, working in opposition to the aircraft's natural stability tendencies.

Sideslip Enhances Roll Rate

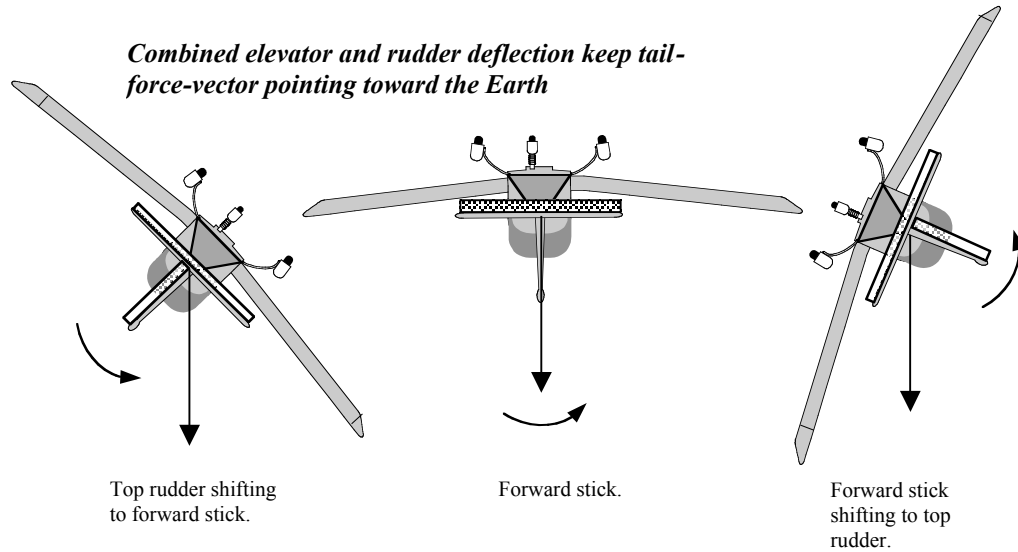
Top rudder causes a sideslip-induced roll moment, in addition to the aileron roll moment. This increases roll rate.



- The roll sequence is done first in one direction to ease the development of perceptual and motor skills. Roll 5, done in the opposite direction, is often confusing for the beginner because the now expected motor sequence is reversed. That's why we do it! Here, your confusion makes us happy. Consider it a memorable training opportunity. Don't freeze! **Keep the roll going with full aileron deflection**—rudder and elevator are secondary to aileron when you are learning to roll.

- Don't expect to fly rolling maneuvers step-by-step using a memorized formula. The maneuver can break down dramatically if the aircraft's attitude falls out of phase with your programmed

Maneuvers and Flight Notes



inputs and expectations. Instead of trying to establish a sequential muscle-motor *program* at the start, concentrate on reacting to the aircraft's attitude with the correct muscle-motor *response*—your muscles will then program themselves. These rolls are building your perceptual familiarity with unusual attitudes along with the motor habits needed to respond as required. ***Learn to fly in response to what you see.***

•On the subject of “flying what you see,” you can tell that we’re suspicious of applying memorized, step-by-step control sequences, or “mantras” at the initial stages of unusual-attitude recovery training. We’d rather try to help you to discover the correct inputs—under guidance—yourself. They’ll stick that way, and you’ll develop the necessary coordination and harmony. Memorized sequences are most appropriate when a pilot can’t figure out what’s happening and sequenced inputs are the only way to catch up and get things under control. In aerobatics, that kind of situation is most likely to occur when spins accelerate or change modes and the pilot loses visual tracking. Mantras are only safe when the initial input can be inserted at any time in the departure: otherwise out-of-phase inputs can actually make things worse. You may feel differently about this. It’s worth talking over.

•Once you’ve done a few rolls and experimented with control inputs and their results, the notion of ***tail-force vector*** will help you understand what you’ve in fact already begun to practice. You’re familiar with an aircraft’s lift vector from the standard illustrations of lift, weight, thrust, and drag. The tail-force vector is our term for the sum and direction of the “lift” produced by the rudder and elevator together. In coordinated, upright flight the tail-force vector comes entirely from the elevator/horizontal stabilizer (we’re neglecting any directional trim forces the rudder/fin might be producing). It usually points earthward, normal to the relative wind over the tail, and balances the nose-down pitching moment that results when an aircraft’s center of gravity is forward of the neutral point (see ground school text “Longitudinal Static Stability”). When flying inverted, forward stick is necessary to produce the same balancing, earthward tail-force vector. Otherwise, the nose heads downhill. In knife-edge flight, top rudder replaces elevator in keeping the tail-force vector pointed down, and the nose (as much as possible) up.

•***To prevent the nose from falling, to delay the onset, or to reduce the rate at which the nose falls in a roll, we keep the tail-force vector pointed toward the Earth—using whatever***

Maneuvers and Flight Notes

changing combination of elevator and rudder the current bank angle requires. Note that, in using the elevator and rudder in this way, we're keeping the aircraft's total lift vector pointed roughly heavenward. See "Axes and Derivatives" in the ground school texts.

- But here come the caveats: In *non-aerobatic* aircraft the effectiveness of these control inputs depends on the effectiveness of the control surfaces in flight attitudes neither they nor the rest of the aircraft were specifically designed to experience! Jet transports typically have a trimmable horizontal stabilizer with an attached elevator. The design facilitates wide c.g. and airspeed range, but pitch authority is limited by the position of the stabilizer. Even if the elevators are effective enough to slow the rate the nose drops while inverted, the resulting decrease in positive g may lead to fuel flow, lubrication, or hydraulic system failure. In the unlikely event the elevators are effective enough to actually *push* the nose up inverted, the resulting negative g may be insupportable structurally.

- There's more to worry about: In an aerobatic aircraft, rudder forces are usually well harmonized with elevator and aileron. Dutch roll is usually well damped. But that may not be the case in a jet, especially swept-wing. In transports, rudder breakout forces can be high—and in some designs at certain speeds can be close to the force required for full deflection, a situation that can lead to over control. Because the sideslip angle has to build up before the resulting rolling moment appears, and because of roll inertia, there may also be a time lag between the rudder input and the roll response. Such factors make it difficult to achieve the rudder-

input harmony and timing possible in an aerobatic trainer. The result of overzealous rudder use can be the build up of such a large sideslip angle and consequent roll moment that the recovering aircraft continues rolling past wings level. If the pilot reacts to the ensuing Dutch roll by deflecting the rudder against the sideslip (left sideslip, left rudder, say), the moments generated by the sideslip angle and the rudder together can "over yaw" the aircraft to the opposite side, causing it temporarily to reach an extreme, overswing sideslip angle. Suddenly reversing the rudder against the swing can set up the forces necessary to damage, or destroy, the vertical tail. ***Always use the rudder cautiously in a swept-wing aircraft.***

- Concerning rudders, review the *Boeing Commercial Airplane Group Flight Operations Bulletin, May 13, 2002*, at: <http://www.nts.gov/Events/2001/AA587/exhibits/240009.pdf>

- As we've shown, in an intentional roll you can finesse with top rudder at knife-edge and with forward stick through inverted in order to keep the nose up. You can use top rudder and slight aft pressure to accelerate the roll rate after passing from knife-edge back toward upright (as long as the wing isn't too near stall and rudder likely to cause a departure). You can apply the same finesse to emergency recoveries as appropriate to your aircraft type, but don't forget the most important control. ***In a recovery from a roll upset, use full aileron.*** It's easy to relax aileron pressure inadvertently. Every student does it. Learn not to!

10. Sustained Inverted Flight

Flight Condition: Inverted, -1g.

Lesson: Situational awareness, trim forces, AI interpretation.

Procedures:

Instructor:

- Check: Seat belt, cockpit, instruments, altitude, outside.
- Cruise power.
- Fly a cardinal heading.
- Instructor asks student to point quickly to cockpit instruments and outside cardinal headings.
- Instructor rolls aircraft inverted and maintains control.
- Instructor asks student to point quickly to cockpit instruments and outside cardinal headings while inverted.
- Student takes control and rolls upright.

Student:

- Raise nose about 20 degrees.
- Roll inverted.
- Forward pressure as required to maintain level flight.
- Rock wings approximately 15-20 degrees left and right (note any sensation of adverse yaw).
- Roll upright.

Flight Notes

We teach full, 360 degree rolls before we teach half rolls to inverted because the distracting physiological effects of negative-g inverted flight are easier on the student when encountered later in training. Negative 1-g level inverted flight is an interesting training experience, but it's actually more an aerobatic than an emergency skill. In reality, unless you assert yourself with forward pressure, and the aircraft has sufficient elevator power, you're not going to experience sustained negative-g during an upset emergency short of an inverted spin (nor would you want to in an aircraft without proper fuel and lubrication systems). The aircraft will assert its longitudinal stability and start pitching toward positive g, as this maneuver illustrates.

- Reference points are hard to retain when you're hanging upside-down. Students who can respond quickly to the instructor's request to point out an instrument inside or a cardinal direction outside the cockpit when right-side-up often have trouble doing the same thing when inverted under actual negative g. There's a tendency to tense the body and stare at a point, and just turning the head and looking around can require real effort. Flight skills don't come naturally under these

conditions, especially when you just discovered that your seat belt wasn't as tight as you thought.

- When the instructor rolls inverted and transfers control and asks you to roll upright, you'll be surprised at the amount of forward pressure he or she was holding. Don't let up and let the nose fall too far. When *you* roll the aircraft from upright to inverted, remember how that push force felt and blend it in as you complete the half

Maneuvers and Flight Notes

roll. Notice inverted that the junk that was on the floor or loose in your pockets is now on the canopy. A little dust is inevitable, but anything that could jam the control system requires immediate recapture and a better preflight next time around.

- On rolling upright from inverted: If you've flown or read about aerobatics, you might know that strict procedure often requires rudder input opposite to aileron, followed by rudder input with aileron, when rolling upright from negative-g inverted flight. That's because inverted adverse

aileron yaw calls for some rudder deflection opposite to stick deflection. Such cross-control technique is usually confusing to the student at first, and tends to delay recovery actions. It's important in precision roll training with aerobatic aircraft equipped with inverted oil and fuel systems. But it creates unnecessary confusion in unusual-attitude training for pilots who will fly non-aerobatic aircraft with conventional systems and much heavier control forces in pitch. Even if the pilot pushes as the aircraft rolls through inverted, the load will probably remain positive and inverted adverse yaw won't occur.

11. Inverted Recoveries

Flight Condition: Inverted, high & low kinetic energy states.

Lesson: Attitude recognition and recovery practice.

Procedures:

Instructor:

- Check: Seat belt, cockpit, instruments, altitude, outside.
- 23"/2,300 rpm.
- Pitch up to about 45 degrees.
- Student closes eyes.
- Roll inverted; decelerate on ascent.
- Idle power.
- Gently pull nose below horizon.

Student:

- Opens eyes on instructor's command.
- Rolls upright to recover.

Repeat from different inverted bank angles.

Student pitches up, closes eyes, rolls inverted, opens eyes and recovers on instructor's command.

Instructor transfers control to the student inverted at a nose-high, low-kinetic-energy state.

To prevent excess airspeed during inverted recoveries, the instructor will normally close the throttle before the student takes control. In that case the student should simulate proper throttle use.

Flight Notes

Identify the Nearest Horizon (fewest degrees away): Push & Roll, Top Rudder, Pull

When using the AI, roll toward the sky pointer, or roll the lift vector toward the sky.

In this maneuver set we'll apply the lessons learned in slow-roll flight dynamics to a more challenging attitude environment. Your instructor will fly the maneuvers to the descent line at the start, allowing you to recover. The initial goal is to get you going downhill, upside-down, *horizon obscured*, at as slow a speed as possible, with as gentle an entry as possible. This makes the fewest demands on your motion tolerance, and keeping the speed down allows you time to discover what the world looks like when you're descending inverted. We may use rudder to accelerate the roll recovery, but we'll take note of the caution required.

Maneuvers and Flight Notes

•In the first maneuvers, you'll already know that you're pointing down and accelerating. In that case, it's correct to **Push** to keep the nose from falling farther. In subsequent *nose-high* transfers of control you'll be very slow. You'll be able to see the horizon, but will need to allow the nose to come down below it to let gravity help accelerate the aircraft so that control authority returns. Don't reflexively push. If the aircraft somehow picks up a yaw rate, pushing while inverted at low speed could lead to an inverted spin.

•***Roll to the nearest horizon with full aileron.***

The nearest horizon is the fewest degrees away. ***On instruments, that means rolling toward the sky pointer, or rolling the lift vector toward the sky.***

•As the aircraft rolls upright from inverted to knife-edge, start applying **Top Rudder** and release the forward pressure. If you hold forward pressure past knife-edge you'll sacrifice some of the dihedral effect necessary to assist the roll, and you'll push the nose down and yourself out of the seat. Top rudder holds the nose up through knife-edge and starts a sideslip that accelerates the roll.

•Begin your **Pull** as the aircraft rolls through roughly 45 degrees. Come off the rudder as you near upright. Ailerons are primary, but past knife-edge combining top rudder and elevator can bring the nose up to the horizon following the shortest line.

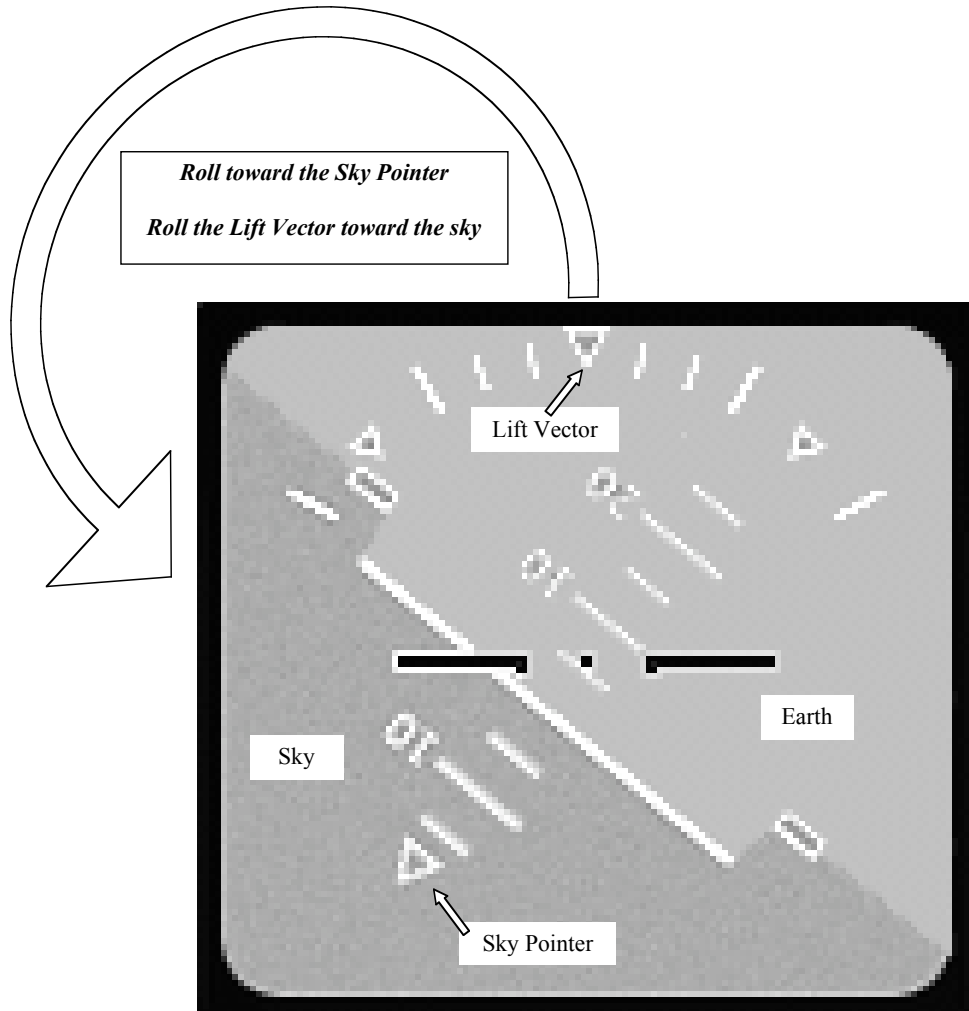
•***The top-rudder deflection accelerates the roll and also keeps the airplane from turning when you begin your pull.*** As you roll upright, rudder and elevator work together to keep the tail-force vector pointing roughly earthward, so that the nose comes up to the horizon in a direct vertical path and sideslip assists roll rate.

•You're using rudder and elevator in an expert way in these recoveries. Just remember that the rudder and the elevator can cause trouble. We've already worried about misapplication of or inappropriate reliance on rudder at high α , because of possible stall/spin departure. We've worried about differences between aerobatic

trainers and swept-wing aircraft in their Dutch roll response to rudder deflection. Now worry about this: If you pull an aircraft to limit load while rolling with aileron and/or rudder (a rolling pull-up) the asymmetrical load generated across the span can take the up-going wing past structural limits. This could occur from the rolling moment generated by modest rudder application alone, since even a small moment applied at limit load would cause the wing to exceed that limit. This wrecks airplanes. See "Maneuvering Loads, High-G Maneuvers" in the ground school text.

•Any general statement about handling an aircraft in an upset emergency has to balance the risks of misunderstanding against the rewards of airmanship. A given control input or combination could either get you into trouble or else help you out of it...depending. So what's best to say? A general statement also has to avoid optimistic assumptions concerning both a pilot's ability and the unknown areas of an aircraft's response. It has to assume that the expertise shown in training will deteriorate and that a pilot will become confused if too many half-remembered nuances exist in his mind. Aerobatic instructors know this from the experience of watching students fumble through roll recoveries as they try to remember what to do with the rudder and elevator. In light of the above, here's a general, baseline, "I'm out of practice so what do I do now?" statement that applies to aircraft with standard flight controls and flying qualities. Embed this in your mind as the primary response: ***In a roll-upset emergency, go to the ailerons first.*** Unless you initially need them to lower the nose to regain airspeed for aileron authority, ***rudder and elevator are secondary.*** So much the better if you're more expert than that!

Maneuvers and Flight Notes



12. Rudder Roll: Yaw to Roll Coupling

Flight Condition: High α , high β , upright & inverted.

Lesson: Roll control by means of sideslip, yaw rate, and angle of attack.

Procedures:

Check: Seat belt, cockpit, instruments, altitude, outside.

25"/2,500 rpm.

Pitch up to 45 degrees.

Full rudder deflection.

Ailerons remain neutral.

Hold aft pressure.

Full rudder throughout.

Repeat as above with **temporary forward pressure at inverted** to observe decrease in roll rate; restore aft pressure to completion.

Flight Notes

The rudder roll is similar to the old-fashioned barrel roll in terms of the flight path the aircraft follows through the sky, except the ailerons remain neutral and the heading changes are not as great. It's also a kind of slow-motion snap roll, although the aircraft doesn't go all the way into autorotation. It's not often taught in civilian aerobatics, but has a history in the military as a way of rapidly reversing bank angle in a high-g turn. We fly rudder rolls to underscore yaw/roll couple, and to add their more complex motions to your unusual-attitude experience. *The rudder roll also demonstrates that yaw/roll couple responds the same to longitudinal stick position whether the aircraft is inverted or upright (or in any other attitude), as long as the wing is at a positive angle of attack.* Caution: Rudder rolls can rapidly erode motion tolerance.

- The aircraft will roll 360 degrees on dihedral effect, roll due to yaw rate, and y-wind-axis pitch/roll couple. Constant pitching, yawing, and sideslip drive the maneuver. Unlike the slow rolls we've been working on, where we try to keep the tail-force vector pointing earthward, in the rudder roll (and barrel roll) the tail-force vector rolls with the airplane.

- Notice how reducing the angle of attack with forward stick (unloading) while inverted reduces the roll rate. If you relax the stick (or rudder) too much the roll rate will really decrease and the nose will just head downhill. If necessary, recover with full aileron in the normal way.

- If you pull too hard the aircraft can snap roll suddenly (high angle of attack + sideslip and yaw rate = departure!). Release aft pressure and rudder if you feel the roll begin to accelerate too quickly. (A snap roll at the top of a loop is called an "avalanche"—which is nicely expressive of the tumbling feeling it produces. A snap departure out of a rudder roll feels the same, and causes the same spatial confusion on first encounters.)

13. Rudder & Aileron Hardovers

Flight Condition: Uncommanded rolls.

Lesson: Effects of pitch inputs during uncommanded rolls.

Procedures:

Demonstrate effect of pitch input during **normal spiral, rudder neutral**.

Power for low cruise.
Enter spiral mode.
At 45-degree bank, observe response to stick-back pitch input.
Release and recover.

Demonstrate effect of pitch input during **rudder hardover spiral, rudder deflected**.

Aileron neutral.
Roll 30 degrees with rudder only.
Hold rudder input.
Hold aileron neutral.
Aft pressure to accelerate roll.
Release and recover.

Alternate aft pressure and forward pressure while holding rudder input and observe roll response.

Demonstrate recovery from **rudder hardover below crossover speed**.

Begin rolling the aircraft with rudder, then apply a **partial aileron deflection** using too little aileron to stop the roll. (The aircraft is below crossover speed for the partial aileron deflection.)
As the aircraft rolls, hold rudder and aileron fixed, pitch down for speed to regain aileron effectiveness.
Add power in the recovery as necessary to remain above crossover speed.

Demonstrate recovery from **uncommanded aileron deflection**, showing the effect of rudder and aft stick.

Partial aileron deflection.
Apply rudder sufficient to slow but not stop the roll.
Stick back (or nose-up trim) to increase α/C_L .

Flight Notes

Concerns about rudder hardovers, and the development of the concept of *crossover speed*, stem directly from accidents involving Boeing 737s, which were caused or complicated by uncommanded rudder deflection. (See <http://www.nts.gov/publicn/2001/aar0101.htm>) Here we start by observing that *in a rudder-neutral spiral attitude, back stick gives you a pure pitch response. But during a rudder-deflected spiral attitude, as produced by an uncommanded rudder hardover, back stick accelerates the roll.*

Although aircraft attitude relative to the horizon might appear identical to the pilot, in the rudder-deflected

Maneuvers and Flight Notes

case the aircraft is in a sideslip toward the high wing. Pitch will couple to roll in the presence of a sideslip. While the hardover issue may not affect all planes and pilots, it's difficult to confirm one's immunity, and the exercise does provide more evidence for flying's least instinctive but most encompassing maxim:

Sometimes you have to aim for the ground to keep from hitting the ground! In the uncommanded rudder deflection case, you aim for the ground to regain aileron effectiveness.

- Here's an official definition, evidently approved by the attorneys, from The *Airplane Upset Recovery Training Aid*. At a given rudder deflection, *crossover speed* is "the minimum airspeed (weight and configuration dependent) in a 1-g flight, where maximum aileron/spoiler input (against the stops) is reached and the wings are still level or at an angle to maintain directional control." (2.5.5.4.3)

- In other (if only slightly more digestible) words, rudder deflection produces a rolling moment, in the direction of deflection, due to sideslip and yaw rate. You can counter an uncommanded rudder deflection with opposite aileron, just as you do in a steady-heading sideslip, but only if you're going fast enough to generate a sufficient opposing moment—that is, if you're going above the speed where excess roll power *crosses over* from rudder to aileron. The more rudder deflection, the greater the corresponding rolling moment and therefore the higher the crossover speed. If you fly below crossover speed the aileron/spoilers can't supply a sufficient opposing roll moment against the rudder, and an uncommanded roll in the rudder direction results. Wing-mounted multi-engine aircraft need powerful rudders to overcome asymmetric thrust conditions during engine failures. Uncommanded rudder deflections can produce powerful roll moments, especially in swept-wing aircraft.

- You're familiar with cross-controlled maneuvers from our earlier steady-heading sideslips, and noticed (maybe) that we reached the rudder stops before reaching the aileron stops. To simulate a crossover problem at a reasonable angle of attack, we simply limit our aileron deflection and pretended we're "against the aileron stops."

- When an uncommanded rudder deflection creates a rolling moment, the aircraft's nose will

begin to fall through the horizon. Since roll couple for a given sideslip angle and aircraft configuration varies directly with coefficient of lift (with α), as does roll due to yaw rate, the rudder-induced roll rate will increase if you try to raise the nose with aft pressure. This just tilts the lift vector more toward the horizon and makes the nose fall even faster (as we demonstrate in this maneuver set).

- ***In an emergency, if the hardover roll continues despite full opposite aileron, lower the nose to regain aileron effectiveness.*** Diving even more to regain bank control is not intuitive if the nose is *already* coming down in an unwelcome manner! But reducing the angle of attack will reduce yaw/roll couple, which in turn reduces crossover speed. Meanwhile, the airflow picks up the dynamic pressure necessary for aileron authority. As you raise the nose, set the power as required for flight above crossover speed. Then take a breath and pull out the Emergency Checklist for the recommended rudder hardover flap setting, if there is such a thing. (Maneuver set 14 demonstrated how flap deployment reduces a sideslip-induced yaw/roll couple, and thus would reduce crossover speed.)

- In an aileron hardover, you'd obviously try opposite rudder. Then if necessary you'd raise the nose to increase the C_L and increase the yaw/roll couple the rudder provides. Flaps would probably stay up, or go up if that were an option, again to increase yaw/roll couple as necessary to combat the ailerons.

- Remember that the basic relationship between what you do in pitch and what happens in roll remains constant. ***Pushing forward reduces rudder/sideslip-coupling effects and increases aileron authority, pulling back (literally toward the rudder) decreases aileron authority and increases rudder/sideslip-coupling effects.***

14. Lateral Effects of Flap Deployment

Flight Condition: Changing β & spanwise lift distribution.

Lesson: Lateral lift distribution and lateral stability.

Procedures:

Power as required for speed in white arc.

Enter steady-heading sideslip.

Hold rudder and aileron fixed.

Lower and raise flaps and observe lateral response.

Observe pitch response due to the changes in downwash angle.

With the flaps down in a sideslip and the aircraft trimmed, hold the rudder and release the stick:

Compare the roll rate with the flaps-up condition explored in maneuver set No 2.

If desired, repeat at idle power, maintaining airspeed in descent, to assess the contribution of propeller slipstream effects.

In the Zlin, full flaps, wings level, apply full rudder.

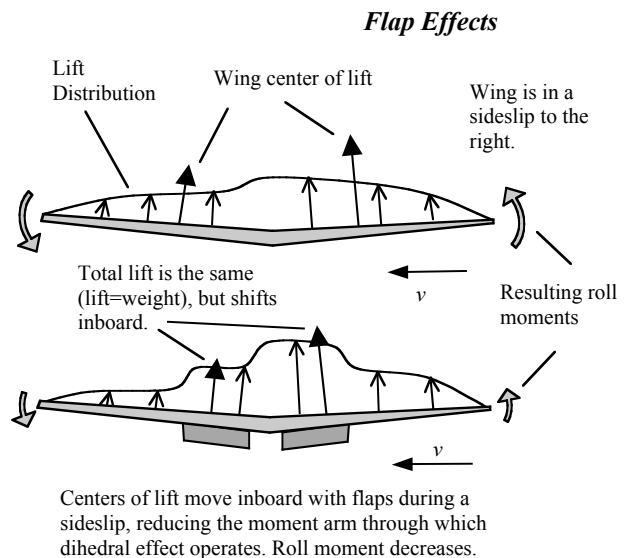
Observe pitch change with downwash/propwash shift.

Flight Notes

Here we'll alter the rolling moments in a sideslipping aircraft by changing flap position. This ties into the concept of *crossover speed* during rudder hardovers. Crossover speed may go down in a flaps-down configuration because of the phenomena we'll observe here.

- Putting the flaps down increases the lift generated at the wing roots and thus shifts the lift distribution inboard. This is partly because of the increased camber inboard, and partly because, after we've re-trimmed, the wingtips operate at a lower angle of attack. In effect, we've increased their washout. The inboard shift in center of lift reduces the effective moment arm and therefore the rolling moment that results from the sideslip. Accordingly, when you lower the flaps in a steady-heading sideslip, the ailerons will have less to fight against and the aircraft will roll in the pro-aileron direction.

- Because of this inboard shift in lift, an aircraft's lateral stability (its tendency to roll away from the sideslip caused when a wing goes down) is typically reduced with flaps deployed. Its roll due to yaw rate may also decrease because of the washout effect. We've already noted the



Maneuvers and Flight Notes

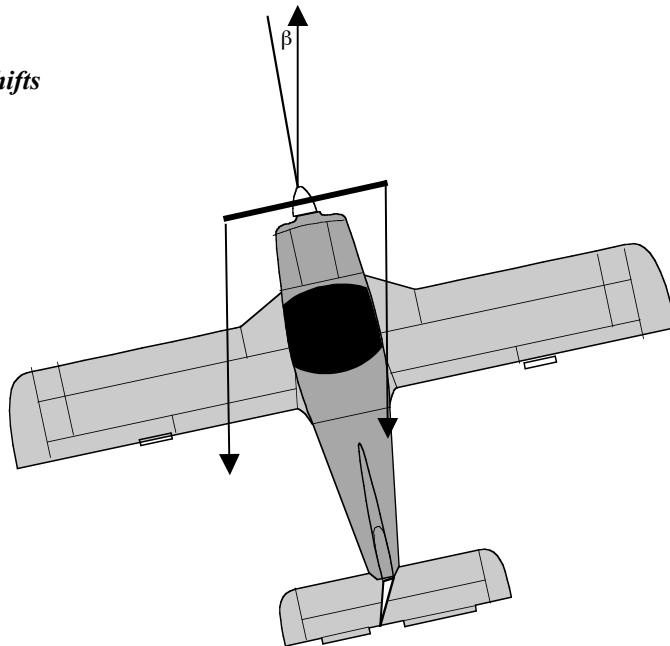
reduction in longitudinal stability with flap deployment caused by downwash effects.

- The flap effect you're seeing is magnified in propeller airplanes by the shifting of the slipstream over the wings toward the side opposite the sideslip, as the illustration shows. This means that the flaps on the high side during our steady heading sideslip work in an area of higher dynamic pressure. This increases the lift on the high wing, reduces it on the low wing, and produces a rolling moment in the same direction as the ailerons. With the power at idle, you'll need more flap deflection to get the same roll response you got when lowering the flaps with power on.

- The last maneuver in the set demonstrates how a sideslip combined with flaps can cause a sudden change in the downwash/propwash over the horizontal stabilizer. The nose may suddenly pitch in response. Unless you really know how it will behave, don't aggressively slip an aircraft with full flaps on final.

- In some aircraft, flaps can decrease aileron authority. This is one reason why using only partial flaps during a gusty, crosswind landing is a good idea. (The other, of course, is that a higher landing speed increases overall control effectiveness and leaves the aircraft vulnerable for less time.)

*Sideslip Shifts
Propwash*



15. Dutch Roll Characteristics

Flight Condition: Coupled yaw/roll.

Lesson: How directional and lateral stability interact dynamically.

Procedures:

About 23"/2,300 rpm.
Trim.
Instructor performs sinusoidal rudder inputs.
Observe roll/yaw ratio at wingtip.
Release rudder and observe rudder-free damping and overshoots.
Compare with rudder fixed damping and overshoots.

Flight Notes

Your instructor will probably want to do this demonstration on the return from the practice area. Dutch rolls can erode motion tolerance rapidly, and that's best saved for other things. FAR Parts 23.181 & 25.181 cover the requirements for Dutch roll characteristics. (Note: Our sinusoidal rudder inputs are consistent with FAR Part 25.351 yaw maneuver load requirements.) The Dutch roll is the natural outcome of aerodynamic stability: an aircraft's tendency to yaw toward but roll away from its velocity vector.

•As already mentioned, the term Dutch roll is often misused. The real Dutch roll is not an exercise in rolling on point, but a coupled combination of yaw rate, sideslip, and roll. You can think of it as a rough marriage between an aircraft's roll axis (lateral) stability and its yaw axis (directional) stability. In the Dutch roll, a disturbance in either axis, whether pilot-induced, as here, or caused by turbulence, creates a sideslip. A sideslip that sends the velocity vector to the left, for example, leads to an opposite rolling moment to the right (through dihedral effect and roll due to yaw rate). At the same time the aircraft's directional stability works to eliminate the sideslip by causing the nose to yaw to the left. However, momentum causes the nose to yaw past center (past zero β), and this sets up a sideslip in the opposite direction, which in turn sets up an opposite roll. The resulting out-of-phase yawing and rolling motions would damp out more quickly if they occurred independently. Instead, each motion drives the other. Part 23

aircraft are required to damp to 1/10 amplitude in 7 cycles. Part 25 requires only positive damping.

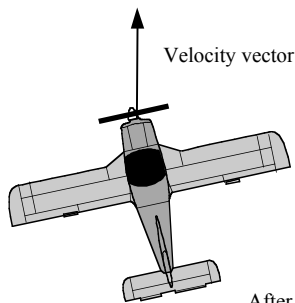
•Aircraft with lots of lateral stability (the tendency to roll away from a deflected velocity vector), compared to their directional stability, tend to Dutch roll. Reducing dihedral effect will ease the Dutch roll problem, but at the expense of reduced lateral stability. Without a yaw damper to do it for them, it's difficult for pilots to use the rudder to control a persistent Dutch rolling tendency because the period is short. It's hard to "jump in" with the correct rudder input at the right time. (Failure of a yaw damper can also cause fin overstress if Dutch roll develops.) Swept-wing aircraft are inherently vulnerable to Dutch roll. Pilots of swept-wing transports are frequently trained to damp the rolling motion with quick, *temporary* applications of aileron against the prevailing roll. Temporary applications prevent the pilot from inadvertently driving the rolling motion. An aircraft with lots of lateral stability may also require lots of aileron

Maneuvers and Flight Notes

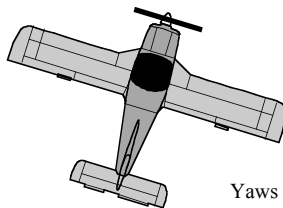
deflection to hold the upwind wing down during crosswind landings.

- Aircraft with greater directional than lateral stability tend to be spirally unstable. Traditionally, the design compromise between Dutch roll and spiral instability suppresses the former and allows the latter, because spiral dives begin slowly and are normally easier to control than Dutch rolls. And Dutch rolls make people airsick. (Which sounds like the dealmaker until you realize that spiral instability can kill you if you lose or misinterpret your instruments in clouds, or in poor visibility at night.)

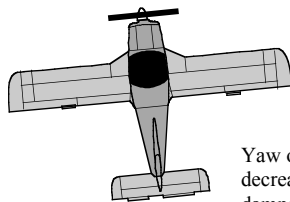
- Watch the wingtip while driving the Dutch roll with continuous, uniform, opposite sinusoidal rudder inputs. Observe if its motion pattern is circular or elliptical. An ellipse lying on its side (1.) means more yaw than roll—in other words a low roll-to-yaw ratio. This is typical of aerobatic and tactical aircraft required to have fast roll



After initial disturbance, aircraft wants to yaw to right but roll to left.



Yaws past center and now wants to yaw left but roll right.



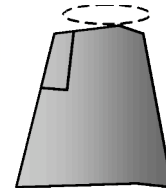
Yaw overshoot decreases as motion damps out.

rates. A circular wingtip motion (2.) indicates equal amounts of roll and yaw, as might be typical of a general aviation aircraft, in which a pilot can use the rudder for bank control.

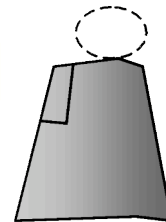
- An upright ellipse (3.) would indicate more roll than yaw—a high roll-to-yaw ratio. That's typical of a sailplane and indicates that roll performance will require good rudder coordination during roll maneuvering. Any uncorrected adverse yaw will generate an opposing sideslip and large roll moments opposite the intended roll direction. (The long wings of high-performance sailplanes produce substantial adverse yaw due to roll rate, so footwork is essential.)

- The tendency to Dutch roll increases at higher C_L , because increasing the coefficient of lift increases both dihedral effect (especially with swept-wings) and roll due to yaw rate. Dutch roll tendency also increases at higher altitudes, where damping effects diminish. Since aircraft fly at high C_L at high altitudes, the problem compounds.

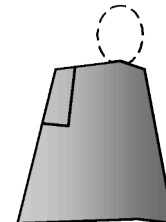
(1.)



(2.)



(3.)



16. CRM Issues: Pilot Flying/Pilot Monitoring

Flight Condition: Various.

Lesson: Upset recovery and the two-person cockpit.

Procedures:

Ground Briefing: Students formulate a plan of response, listing potential unusual attitudes and potential control errors, plus appropriate pilot monitoring actions.

Instructor:

Check: Seat belt, cockpit, instruments, altitude, outside.
Places aircraft in an unusual attitude.
Announces: “Now recovering.”
Begins recovery.

Student:

Monitors instructor’s recovery technique.
Guards controls with hands against improper deflections.
Verbally coaches best recovery.
Takes control as required.

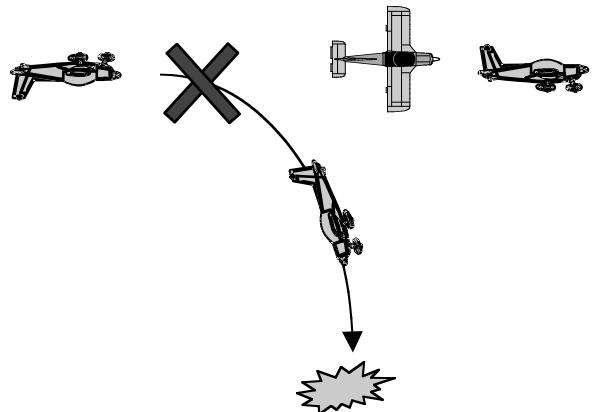
Flight Notes

“Pilot monitoring” has replaced the earlier term “pilot not flying.” The change keeps both pilots in the loop, at least rhetorically. As pilot monitoring, your ability to coach your instructor and respond as necessary will confirm your understanding of recovery techniques. And you’ll be exposed to potential conflicts in CRM—in this case, *recovery* management.

- Your instructor may initiate recovery with the proper control inputs, but with inadequate control deflection. In that case you might coach, “More aileron,” then push the aileron if he doesn’t respond. Or your instructor may call out “Vertigo!” or initiate an incorrect recovery, in either case requiring rapid intervention on your part. One example might be a pull when inverted.

- If relevant, it’s important that all pilots in your flight department discuss the results of this drill at the completion of the course, and the possible

changes or additions you might make to your CRM procedures.



17. Primary Control Failures

Flight Condition: Stick failure/loss of elevator, elevator trim, aileron.

Lesson: Re-establishing and evaluating control.

Procedures:

Fly parallel to a ground reference line (simulated runway).

Instructor places aircraft in nose-high or nose-low bank angle.

Student recovers and maintains control **with rudder, elevator trim, and throttle only.**

Turn 180 degrees and descend over reference line.

Establish landing attitude and a zero rate of descent at an altitude the instructor specifies.

Repeat without elevator trim.

Flight Notes

This maneuver set assumes the loss of both primary longitudinal (elevator) and lateral (aileron) control systems. Below are the FAR Part 23 requirements concerning loss of primary controls. In this maneuver set you'll conduct, in essence, a FAR Part 23.145(e) and Part 23.147(c) flight test. The initial recovery from a nose-high or nose-low bank angle would not be part of such a test. That's ours. Attempting the procedure without elevator or trim is also ours.

FAR Part 23.145(e) By using normal flight and power controls, except as otherwise noted in paragraphs (e)(1) and (e)(2) of this section, it must be possible to establish a zero rate of descent at an attitude suitable for a controlled landing without exceeding the operational and structural limitations of the airplane, as follows:

- (1) For single-engine and multiengine airplanes, without the use of the primary longitudinal control system.
- (2) For multiengine airplanes --
 - (i) Without the use of the primary directional control; and
 - (ii) If a single failure of any one connecting or transmitting link would affect both the longitudinal and directional primary control system, without the primary longitudinal and directional control system.

FAR Part 23.147(c) For all airplanes, it must be shown that the airplane is safely controllable without the use of the primary lateral control system in any all-engine configuration(s) and at any speed or altitude within the approved operating envelope. It must also be shown that the airplane's flight characteristics are not impaired below a level needed to permit continued safe flight and the ability to maintain attitudes suitable for a controlled landing without exceeding the operational and structural limitations of the airplane. If a single failure of any one connecting or transmitting link in the lateral control system would also cause the loss of additional control system(s), compliance with the above requirement must be shown with those additional systems also assumed to be inoperative.

Maneuvers and Flight Notes

Observations:

1. Using rudder, how aggressively should you bank the aircraft?

Does a phugoid appear during the turn?

How much altitude is lost after turning if you can't trim?

2. Do the flaps produce a pitching moment that can be easily trimmed?

3. Do flaps affect the ability to turn using rudder (diminished dihedral effect)?

4. With the aircraft at a given trim state, gear down, what power settings are necessary for:

Level flight?

Positive rate of climb at moderate pitch attitude?

Controlled descent along a standard glide path?

5. Without trim available, can you achieve a landing attitude using power and/or flap deployment?

•FAR Part 23.145(e) assumes that the power and trim systems are available. It doesn't require the test pilot to complete an actual landing. Flying without elevator but with trim in a more-or-less normal fashion presupposes that the elevator floats free, as it might with a broken cable. A jammed elevator is rotten news, even if it jams at a favorable angle. With the elevator frozen and trim tabs operating, trim input will reverse (nose-up trim will produce a nose-down pitch moment, for example). But don't expect a trim tab to be an effective longitudinal control under these conditions. They're designed to generate enough moment to deflect the elevator, not pitch the aircraft.

•Without the stick for primary longitudinal and lateral control, and *without elevator trim*, the phugoid suddenly becomes your constant pal. You'll provoke a phugoid every time you bank using rudder. It's difficult to damp a phugoid with power, but you should try during this exercise, just to see. Without trim control, your best policy is to ride the phugoid out. An aircraft at an aft c.g. may have a neutral or a divergent phugoid, however.

•Without primary controls, a long, stabilized final approach is absolutely essential. Without primary longitudinal and trim control, you're stuck with an approach speed according to the aircraft's trim state. Manipulate the glide path with power. Find a long runway, into the wind!

18. Spins

Flight Condition: High angle of attack plus roll due to sideslip and yaw rate.
 $(\alpha + C_{l\beta} + C_{lr})$

Lesson: Departures and recoveries.

Entry Procedures:

1. Basic spin entry:

- 4,000 feet agl.
- Rudder and elevator trim to neutral.
- Mixture rich.
- Power idle.
- Back stick for standard 1-knot-per-second deceleration.
- Ailerons neutral.
- Full rudder in desired spin direction at buffet onset.
- Stick full back.

2. Nose-high, yaw-rate entry:

- 4,000 agl.
- Cruise power.
- Hold steep climb attitude, **rudder free**.
- Allow propeller effects to yaw aircraft to the left.
- Back stick until stall/spin break.

3. Skidding-turn-to-final entry:

- 4,000 feet agl.
- Rudder and elevator trim to neutral.
- Mixture rich.
- 12 inches manifold pressure or as required.
- Begin skidding turn with rudder.
- Hold wings level with aileron.
- Apply back stick until stall/spin break.

Experiment with power to determine propeller effects.

Apply sudden aileron toward the direction of the turn while holding rudder and elevator.

4. “Lazy-eight” departure/recovery drill:

- Linked opposite-side half-turn spin departures and recoveries.

PARE Recovery Procedure:

- Power as spin state requires.
- Ailerons neutral.
- Rudder full opposite rotation.
- Elevator forward to neutral or past neutral according to AFM or POH.
- Recover from dive with rudder neutral.

Flight Notes

Spins have become a culminating skill in wide-envelope stick-and-rudder airmanship. In earlier days, under a different training philosophy, they were a pre-solo foundation skill. Pilots—and also aircraft—are different today as a result of this fundamental shift. The ground school text contains extensive material on spin procedures and theory. We review the PARE recovery technique here.

Power to idle. (Reduces propeller gyroscopic effects and slipstream-induced yaw.)

Ailerons neutral. (Removes any inadvertent deflection that may delay recovery. In a fuselage-loaded aircraft the ailerons go toward the spin direction to produce an anti-spin inertia moment in yaw.)

Rudder opposite yaw direction. (Provides anti-spin aerodynamic yaw moment.)

Elevator forward to neutral or past neutral. (Unstalls the wings; for wing-loaded aircraft generates anti-spin inertia moment in yaw.)

When the spin stops, pull out with the rudder neutral. (If recovery rudder is still deflected and you pull too hard, the aircraft can snap roll into a spin going the opposite way. Holding recovery rudder is a common mistake.)

•Power to idle depends on spin state. It's already at idle in a practice spin. For an immediate recovery from a stall/spin break, power can usually be left on in a single-engine training aircraft, and brought back as necessary for speed control in the pull out from the dive. (A prop twin on one engine requires immediate power to idle on the operating engine, since the slipstream produces both rolling and yawing moments in the direction of the dead engine. Most bets are off in twins, however, because no spin testing is required for certification.)

•The PARE sequence comes from certification demonstration requirements that assume spin recovery will only begin after a certain time or number of turns, depending on aircraft category, and not immediately after the stall/spin break.

Recovery inputs immediately following the break may be less critical (but not always).

•Note that in the PARE sequence, *opposite rudder precedes forward stick*. Forward stick applied before opposite rudder can accelerate the spin through aircraft gyroscopic effects, and can also cause the elevator to block the airflow to the rudder in some aircraft, each of which delays recovery. The acceleration isn't necessarily the case in an *immediate* recovery right after departure, however, as we'll demonstrate and discuss. In our trainers the roll acceleration on departure is initially high; then the yaw rate picks up. As a result, angular momentum is greater in roll initially than in yaw. Pushing the stick forward causes gyroscopic precession around the roll axis that leads to an anti-spin moment in yaw. Plus, pushing gets the angle of attack back down. But once the aircraft's yaw rate and angular momentum about the yaw axis have begun to build, forward stick will cause momentary gyroscopic acceleration in roll, even when it follows the rudder in proper sequence. Our introductory spins will go at least to the point where you can begin to feel the "push back"—the increase in pressure needed to bring the stick forward for recovery as angular momentum picks up in yaw and the aircraft becomes increasingly resistant to displacement, and also experience the momentary roll acceleration. It's important to observe these characteristics and to recognize them as normal. One to one-and-a-half turns before initiating recovery will accomplish this in our aircraft. Multiple-turn spins beyond that have dubious value in introductory training. In the beginning it's better to go for lots of entries and recoveries, do a careful analysis each time, and not waste training time recovering large chunks of altitude.

• As part of the analysis, after each spin try to describe the aircraft's motions to your instructor.

Maneuvers and Flight Notes

You may find post-stall spin behavior difficult to follow at first, especially if your attention is occupied with remembering the recovery steps and wondering if they'll actually work. But report each time. The task helps build tracking skills and confidence, and keeps the instructor updated on your progress.

- The infamous skidding-turn-to-final spin (spin entry 3) will produce a departure in some aircraft, while others are resistant (too much directional stability for the available rudder power; too little elevator power). Some will do it engine power off; some need a boost in yaw and pitch from the slipstream hitting the stabilizer and tail. The slipstream increases the upwash on the left wing, which then operates at a higher angle of attack and in a left turn stalls first. Spiraling slipstream also encourages a departure to the left. Frankly, a high- α skidding turn is hard to imagine from a properly trained pilot—the necessary control forces ought to warn the pilot off. But what about after an engine failure in an aircraft with a departure-prone wing, or when some other distraction arises? At low altitude and low speed, no matter how good the pilot, if obstacles are approaching it will be hard to resist the impulse to rudder rather than bank the airplane. If the pilot then pulls up the nose—there's your spin.

- In the Zlin, and quite probably in many other aircraft, a rapid reversal of the ailerons toward the turn direction, while in-turn rudder and back stick are still being held, can cause a departure. When the opposite aileron is removed, the aircraft rolls and yaws suddenly in the direction of the skidding turn, and enters a spin. This may in fact be the true cause of many skidding-turn-to-final accidents. The pilot suddenly realized his error, but corrected with aileron alone.

- The fourth spin exercise is based on the lazy-eight. It's done back and forth across a reference line on the ground. Each reversal of direction is accomplished as a spin departure, followed by a recovery to the half-turn point. Then you add power and pull up across the line, then cut power and spin a half turn to the opposite side. Next, go the other way. Your feet and hands are busy departing and recovering; you have to maintain orientation with the ground and stay well ahead

of the aircraft to do the maneuver smoothly. If you can do all this, you're definitely a hot stick!

- The pull up when the spin stops is full of important lessons. Depending on when in the spin the recovery was introduced, and whether the pilot as forgotten to neutralize the rudder (holding recovery rudder too long is a universal beginner's mistake), the aircraft may end up in a sideslip, and may roll rather than raise its nose when the pilot applies back stick. Or, even if the pilot uses the rudder correctly, but pulls too hard before the aircraft has gained sufficient speed, the aircraft may enter the buffet and lose nose-up pitch authority. ***Remember this: When you see a substantial increase in pitch rate at low speed, the buffet won't be far behind. If you penetrate the buffet too far, nose-up pitch authority may largely disappear!*** Ease off.

Flightlab Ground School Texts

This material supplements the practical demonstrations given during the training flights. It's useful in preparing for the course (especially 1-4, 8, and 10 if applicable) and for follow-up reading.

1. Axes and Derivatives

(Descriptive concepts, vectors, moments, cause and effect)

2. Two-Dimensional Aerodynamics

(Lift and stall fundamentals: pressure, boundary layer, circulation)

3. Three-Dimensional Aerodynamics

(How wing planform affects stall behavior)

4. Lateral-Directional Stability

(Sideslips, yaw/roll coupling, straight and swept-wing dihedral effect, Dutch roll)

5. Longitudinal Static Stability

(Aircraft in trim, pitch control forces in 1-g flight)

6. Longitudinal Maneuvering Stability

(Pulling g)

7. Longitudinal Dynamic Stability

(Oscillations in pitch)

8. Maneuvering Loads, High-G Maneuvers

(V-n diagram, corner speed, radial g)

9. Rolling Dynamics

(Roll performance, adverse yaw, coordination)

10. Spins

(History, spin phases, momentum effects, recovery)

11. Some Differences Between Prop Trainers and Passenger Jets

(Differences in control and response)

12. Vortex Wake Turbulence

(Aircraft/vortex flow field interaction)

13. A Selective Summary of Certification Requirements

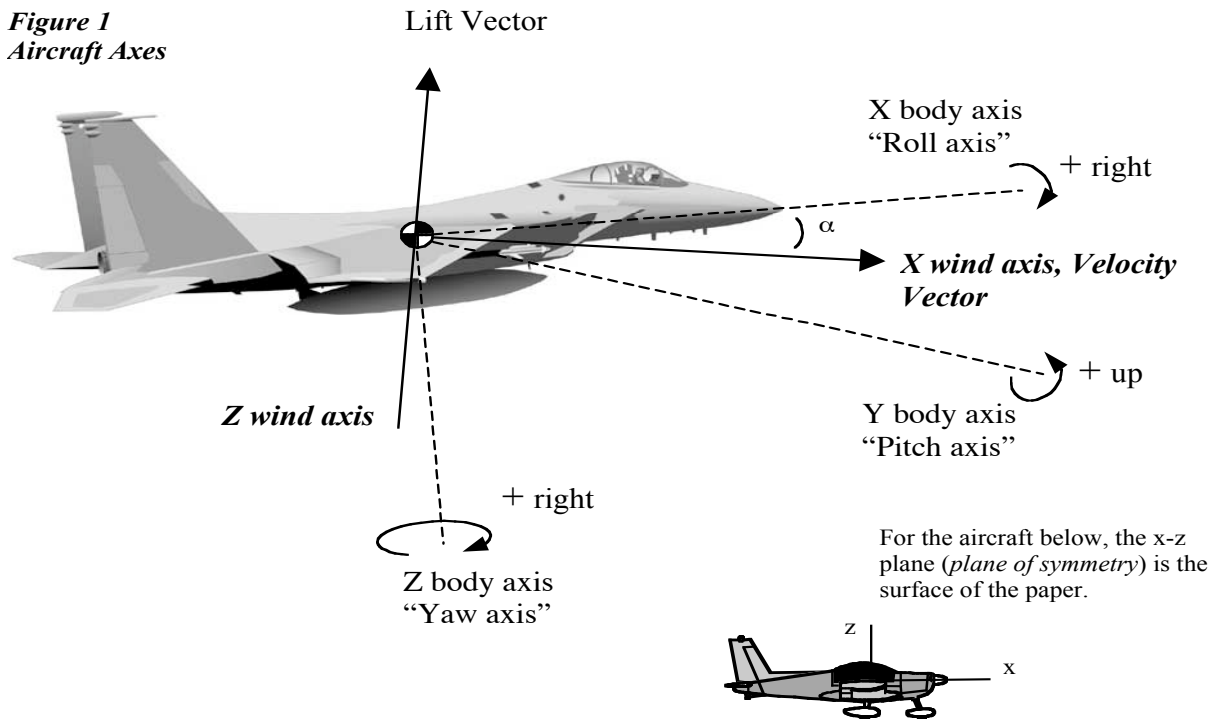
(What the regulations say about aircraft stability and control)

Flightlab Ground School

1. Axes and Derivatives

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For Training Purposes Only

Figure 1
Aircraft Axes



Introduction

If you didn't much care for symbols, formulas, and coefficients back in primary ground school, the following may raise warning signals. Ignore them and don't be a wimp. You'll want to understand the axis system and also to take a look at the tables of aerodynamic derivatives (which we'll review in person, as well). The derivatives break aircraft behavior down to cause and effect, giving the engineers lots to calculate and giving us the terms needed to evaluate aircraft in an informed, qualitative way—a way that links the demands of airmanship to the specific personalities of our machines.

Aircraft Axes

The dashed lines in Figure 1 describe an aircraft's x-y-z *fixed body axes*, emanating from the center of gravity. This system, with the mutually perpendicular axes in fixed reference to the aircraft, is the one most pilots recognize. The exact alignment is a bit arbitrary. Boeing sets the x-axis parallel to the floorboards in its aircraft.

The geometrical plane that intersects both the x and z body axes is called the *plane of symmetry*, since a standard aircraft layout is symmetrical left and right (Figure 1, bottom).

There are alternative axis systems (zero-lift body axis, stability axis, for example). For pilots, the *wind axis* system is the most useful, because it best helps in visualizing how aircraft actually behave.

Axes and Derivatives

The wind axis system sets the x-axis in alignment with the aircraft's *velocity vector*, which points in the direction in which the aircraft is actually moving. Usually the velocity vector/wind axis lies on the aircraft's plane of symmetry, but not always. If the aircraft is in a sideslip, the velocity vector moves off the plane to some sideslip angle, β ("beta"), as Figure 2 illustrates.

The velocity vector also changes direction when aircraft angle of attack, α ("alpha"), changes.

The velocity vector is projected onto the x-z plane of symmetry for measuring α , and onto the x-y plane for measuring β . Thus it contains both α and β , as the bottom of Figure 2 shows.

Both the y and z wind axes remain perpendicular to the x wind axis (and to one another). So, as the velocity vector changes direction, these axes change orientation, as well. Thus they're carried along by the aircraft, but not "fixed."

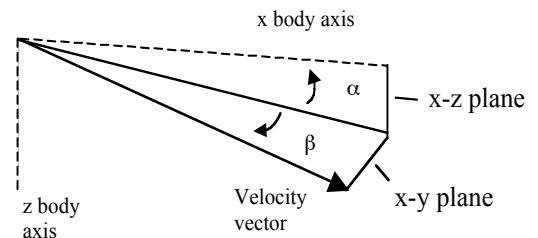
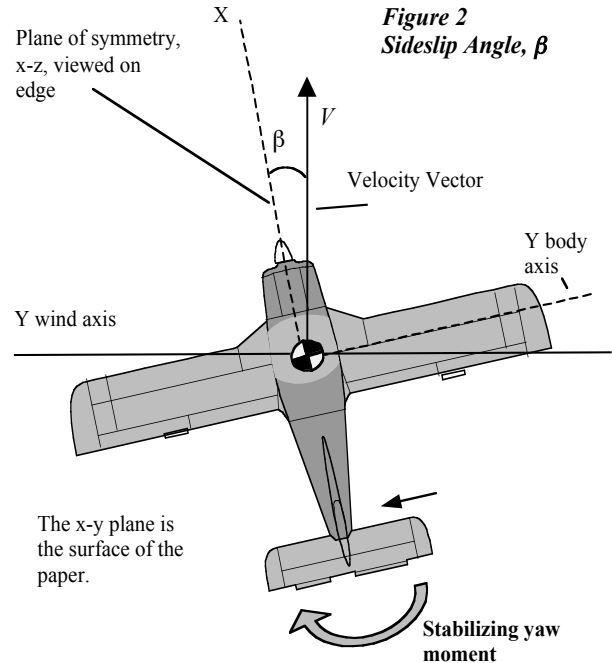
Here's the essence of why the velocity vector is important to pilots: Much of aircraft response is pinned to it, both during normal flight and in unusual attitudes.

Laterally and directionally stable aircraft normally tend to roll away from, but yaw toward, the velocity vector when the vector is off the plane of symmetry. Unstable aircraft lack these instincts, or lack them in proper combination.

In addition, ***a trimmed, longitudinally stable aircraft tends to hold the velocity vector at a constant angle of attack, unless commanded otherwise.*** An unstable aircraft does not.

Aerodynamically stable aircraft tend to roll, pitch, and yaw around their respective wind axes—not around their fixed body axes, as most pilots are taught. The picture becomes more complicated when those axes then begin to change their direction in space,¹ but a simplified notion of wind axis rotation is often helpful in visualizing maneuvering flight.

¹ Kalviste, J., "Spherical Mapping and Analysis of Aircraft Angles for Maneuvering Flight," AIAA-86-2283.



There's another axis system, based on the aircraft's distribution of mass: the *inertia* (or *principal*) axis system. The moments of inertia about the three, mutually perpendicular, principal axes determine how quickly rates of roll, pitch and yaw can change around the aircraft's center of gravity. (For example, an aircraft with tip tanks has more x-axis roll inertia when the tanks are full than when empty, and for a given airspeed, altitude, and aileron deflection will take longer to achieve a roll rate. It will also take longer to stop rolling.) The principal axes are the lines around which mass is symmetrically arranged. They may not always be shown as coincident with the aircraft fixed body axes—although, because aircraft are essentially symmetrical, they're often close enough to be considered as such. Differences in moments of inertia around each axis can lead to various coupling effects. We'll leave the details until our discussion of spins.

Axes and Derivatives

Lift Vector

A directionally stable aircraft returns the velocity vector to the plane of symmetry if the vector becomes displaced to some sideslip angle, β (as the “stabilizing yaw moment” is doing in Figure 2). ***In coordinated flight, the velocity vector lies on the plane of symmetry, as does the lift vector.***

As illustrated in Figure 1, the lift vector is the upward projection of the z wind axis. Since lift is perpendicular to the air stream generated by the aircraft’s velocity, it makes sense to think of its vector in wind axis terms. Fighter pilots talk cryptically of keeping the lift vector on the bogey, while an instructor might direct an inverted-attitude recovery by saying “roll the lift vector toward the sky.” They generally mean a fixed vector perpendicular to the wingspan—bolted on, figuratively speaking. That’s sufficient and appropriate most of the time. The direction relative to the horizon of the lift vector so defined has a profound effect on an aircraft’s maneuvering performance (see the ground school text “Maneuvering Loads, High-G Maneuvers”), but it’s also possible to consider the lift vector as free to rotate around the x-axis, as it does in uncoordinated flight. For example, if a pilot uses top rudder (fuselage lift) to keep the nose up during a steep bank, the lift vector will tilt toward the high wing. Sometimes it’s useful to think of the lift vector as staying oriented in space while the aircraft rotates beneath it, as it does, essentially at least, during a properly flown “slow” roll. Halfway through the slow roll, when

the pilot pushes on the stick and the aircraft is producing lift inverted, the lift vector points heavenward, as it does normally, but now poking out the belly. At each knife-edge, when the wings are unloaded and the pilot presses top rudder so that the fuselage is used briefly for lift, the vector still points heavenward, but out the side. We’ll refer to a fixed or free lift vector, as the situation requires.

Signs, Moments, Symbols

In the sign system used with the axis notation, positive values are in the direction shown by the curved arrows in Figure 1, negative values are opposite. For example, when you pull the stick back and add left aileron, you’re generating a positive pitching moment and a negative rolling moment (therefore a positive pitch rate and angle, and a negative roll rate and angle). The signs are not related to the aircraft’s attitude relative to the earth or to the pull of gravity.

A moment is a force producing rotation around an axis. An aerodynamic moment is the product of a force acting on a surface—say the center of pressure of a vertical stabilizer with a deflected rudder—times the perpendicular distance from that surface to the respective axis—the z-axis for a deflected rudder. *When an aircraft is in equilibrium about an axis, all the positive and negative moments around the axis sum to zero.*

We’ll often break down our training aircraft’s behavior into its x-y-z, roll-pitch-yaw components. Changes in aircraft attitude or angular velocity (rotation rate) are the result of

Axis	Moment Applied	Angular Velocity	Angular position	Moment of Inertia	Control Deflection
x	l	Roll rate, p	Roll angle ϕ (phi)	I_{xx} Roll Inertia	Aileron (δa)
y	m	Pitch rate, q	Pitch angle θ (theta)	I_{yy} Pitch Inertia	Elevator (δe)
z	n	Yaw rate, r	Yaw angle ψ (psi)	I_{zz} Yaw Inertia	Rudder (δr)

Axes and Derivatives

changes in moments applied around each axis. You already know the primary moments (ailerons produce rolling moments, elevators pitching moments, rudders yawing moments), but there's a further collection of direct and cross-coupled moments essential to aircraft control and often complicit in unusual attitudes. We'll talk about them on the ground and observe them in flight.

For reference, the table above shows notations used for moments, angular velocities, angular positions, moments of inertia, and control deflections about each aircraft axis. You don't need to memorize any of this for our course, but you might find it useful for future technical reading. Notice the preference for arranging things by alphabetical order. Thus the letters don't always mean what your mnemonically inclined brain would like them to mean ("r" doesn't stand for roll rate; "p" doesn't stand for pitch rate, and, while "L" stands for lift, a lowercase "l" stands for roll moment).

Stability and Control Derivatives

Moments about the axes drive aircraft attitude. Stability is the tendency of an aircraft to generate the aerodynamic moments necessary to return it to its original equilibrium, when disturbed. During unusual attitudes, if an aircraft is left to its hands-off free response, those same moments can become destabilizing. At high bank angles, for example, directional stability (a yawing moment) causes the nose to descend below the horizon and speed to increase. When an aircraft is inverted, longitudinal stability (a pitching moment) causes the nose to fall below the horizon, as well. And at angles of attack past stall, rolling moments that would ordinarily damp out can instead produce autorotation and spin departure.

In normal maneuvering in a stable aircraft, a pilot uses the controls to overcome the aircraft's stabilizing moments and to establish a new equilibrium, at least temporarily. This may be easy or not so easy, depending on the degree of inherent stability and the availability of control power to do the job

Stability and control are measured in terms of derivatives—the rate of change of one variable with change in another. During our flights, especially early on, we're going to see how the

rates of change of moments in pitch, roll, and yaw can vary with angle of attack, sideslip angle, the presence of aerodynamic and/or inertial couples, control deflections, and with airspeed. The derivatives in the tables that follow form the basic vocabulary of cause and effect that we'll apply in analyzing departure modes and in learning to recover from unusual attitudes. Some will be new to you (as perhaps all the symbols), and some you'll remember, at least in general terms, from the days of primary ground school. Don't worry about learning the symbols. We'll refer to things by name.

Initially, you might want to review the descriptions—which are by necessity condensed—and then refer to the Flightlab Ground School texts for more explanation. We'll also brief the material before flying. Don't feel responsible for immediately understanding all of the bulleted items. You'll get there in stages. Top priority goes to acquiring new flying skills.

A note on signs: The derivatives carry signs that might be confusing at first. A negative (–) sign doesn't indicate the lack of stability, but rather helps determine the direction of response. Review the sign system used with the axis notation in Figure 1. Then, in the derivative table, note for example that $C_{l\beta}$, the lateral stability derivative, carries a negative sign. When a laterally stable aircraft slips to the right (positive direction) it will roll to the left (negative direction). Algebraically, a negative (the derivative) times a positive (sideslip direction) equals a negative (roll direction). If the aircraft slips to the left, it will roll to the right, since a negative derivative times a negative direction equals a positive. For us, the signs will come in handy when analyzing spins, where they simplify the perplexity inherent in understanding a flight regime where an input in one axis can produce an output in another.

The flow chart at the end of this section shows a related way of describing the basics of aircraft response.

Axes and Derivatives

Selected Aerodynamic Derivatives for Roll

Aerodynamic Stability Derivative Symbol	Name	Description
$-C_{l_{\beta}}$ C = coefficient l = roll moment β = sideslip angle	Rolling moment due to sideslip. (Lateral stability produced by dihedral effect)	Aircraft rolls away from the direction of sideslip. Main causes are geometrical dihedral and/or wing sweep, and fuselage-induced airflow changes that place the wings at different angles of attack. <ul style="list-style-type: none"> Roll due to sideslip is proportional to sideslip angle, β, and to the coefficient of lift, C_L, up to the stall, but may vary afterwards. Roll rate commanded by aileron/spoilers is affected by sideslip angle and direction. Wingtip washout, and/or flap deployment, reduce $C_{l_{\beta}}$. Depends on wing position relative to fuselage. Decreased by wing taper and low aspect ratio (wingspan²/wing area)
$-C_{l_p}$ l = roll moment p = roll rate	Rolling moment due to roll rate. (Roll damping)	As an aircraft rolls in response to a disturbance, the angle of attack increases on the down-going wing and decreases on the up-going wing. The resulting change in lift produces an opposing rolling moment. The aircraft stops rolling. If the pilot holds aileron deflection, roll damping moment builds until it's equal to the opposing moment produced by the aileron deflection. Roll rate then becomes constant. <ul style="list-style-type: none"> Roll damping disappears on wing sections at stall; autorotation is the reversal of roll damping. Damping increases with the slope of the C_L curve. Reduced by low aspect ratios and/or wing taper. Roll damping decreases with altitude.
$+C_{l_r}$ l = roll moment r = yaw rate	Rolling moment due to yaw rate.	Yaw rate causes airflow velocity to increase on the advancing wing and decrease on the retreating wing, causing a spanwise change in lift and a rolling moment. <ul style="list-style-type: none"> The effect follows the lift curve, becoming greatest at $C_{L_{max}}$ and then falling off after the stall. (C_{l_r} = approx. $C_L/4$). Rolling moment due to yaw rate contributes to spiral instability and to spin departure. When entering a sideslip, rolling moments due to the temporary yaw rate and the growing sideslip angle are additive. Wingtip washout, and/or flap deployment, reduces C_{l_r}. Little affected by wing position on fuselage. Increases with aspect ratio, decreases with wing taper. Varies with the square of the difference in tip speed (since lift varies with V^2).

Axes and Derivatives

Selected Aerodynamic Derivatives for Yaw

Aerodynamic Stability Derivative Symbol	Name	Description
$+C_{n\beta}$ n = yaw moment β = sideslip angle	Yawing moment due to sideslip. (Directional stability)	<p>Also known as weathercock stability. Aircraft yaws toward the direction of sideslip to align the longitudinal, x-axis with the relative wind.</p> <ul style="list-style-type: none"> The fuselage alone is usually destabilizing; principal stability contribution comes from vertical tail, although swept wings are stabilizing, an effect that increases with C_L. Spiral instability occurs when directional stability is high and lateral stability is low. Low directional stability and high lateral stability promotes Dutch roll.
$-C_{np}$ n = yaw moment p = roll rate	Yawing moment due to roll rate.	<p>The induced change in angle of attack on a rolling wing causes the lift vector to tilt back on the wing going up, and forward on the wing going down. This adds components of thrust and drag, which produce a yawing moment opposite the direction of roll (similar to adverse aileron yaw).</p> <ul style="list-style-type: none"> Increases with aspect ratio, roll rate. Increases with C_L. Wingtip washout, and/or flap deployment, reduces C_{np}. Largely independent of taper. ($C_{np} = \text{approx. } C_L/8$). Reverses effect when the wing goes into autorotation.
$-C_{nr}$ n = yaw moment r = yaw rate	Yawing moment due to yaw rate. (Yaw damping)	<p>When an aircraft has a yaw rate, opposing aerodynamic damping forces build up ahead and behind the center of gravity.</p> <ul style="list-style-type: none"> Main contribution comes from the vertical tail, but the forward fuselage can also contribute (unlike $C_{n\beta}$, in which the fuselage forward of the wing is destabilizing). Wings also contribute, since the advancing wing produces more induced and profile drag than the retreating wing. Wing contribution to yaw damping increases with angle of attack; the tail's contribution may decrease due to disrupted airflow at high α. Yaw damping decreases with altitude.

Axes and Derivatives

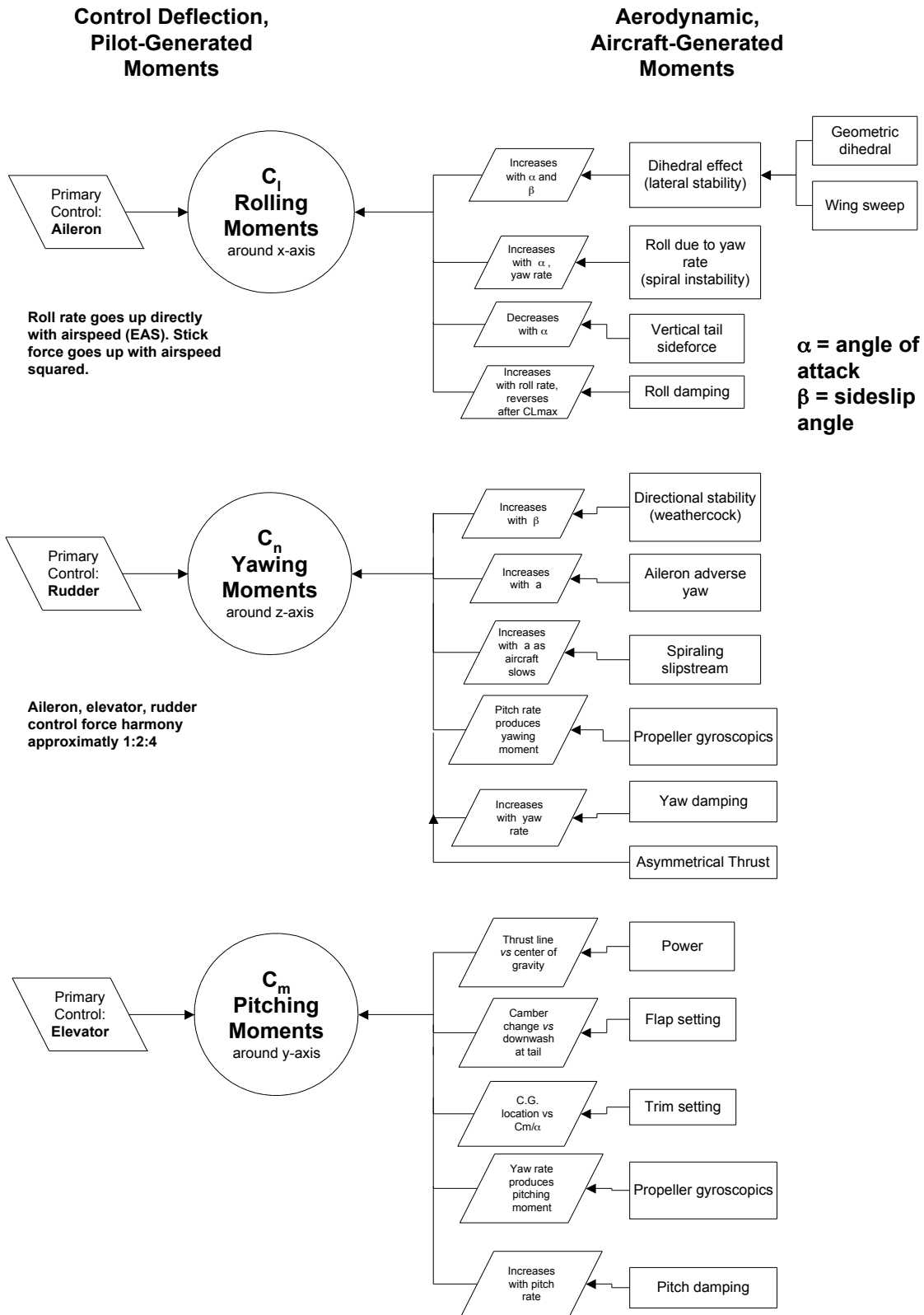
Rudder/Aileron Cross Derivatives

Control Derivative Symbol	Name	Description
$C_{l_{\delta r}}$ l = roll moment δ = deflection r = rudder	Rolling moment due to rudder deflection.	<p>A roll moment is produced if the lift generated by rudder deflection acts at a point above the roll axis. Right rudder, for example, produces a left rolling moment. This can become apparent in aircraft without dihedral effect.</p> <ul style="list-style-type: none"> • Diminishes as angle of attack increases.
$C_{n_{\delta a}}$ n = yaw moment δ = deflection a = aileron	Yawing moment due to aileron deflection. (Adverse yaw)	<p>An aileron deflected down creates more <i>induced</i> drag than the opposite aileron deflected up. The result is a yawing moment opposite the direction of bank. <i>Profile</i> drag increases on both wings when the ailerons are deflected, the difference depending on aileron design.</p> <ul style="list-style-type: none"> • Adverse yaw increases with wing angle of attack, because drag rises faster than lift at high α. • Spoilers for roll control can produce proverse yaw. • Differential ailerons or Frise ailerons counteract adverse yaw with opposing drag—although their primary function is to lower aileron control force.

Pitch Damping

Aerodynamic Stability Derivative Symbol	Name	Description
C_{m_q} m = pitching moment q = pitch rate	Pitching moment due to pitch rate. (Pitch damping)	<p>When aircraft pitches up or down, the motion of the horizontal stabilizer causes a change in the stabilizer's angle of attack, which generates an opposing, or damping, pitching moment.</p> <ul style="list-style-type: none"> • Pitch-damping moment increases with pitch rate (and thus with g load). • Pitching moment due to pitch rate affects short-period response and stick force per g in pull-ups and turns. • Pitch damping decreases with altitude. • Pitch damping increases with increased distance between the horizontal stabilizer and the aircraft c.g.

Axes and Derivatives



Flightlab Ground School

2. Two-Dimensional Aerodynamics

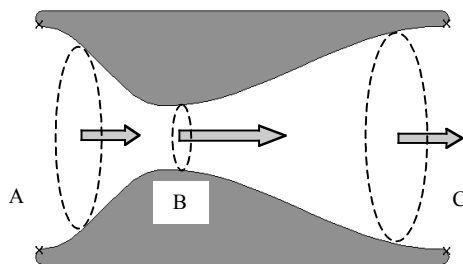
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For Training Purposes Only

Our Plan for Stall Demonstrations

We'll do a stall series at the beginning of our first flight, and tuft the trainer's wing with yarn before we go. The tufts show complex airflow and are truly fun to watch. You'll first see the tufts near the root trailing edge begin to wiggle and then actually reverse direction as the adverse pressure gradient grows and the boundary layer separates from the wing. The disturbance will work its way up the chord. You'll also see the movement of the tufts spread toward the wingtips. This spanwise movement can be modified in a number of ways, but depends primarily on planform (wing shape as seen from above). Spanwise characteristics have important implications for lateral control at high angles of attack, and thus for recovery from unusual attitudes entered from stalls. Our rectangular-planform trainers have excellent stall characteristics. Other planforms may need to be cajoled into behaving as if they were rectangular, stalling first at the root while the ailerons keep flying.

We'll first examine two-dimensional airfoil sections, then three-dimensional wing planforms. We'll only spend a few minutes during our flights watching the wing tufts, but those minutes can be full of information.

Figure 1
Velocity in a Venturi



Arrow length indicates velocity. Velocity actually starts rising before air enters the venturi.

$$(\rho AV)_A = (\rho AV)_B = (\rho AV)_C = \text{constant}$$

Remember Mass Flow?

Remember the illustration of the venturi from your student pilot days (like Figure 1)? The major idea is that the flow in the venturi increases in velocity as it passes through the narrows.

The Law of Conservation of Mass operates here: The mass you send into the venturi over a given unit of time has to equal the mass that comes out over the same time (mass can't be destroyed). This can only happen if the velocity increases when the cross section decreases. The velocity is in fact inversely proportional to the cross section area. So if you reduce the cross section area of the narrowest part of the venturi to half that of the opening, for example, the velocity must double at that point.

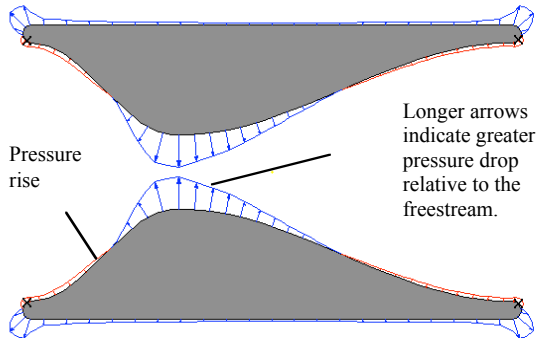
For a fluid (like air), the density, ρ , times the cross section area, A , of the venturi times the velocity, V , equals the *mass airflow*. Mass airflow, in and out, remains constant, so:

$$\rho AV = \text{Constant}$$

The above is known as the continuity equation.

Density (denoted by the Greek letter ρ , pronounced "roh") is the mass of air (in slugs) per volume (one cubic foot). Air is considered incompressible at the low, subsonic speeds we fly our trainers—so density doesn't change for us, only velocity.

Figure 2
Pressure Decreases as Velocity Increases



Remember Bernoulli?

Bernoulli's Theorem deals with conservation of energy. It tells us that for an ideal fluid (incompressible and frictionless) the total energy of the flow in the venturi remains constant. If we convert the total energy per unit volume of mass times flow rate into pressures, the sum of the static pressure and the dynamic pressure will equal a constant total pressure. Static pressure is the ambient pressure exerted by a column of fluid at a given level. Dynamic pressure is the pressure exerted by a mass of fluid in motion. In the formula below, static pressure is P_s . Dynamic pressure is $1/2 \rho V^2$, or one-half the density, ρ , of the fluid times its velocity, in feet-per-second, squared. P_T is the total pressure:

$$P_s + 1/2 \rho V^2 = \text{Constant } P_T$$

Or in English:

Static pressure + Dynamic pressure = Constant Total Pressure

So if velocity and thus dynamic pressure increases, static pressure will decrease. In the venturi in Figure 2, the increase in dynamic pressure with velocity produces a decrease in static pressure as the tube narrows. The static pressure then rises again as the tube widens downstream and the airflow slows down.

Of course, air isn't an ideal fluid: It's compressible and viscous. Compressibility

obviously becomes important approaching the speed of sound, but for present purposes can be ignored. But we won't ignore viscosity for long, because the nature of the airflow within the boundary layer over a wing depends on friction.

After looking at the behavior of velocity and pressure in a venturi, it's tempting to declare that the reason airflow accelerates over the top of a wing, and static pressure consequently decreases, is that a wing is just one half of a venturi, with the mass of the atmosphere playing a roll equivalent to the other half. That's a valid way of thinking about it, and easy to visualize. But aerodynamics is a subject in which alternative visualizations exist side-by-side. A different but not necessarily contradictory understanding of the acceleration of flow has to do with the idea of *circulation*. Circulation in turn gives us a way of visualizing the generation of wingtip vortices, and understanding how the strength of the vortical flow relates to the particular conditions under which the wing was producing lift. We'll return to this farther on.

Two-Dimensional Aerodynamics

Streamlines

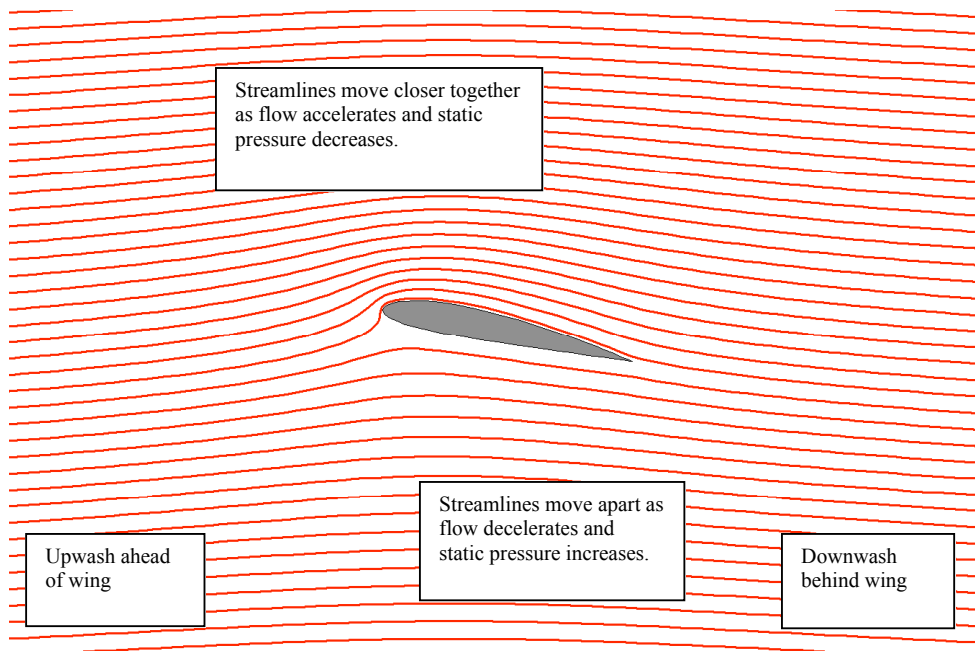
An airfoil section is equivalent to a hypothetical wing of infinite span (therefore no tips) or to a wing model in a wind tunnel, when the model extends right to the tunnel walls. Because of the absence of the spanwise flow induced by the presence of wingtips, no tip vortex and no variations in downwash behind the wing occur. A two-dimensional representation is all you need to depict what's happening.

The streamlines generated by injecting smoke into a wind tunnel, or calculated in a computer simulation (Figure 3), allow us to visualize not just the direction of flow around a wing, but also its velocity and pressure. The flow direction at any instant or point along a streamline is always tangential to the line. An important feature of streamlines is that air particles never cross them; adjacent pairs of streamlines thus behave like the walls of a flexible tube. When the flow accelerates, the resulting decrease in static pressure within them causes the streamtubes to contract, and the streamlines move closer together. The distance between streamlines is thus an indication of relative velocity and static

pressure. Notice in the figure how the streamtubes passing over the leading edge contract, indicating an accelerating flow and a pressure decrease. As they move down the wing they expand, indicating a decelerating airflow and a pressure rise. This is shown in closer detail in Figure 5.

Note the upwash in the airflow ahead of the wing, and the downwash behind. In the two-dimensional case illustrated, the upwash and downwash angles are equal. In the three-dimensional case of a finite wing, the tip vortex can add significantly to the downwash behind the wing, as we'll see later.

Figure 3
Streamlines
Upwash/Downwash

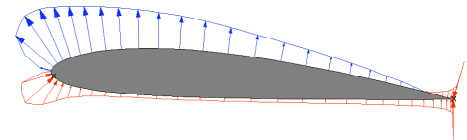
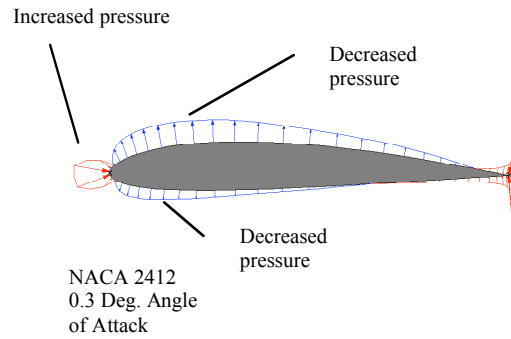


Pressure Distribution

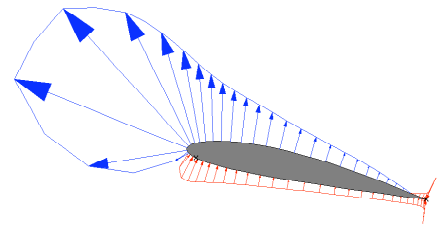
Figure 4 shows the surface pressure distribution along an airfoil section at three different angles of attack. The longer arrows represent increasingly higher or lower static pressures, as indicated, relative to the static pressure of the freestream, undisturbed air ahead of the section. The velocity over the forward, upper part of the wing increases as the angle of attack increases, resulting in a greater decrease in local static pressure, as well as a shifting of the pressure pattern. The illustrations show how the point of lowest static pressure (longest arrow) moves forward as angle of attack, α , increases.

Notice that at low α (as in the top illustration) the static pressure can drop below freestream under the wing as well as above. Lift results as long as the overall reduction in pressure above the wing is greater.

Figure 4
Pressure Distribution
versus Angle of Attack



NACA 2412
4 Deg. Angle of
Attack



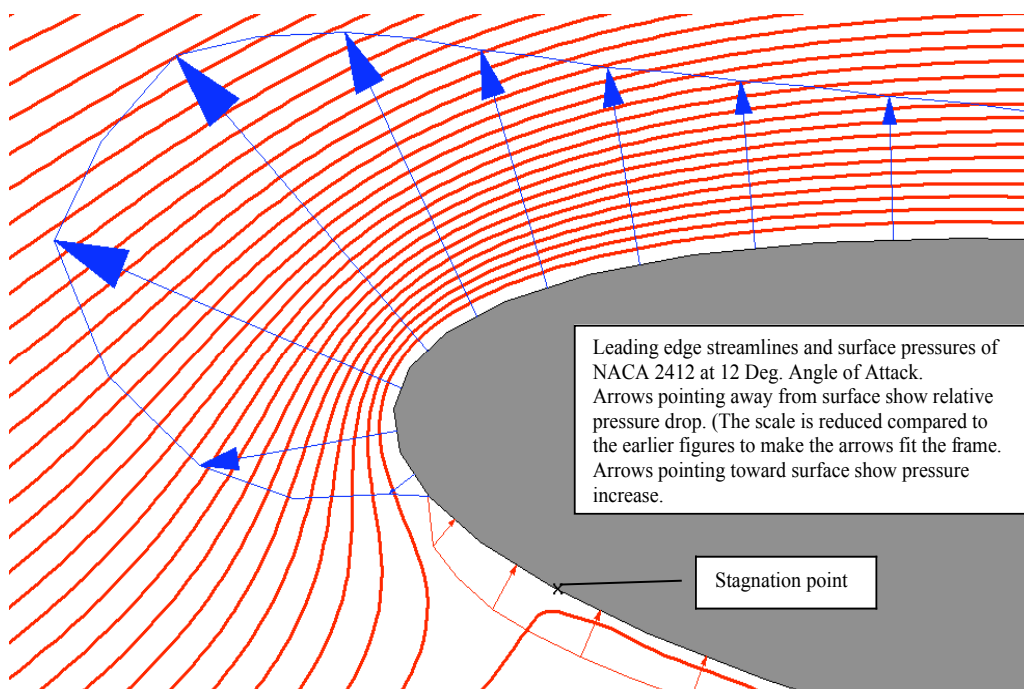
NACA 2412
12 Deg. Angle
of Attack

Two-Dimensional Aerodynamics

Figure 5 illustrates streamlines and surface pressures together. Pressure is highest at the stagnation point (where it equals static plus dynamic pressure). Here airflow comes to a stop, and the streamlines split on either side to follow either the upper or lower surface. (Stagnation pressure is what the pitot tube senses. The static side of the pitot system eliminates the static component, and the remaining dynamic pressure appears as an airspeed indication.)

The low pressure generated by the acceleration of the flow over the leading edge creates a suction that draws the airflow forward from the stagnation point—against the general, leading-to-trailing-edge flow. Below stall, any increase in α further accelerates the upper-surface flow and further decreases the pressure around the leading edge. Because the increasing suction pulls additional lower-surface air forward, the stagnation point actually moves aft along the lower surface as α increases. It also moves aft when you extend the flaps or deflect an aileron down.

*Figure 5
Streamlines
and Surface
Pressures*



Pressure Gradient

Air flowing over the top of the wing initially moves through an area of decreasing static pressure (Figure 6). Since higher pressures flow toward lower, this *favorable pressure gradient* encourages the airflow. But once past the point of highest velocity and lowest static pressure on the airfoil, local static pressures begin to rise (although still remain negative) and the pressure distribution tends to retard the flow. This *adverse pressure gradient* becomes steeper and occupies more of the airfoil as the angle of attack, α , increases and the low-pressure over the wing intensifies and shifts forward (Figure 7).

Figure 8 defines the concept of coefficient of pressure, C_p , and shows how its distribution changes along the chord as α rises. Negative values mean local static pressures lower than freestream static pressure; positive values mean local static pressures higher than freestream static. Note how the adverse gradient increases over the top of the wing when α rises, as indicated by the increasing negative slope.

As α rises, the adverse gradient increasingly retards the airflow within the boundary layer, until the boundary layer ultimately separates from the surface, like a sheet blown away from beneath (Figure 9). As adverse pressure rises the separation point moves forward; lift drops and the airfoil stalls.

Figure 6
Pressure Gradient

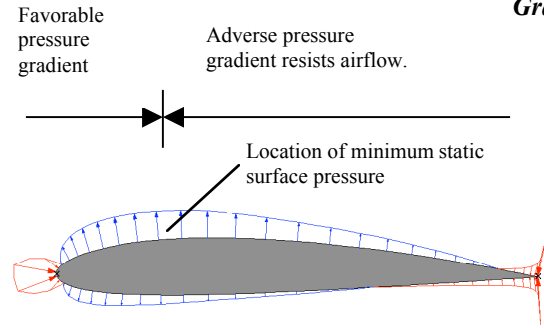


Figure 7
Increase in Adverse Pressure with Angle of Attack

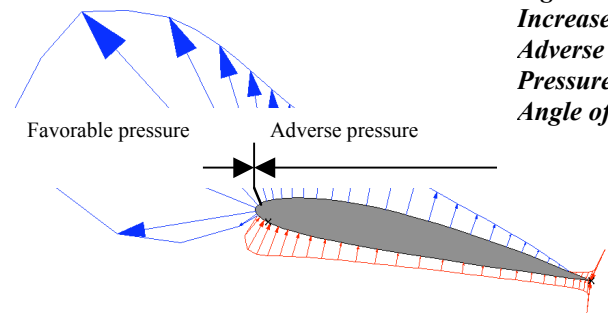


Figure 9
Separation

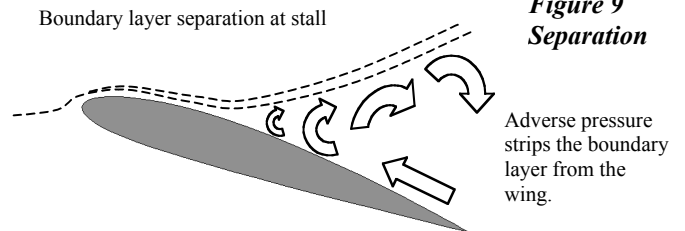
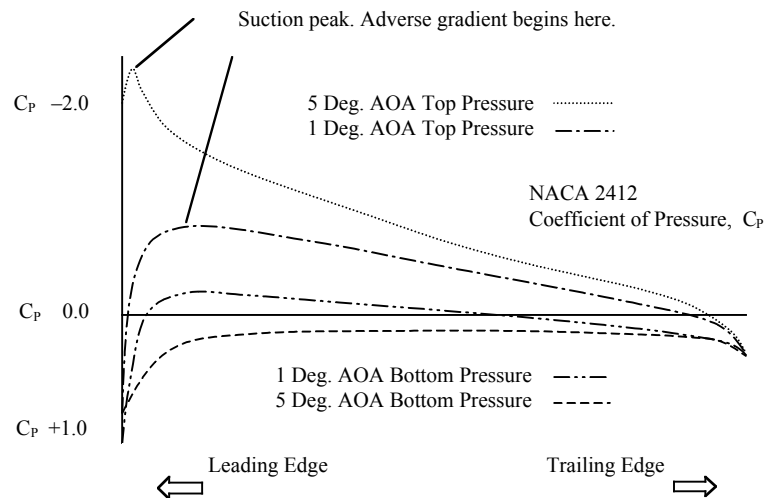


Figure 8
Coefficient of Pressure, C_p



Boundary Layer

In exaggerated scale, Figure 10 shows the regions of the boundary layer atop the wing, and the changing velocity profile within the boundary layer, as indicated by the length of the arrows. In both the laminar and turbulent regions, the viscosity of air causes the particles right next to the wing to come to a halt, due to friction. Their velocity relative to the wing is zero. The particles flowing immediately above are slowed down almost to zero by friction, and they in turn slow the particles above them. Initially, a profile of shear layers (lamina) develops, with the velocity of the layers increasing with their distance from the surface as the effect of friction diminishes. By definition, the boundary layer is the area from the surface out to the point where the flow reaches 99 percent of the freestream velocity.

The viscous, frictional forces generated within the boundary layer are responsible for the component of drag known as *skin friction* drag. Outside of the boundary layer, viscosity has no important effect when it comes to predicting airfoil characteristics.

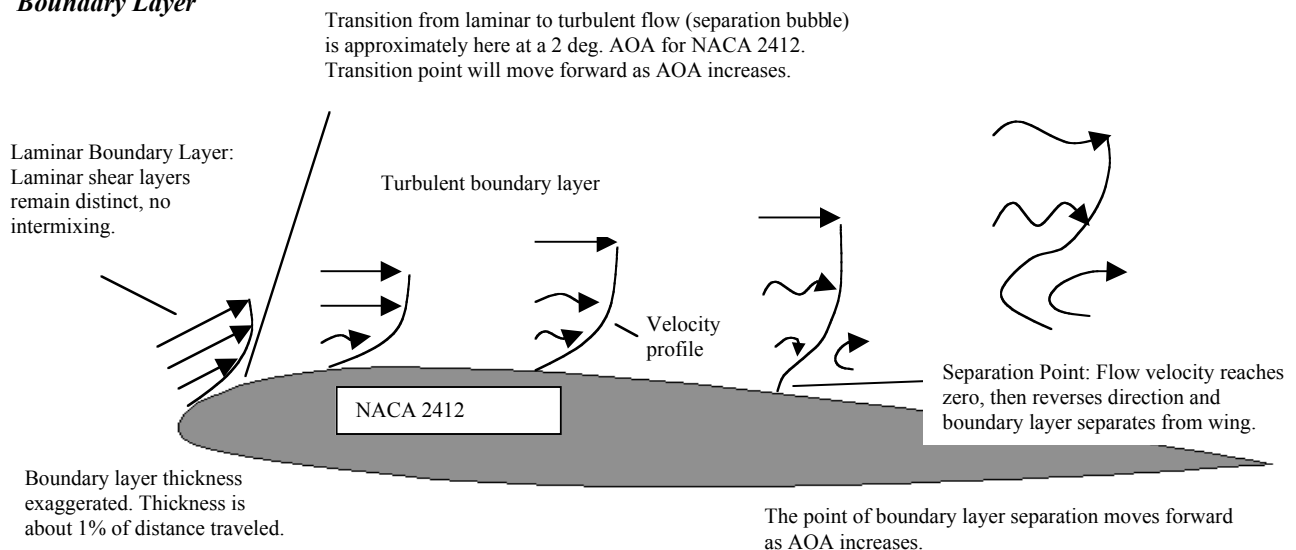
The initial, laminar region of the boundary layer is very thin. The flow remains layered—there's no interchange of fluid particles across the lamina. Moving downstream from the leading

edge, the laminar flow gains kinetic energy as it accelerates through the favorable pressure gradient. The favorable gradient also helps damp out irregularities in the flow. But the flow begins to slow as it enters the destabilizing resistance of the adverse gradient. The laminar boundary layer separates from the wing, becomes turbulent, and then reattaches, forming a *separation bubble* as it makes the transition. Roughness on the wing surface can cause the boundary layer to trip prematurely from laminar to turbulent flow.

Whether the laminar flow reattaches as turbulent flow depends on Reynolds number—on the ratio of the inertial forces to the viscous forces within the flow. Low Reynolds numbers are associated with laminar flow (viscous forces prevail), high Reynolds numbers with turbulent flow (viscous forces unimportant, inertial forces dominant). If the Reynolds number is too low, a detached laminar flow won't reattach as turbulent flow.

Up to a point, an airfoil produces higher maximum lift at higher Reynolds numbers, because the reattached turbulent flow can better resist the adverse gradient and remain attached to the wing at higher angles of attack. Wind tunnel data for airfoil sections often includes curves for different Reynolds numbers and surface textures. (Reynolds number is more complicated, but the above gives you a start if the concept is new.)

Figure 10
Boundary Layer



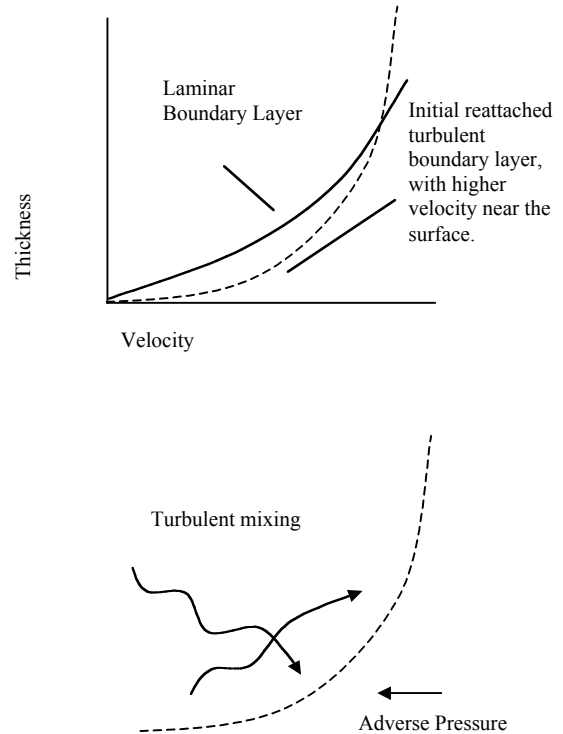
Two-Dimensional Aerodynamics

In Figure 11, you can see that the velocity gradient curve in the initial turbulent region (dashed line) starts out shallower than in the laminar region, but as the curve rises becomes steeper and the boundary layer grows thicker. The turbulent boundary layer produces a lot more drag than the laminar layer (laminar-flow wings achieve their low drag by moving the lowest pressure point farther back along the chord, thus extending the laminar region). On the other hand, a turbulent layer stays attached to the wing better than a laminar layer as angle of attack rises, because the turbulence transfers kinetic energy down to the surface, which helps overcome the adverse pressure gradient. (This turbulent energy boost is the principle behind vortex generators. The vortices add energy to the flow, delaying separation caused by adverse pressure.) Figure 10 shows how the velocity profile of the turbulent boundary layer changes along the wing chord as the retarding effects of the adverse gradient accumulate.

The tufts on the trainers can give you an idea of how the turbulent boundary layer increases in thickness. The tufts themselves would trip any laminar to turbulent flow. At low angle of attack the trailing tips of the first row of tufts should lie fairly quietly against the surface of the wing, but by the second row the flow will have become more turbulent and the tips will shake perceptibly. The tips will show increasing movement, bouncing between the wing and the top of the boundary layer, as you look farther back along the chord. You can easily see how the boundary layer thickens as it goes downstream.

More important, the tufts show how flow reversal and turbulent boundary layer separation move up the chord from the trailing edge. You'll be able to see the effect of the adverse pressure gradient intensify as angle of attack rises. The turbulent boundary layer's separation point will move forward along the chord and the tufts will reverse direction, the free ends actually pointing toward the leading edge. The reversal of the tufts in order back up the chord means that the wing is generating a larger and larger turbulent wake. Pressure drag is rising rapidly.

Figure 11
Velocity Profiles



Intermixing in the turbulent boundary area brings high-kinetic-energy (high inertia) particles down toward the surface, increasing the boundary layer's ability to overcome the adverse pressure gradient. Intermixing also sends low-energy (low inertia) particles up to the top, delaying the return to freestream velocity and causing the boundary layer to become thicker.

The higher velocities closer to the surface increase friction in the turbulent boundary layer, and thus friction drag.

The Lift Curve

Figures 12 and 13 show typical lift curves, which plot angle of attack against coefficient of lift (C_L). You may have grown accustomed to using the term coefficient of lift (or just as happy not using it) without quite remembering how it's derived. It's just an indication of how efficiently an airfoil shape turns dynamic pressure (defined earlier as one-half the density of the air times velocity squared: $1/2\rho V^2$) into lift at any given angle of attack. S stands for total wing area in square feet. L stands for lift in pounds.

$$C_L = \frac{L}{1/2\rho V^2 S}$$

Looking at the formula, it's clear that the more lift generated for a given combination of dynamic pressure and wing area, the greater the C_L . The formula for dynamic pressure is typically shortened to q , so that the above becomes:

$$C_L = \frac{L}{qS}$$

You can determine q in the cockpit, in pounds per square foot, simply by multiplying the square of the indicated airspeed in miles per hour by 0.0025577. That's q . Then multiply the result by the wing area, found in the aircraft manual, and divide the product into the aircraft weight (since lift equals weight in equilibrium flight). The result is your current C_L for the wing *as a whole* (the coefficient at a given *section* along the span, called C_i to make the distinction when necessary, is often different than that of the wing as a whole). At a constant IAS, your C_L must slowly decrease as you shed fuel weight and need less lift. Any change in airspeed (thus in q) requires a change in C_L for level flight.

It's good aerodynamics, and good piloting technique, never to think about lift without also considering its inevitable pal, drag. Substituting drag for lift, we derive the coefficient of drag, C_D , just as above. D stands for drag in pounds:

$$C_D = \frac{D}{qS}$$

In a lift curve, as in Figure 11, the coefficient of lift initially shows a linear increase with angle of attack. A slope of about 0.1 in lift coefficient increase for each degree increase in angle is

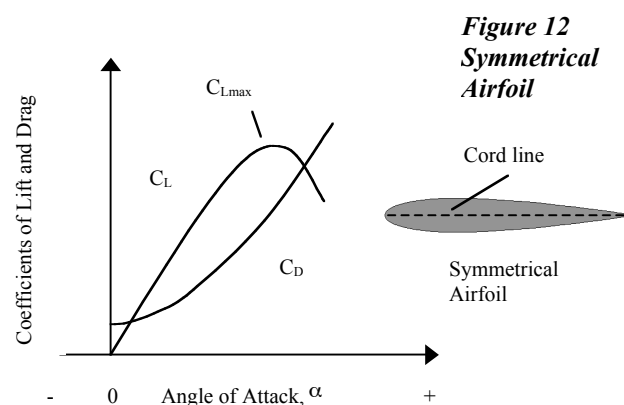


Figure 12
Symmetrical
Airfoil

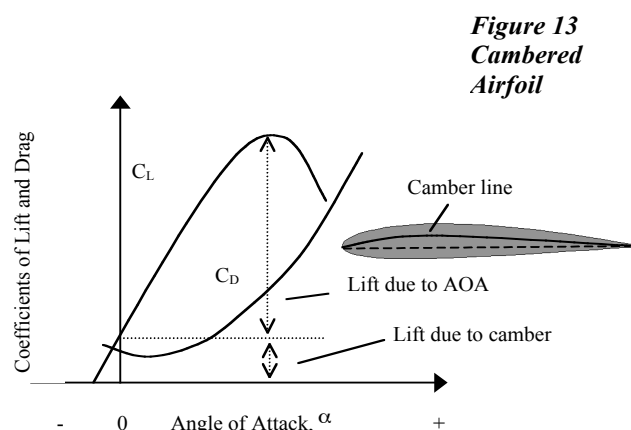


Figure 13
Cambered
Airfoil

typical for all two-dimensional airfoil section curves. Variations in slope come from planform, as we'll see.

The curve begins to shallow and reverse as airflow separation occurs on the upper surface of the airfoil. The point where maximum C_L versus α is reached (C_{Lmax}) marks the stalling angle of attack.

At C_{Lmax} , depending on airfoil shape, airflow separation may have already reached some 20 to 50 percent of the chord. Notice that an airfoil will still produce lift, *and a lot more drag*, even past the stalling angle of attack.

The airfoil in Figure 12 is symmetrical, and characteristically produces no net lift (and its minimum drag) at zero angle of attack. A cambered airfoil, as in Figure 13, can produce lift at small negative angles of attack. Its lift curve shifts up and to the left (producing a higher C_{Lmax}), compared to a symmetrical airfoil's. The drag curve shifts to the right.

Two-Dimensional Aerodynamics

Note how the rates of change in the lift and drag curves vary with angle of attack. The lift curve shows a constant rate until near its peak, when the slope diminishes so that a given change in angle of attack produces a smaller change in lift. The drag curve is different. At low angles of attack, drag doesn't change much, but as the angle of attack approaches stall, drag increases at an accelerating rate. You learn this, at least implicitly, when you learn to land an airplane. The technique of balancing the rates of change of lift and drag at high angles of attack is one of aviation's foundation skills. The technique can depend on whether the wing is long or short, swept or straight, as we'll note.

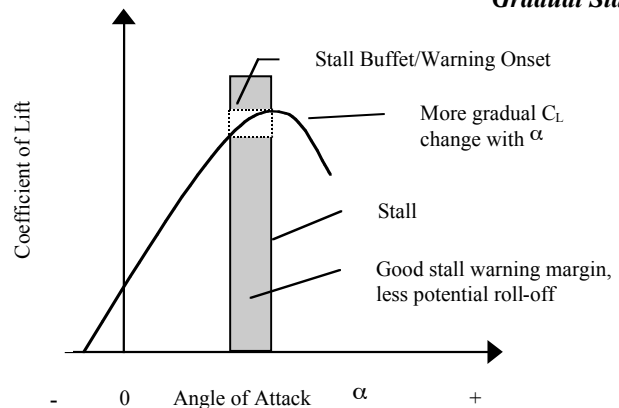
Airfoil thickness, the amount of camber and position of maximum camber along the chord, the radius of the leading edge, plus Reynolds and Mach numbers, are all factors that affect the velocities and pressures and therefore the aerodynamic forces generated by an airfoil. They also affect the characteristics of the boundary layer, its profile and turbulent transition, and its separation from the wing at high angles of attack.

Increasing the camber of an airfoil increases its C_{Lmax} . It also tends to increase the adverse pressure gradient as angle of attack rises, which in turn encourages earlier boundary layer separation, making the section then stall at a lower angle of attack, relative to one with less camber. A wing in which camber has been increased by lowering the flaps will stall at a lower angle of attack (See Figure 17).

It's usually best if the separation of the turbulent boundary layer from the wing surface moves slowly forward along the chord as angle of attack rises near the stall. This allows a relatively gradual, parabolic change in the slope of the lift curve as the section approaches C_{Lmax} , and results in less abrupt stall characteristics, better opportunity for aerodynamic stall warning (which also depends on wing planform and tail design), and less roll-off tendency if one wing starts to stall before the other. (See Figures 14 and 15.)

But abrupt turbulent boundary layer separation is sometimes useful. Modern, high-performance aerobatic wings often have large leading-edge radii and then become flat from the point of maximum thickness back to the trailing edge. The profile of these "ice cream cone" wings places the location of maximum thickness

Figure 14
Gradual Stall



forward on the chord, which limits the possible region of favorable pressure gradient and causes early laminar-to-turbulent boundary layer transition. Compared to wings designed for better laminar flow, they tend toward higher drag. Drag helps speed control in vertical down lines, but the major aerobatic benefit is the tendency for the stall separation point to remain near the trailing edge as angle of attack increases, and then suddenly to move forward up the chord. This allows the wing to hold airflow attached during high-g maneuvers, but stall abruptly for quick snap roll, spin, and tumbling entries. Wing tufts show how rapidly the separation point advances and how quickly the stall breaks, as you'll see in our ground-school video.

Leading-Edge Stall

A thin airfoil with a sharp leading edge radius can suffer sudden leading-edge stall (or simultaneous leading-edge and trailing-edge stall) due to the sudden bursting of the leading-edge separation bubble. The bubble occurs where the laminar flow separates from the wing and reattaches as turbulent flow. As angle of attack rises, the bubble follows the suction peak (Figure 8) forward. As the curvature of the wing increases, the detached laminar flow can no longer “make the turn” necessary to reattach as turbulent flow. The bubble bursts, causing rapid, complete boundary layer separation along the entire chord. This sharpens the peak of the lift curve, with the result that, near stall, a small change in angle of attack produces a sudden drop in C_L . This can lead to an abrupt stall with limited or no aerodynamic warning, and to a sudden roll-off when inevitable variations in wing surface or contour cause the separation bubble to burst on one wing ahead of the other.

Depending on how the airfoil section varies along the span, it's possible for one part of a wing to have a trailing-edge stall, while another part has a leading-edge stall, or demonstrates a combined leading-edge/trailing-edge stall.

Learjet wings built before the introduction of the Century III wing section had roll-off problems due to asymmetrically bursting separation bubbles. A stick pusher was necessary to keep the wing out of stall territory. In addition to adding inboard stall strips and stall fences, improving the pusher-off stall characteristics involved breaking the bubble into stable, spanwise segments by mechanically tripping the laminar flow with small triangular shapes attached to the outboard leading edge, ahead of the ailerons. Placed on the chord ahead of the normal laminar separation point, the triangles caused the flow to become turbulent and reattach, preventing a spanwise, continuous separation bubble from forming and thus from bursting. This dramatically reduced roll-off at stall.

Figure 15
Abrupt Stall

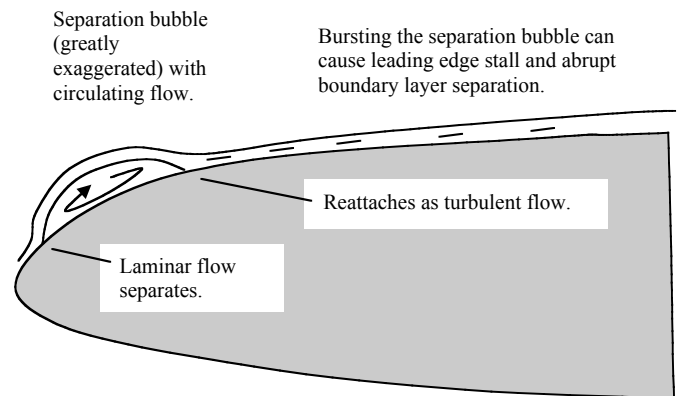
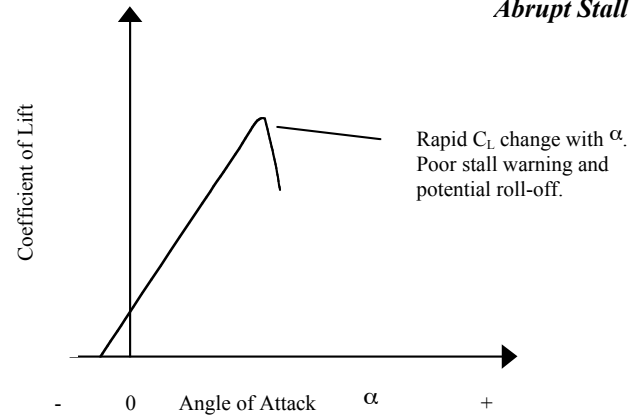
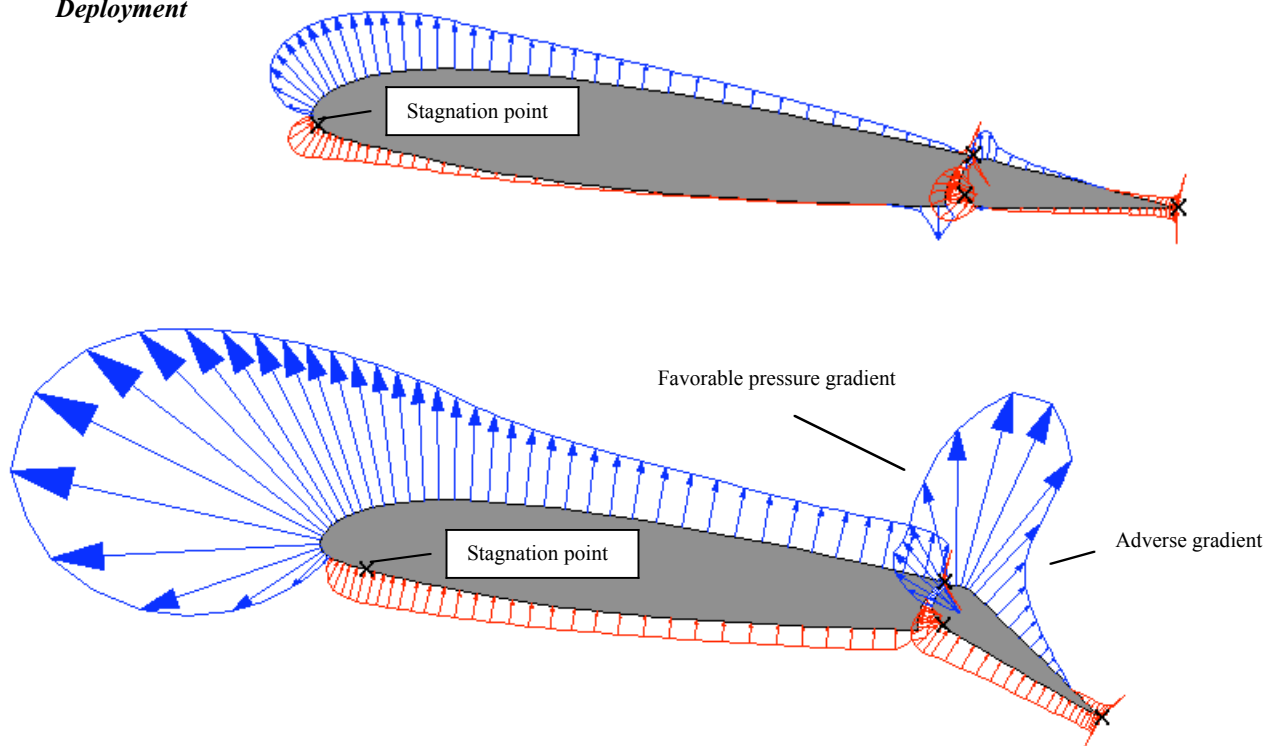


Figure 16
Flap
Deployment



Flaps

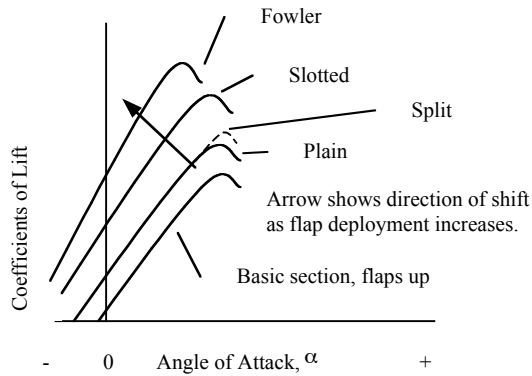
When you start to lower the flaps on our trainers, you'll see the tufts begin to show airflow separation along the trailing edge. The flaps increase local wing camber, which adds a second low-pressure peak (as shown in Figure 16) and a steep adverse pressure gradient at the trailing edge. If you increase the flap deflection further, or increase angle of attack, the adverse gradient over the flap becomes more severe. Flow reversal and separation occur and the tufts start dancing.

By studying Figure 16 you'll gain some insight into how flaps (and ailerons and rudders) work. Fundamentally, they modify lift by changing the velocity of the airflow. Notice how the increase in camber over the rear of the airfoil affects the overall pressure pattern. Camber increases local flow velocity, which decreases local surface static pressure. The result is a more favorable pressure gradient immediately *forward* of the deflected surface, which in turn causes air to accelerate over the wing ahead, resulting ultimately in lower surface pressures at the leading edge. At the same time, airflow below

the wing slow down, resulting in higher pressures there. (Notice the rearward shift in stagnation point that follows flap deployment. The flap-induced increase in leading-edge suction pulls more air forward from beneath the wing, sending the stagnation point further aft.)

Figure 17 shows how the lift curve changes with flaps of different types. The Fowler flap is the most efficient because it produces the greatest increment in lift with the least increment in drag. Flaps shift the lift curve up and to the left as you increase the deflection angle. The shift is the result of the increase in camber. With the exception of the Fowler flap's curve, which becomes steeper, the slope of the lift curve remains unchanged with flap deployment. Maximum C_L increases with flaps, but occurs at a lower angle of attack than when the flaps are up. The zero-lift angle of attack becomes more negative (nose down).

Figure 17
Lift Curve shift
with Flaps



Because it reaches a higher maximum coefficient of lift, $C_{L_{max}}$, with flaps extended, the wing will stall at a slower speed for a given aircraft weight. The benefit is disproportional, however, because large increases in $C_{L_{max}}$ are necessary to gain any substantial decrease in stall speed. For example, a 50 percent increase in $C_{L_{max}}$ produces only an 18 percent decrease in stall speed. A 100 percent increase in $C_{L_{max}}$ reduces stall speed by 30 percent, but at the expense of a large increase in drag.

Any type of flap is less effective on a thin wing than on a wing of greater thickness. Flaps are also less effective on swept wings compared to straight wings when their hinge line follows the sweep angle. You'll often see that the flaps themselves are not swept on an otherwise swept wing.

Plain Flap



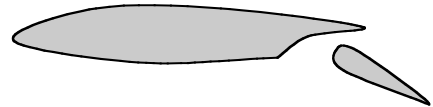
Slotted Flap



Split Flap



Fowler Flap



Circulation

Airflow passing over the top of a wing speeds up, while airflow passing beneath the wing slows down. These changes in velocity produce pressure differences between top and bottom, and thus lift.

Figure 18 shows what happens when you subtract the freestream flow from the accelerated flow over the top of the wing and from the decelerated flow beneath. The result reveals an embedded circulatory flow. (The circulation has a positive value above the wing; a negative value beneath.)

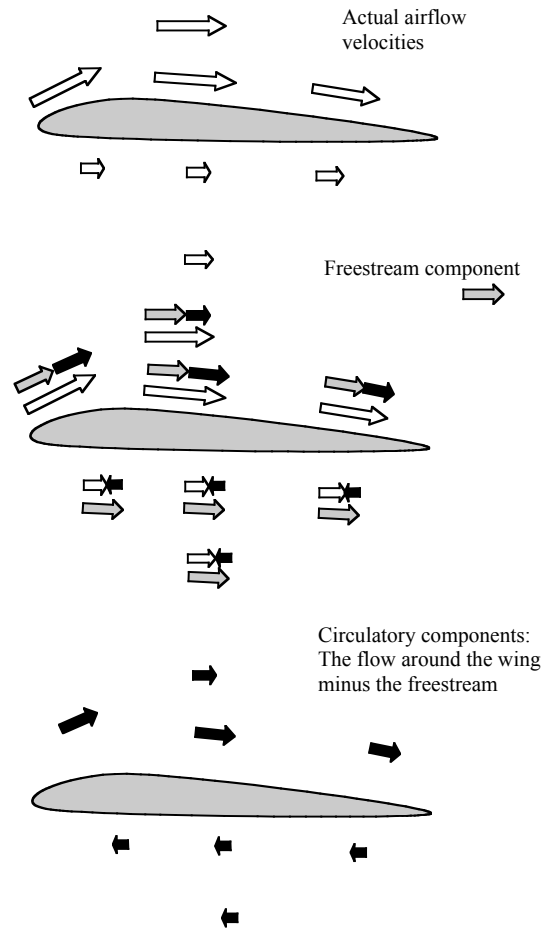
Circulation of this type doesn't mean that individual air particles actually travel completely around the wing, only that a circulatory tendency about the wing exists at any moment. The circulation is outside the boundary layer and extends well above and below the wing.

Although the idea of circulation pre-dates the Wright brother's first powered flight (the brothers weren't aware of it) and has great mathematical use, it's never been popular as a means of explaining lift to pilots. Imagining circulation around a wing isn't easy. It's easier to think of airfoils in wind-tunnel terms, the air moving in streamlines past a fixed airfoil that accelerates the air by means of an easily visualized venturi effect. In terms of the forces and moments produced, it doesn't matter whether the air or the wing moves. But in actual flying it's of course the wing that does the traveling. At subsonic speeds, it telegraphs its approach by the pressure wave it sends ahead, and the flow field starts accelerating or decelerating even before the wing arrives. Try to shift your frame of reference and to think in terms of the effects that the wing carries along with it, as it whizzes by, and of the effects it leaves behind in originally stationary air.

Circulation depends on airfoil design (leading edge radius, maximum thickness and its location, maximum camber and its location). Circulation increases with angle of attack up to the stall, and also with wing camber as modified by flaps. An aileron deflected down increases circulation over the affected part of the wing. One deflected up reduces circulation.

Other factors remaining equal, the greater the circulation the greater the velocity difference

Figure 18
Circulation



above and below the wing, and thus the greater the pressure difference and the resulting lift.

The circulation needed to produce lift of a given value increases as airspeed or air density *decreases*. The pertinent formula, in plain English, is:

$$\text{Lift} = \text{Density} \times \text{Freestream Velocity} \times \text{Circulation} \times \text{Span}$$

Bound Vortex/Tip Vortex

The circulation around an airfoil is called the bound vortex (Figure 19). On an actual three-dimensional wing, as opposed to a two-dimensional section, the bound vortex in effect turns the corner and becomes a trailing, tip vortex. The tip vortex is no longer an embedded flow bound to and carried along by the coordinates of the wing, but now a “free” or “true” vortex that remains attached to the same fluid particles and continues circulating long after the wing is gone. Because the tip vortex is generated by the pressure difference between the top of the wing and the bottom, and by the tendency of the airflow to try to even out that difference by “leaking” around the wingtip, ***tip vortex strength is a function of circulation.***

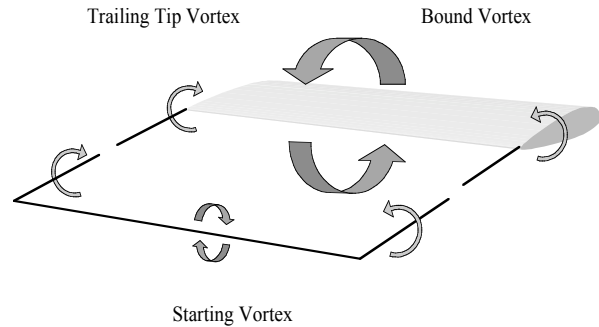
At low speeds and high angles of attack, when circulation necessarily rises, tip vortices increase in intensity. The heavier the aircraft and therefore the greater the required lift (lift equals weight in steady flight) the stronger the circulation has to be at a given airspeed. Consequently, heavy airplanes flying at slow approach speeds produce the most dangerous tip vortices. One reason to describe circulation is to give pilots a better sense of how potentially dangerous tip vortices are generated, and how their strength depends on the components of the lift formula:

$$\text{Lift} = \text{Density} \times \text{Freestream Velocity} \times \text{Circulation} \times \text{Span}$$

As the formula indicates, the circulation needed to generate lift equal to aircraft weight is also a function of wingspan. The longer the span the less circulation required. Consequently, at the same aircraft weight, long wings produce less intense tip vortices than short wings. This in turn lowers induced drag, as we’ll see.

In principle, a vortex can’t suddenly terminate in mid air. It has to form a continuous enclosed loop. Figure 19 shows the starting vortex that completes the loop. Figure 20 shows the role the starting vortex plays in getting circulation going.

Figure 19
Vortex System

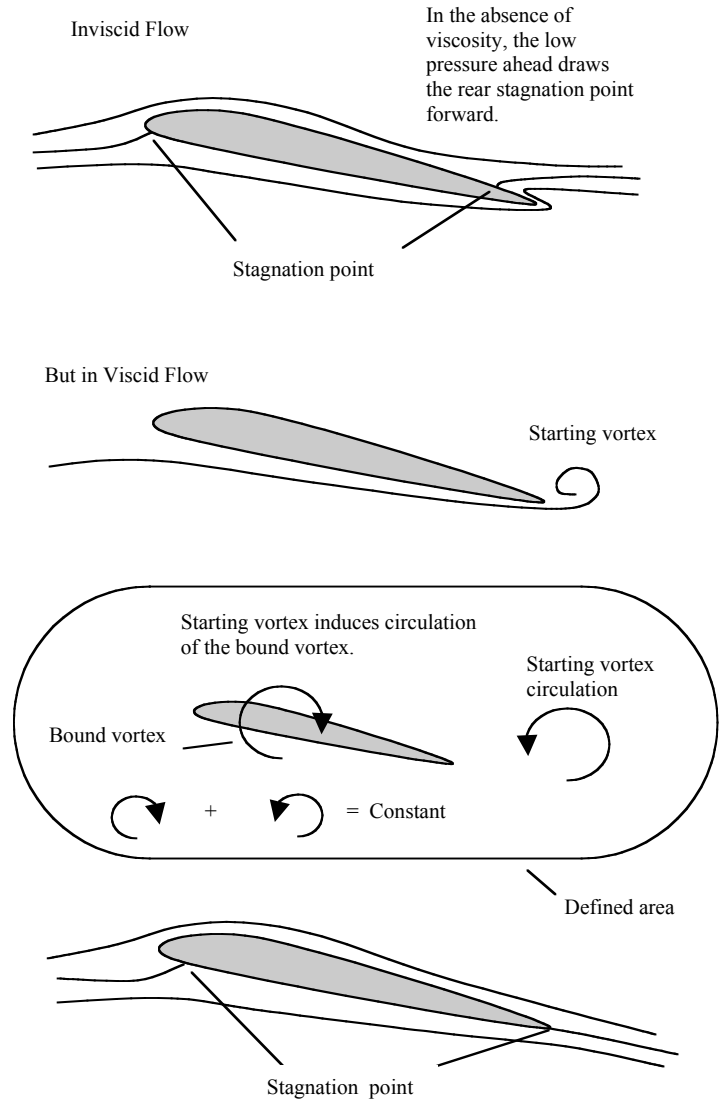


The Kutta Condition

The top of Figure 20 shows the theoretical streamline flow around an airfoil that would occur in the absence of friction and the resulting viscosity. The streamlines coming out from beneath the wing reverse direction. The rear stagnation point lies on the top of the wing, forward of the trailing edge.

That can't happen in nature, however, because the viscosity of the air prevents it from making the necessary sharp turn. Instead, as a wing begins to move forward from a standstill, a starting vortex forms. Because nature also says that the total circulation within any arbitrarily defined area must remain constant, an opposite vortex begins to form, the bound vortex. The wing begins to develop the circulation described earlier, and the airflow leaves the trailing edge smoothly, as shown in the bottom illustration. The starting vortex is left behind. This smooth departure is known as the Kutta condition. The upshot is that as angle of attack, camber, or airspeed change, the wing develops whatever circulation is necessary to maintain the Kutta condition. An increase in angle of attack, for example, causes a new starting vortex to form and be left behind. If angle of attack is decreased, a stopping vortex of opposite sign is formed and shed. A stopping vortex forms if the aircraft accelerates (since circulation required for lift goes down as airspeed increases). Ultimately, the vortices left behind break down due to friction and turbulence.

Figure 20
Kutta
Condition



Real viscid airflow requires meeting the Kutta condition. The circulation generated causes the front and rear stagnation points to shift as shown.

Flightlab Ground School

3. Three-Dimensional Aerodynamics

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Real Wings

So far, we've been talking about two-dimensional airfoil sections. When you move from a two-dimensional, or "infinite," section to an actual three-dimensional wing of finite span, the slope of the lift curve changes. Figure 1 shows how decreasing the aspect ratio or increasing wing sweep decreases the C_L/α slope.

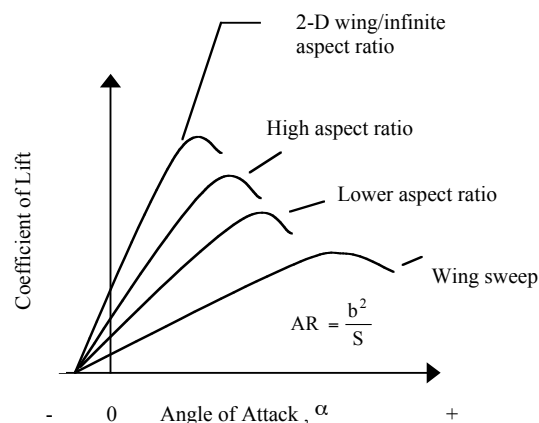
Notice in the figure that, while the zero-lift angle of attack stays the same (the curves all start at the same point), the maximum C_L decreases and requires a higher angle of attack to attain.

Wing sweep tends to generate weaker adverse pressure gradients, which in turn causes the stall area of the curve to become flatter. Larger angle of attack changes are necessary to produce changes in lift, compared to wings of higher aspect ratio. Because lift changes more slowly on a swept wing, stalls are less pronounced than is usually the case in straight-wing aircraft that generate stronger adverse gradients—although drag increases quite fast with swept wings and the airplane can develop a high sink rate.

While watching the tufts on our trainers, you'll see that the boundary layer separation moves outward along the span, as well as up the chord. How that separation advances depends on how the local, section angle of attack varies along the span. This is key to understanding how a three-dimensional wing operates, but several concepts have to be brought together to make that understanding work.

Here's the short explanation: *A lifting wing produces a downwash in the air behind it, and an upwash ahead. We described earlier how a two-dimensional (no tips) wing section generates equal upwash and downwash. In the three-dimensional case, however, the downwash is greater because of the added wingtip vortices. Variations in downwash along the span behind the wing, caused by vortex effects, can produce spanwise variations in the oncoming flow ahead*

Figure 1
Lift Curve
Slope



Aspect ratio = wingspan (b) squared, divided by the wing area (S). Wingspan is measured directly from tip to tip.

of the wing, and thus local differences in section angle of attack.

As we'll see, that's also the reason why the slope of the lift curve changes with aspect ratio.

Three-Dimensional Aerodynamics

The pressure differences between the top and bottom of a wing, which generate the tip vortices, also produce an overall spanwise flow, as shown in Figure 2. Air over the top of the wing flows somewhat inward, while air on the bottom flows outward. The result is that small vortices form along the trailing edge where the inward and outward flows meet. Since the relative deflection of the two flows is smallest at the wing roots, the vortices there are less intense than at the tip. The weaker inboard trailing edge vortices quickly merge downstream with the stronger wingtip vortex.

Figure 3 suggests how the circulation generated by the tip vortex adds to the downwash behind the wing. The influence of the downwash actually extends ahead of the wing. The air ahead begins to be pulled down in response to the flow behind the wing, in proportion to the downwash velocity, even before the wing arrives. Remember the upwash ahead of the wing, from two-dimensional aerodynamics? The net result is a reduction in the upwash and a reduction in the effective angle of attack.

Figure 2
Trailing Edge
Vortex
Generation

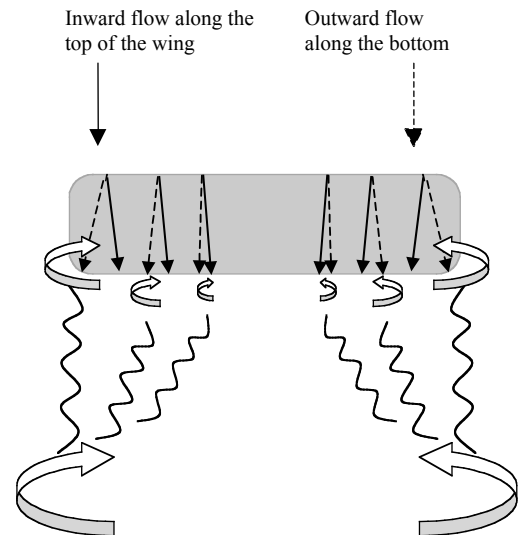
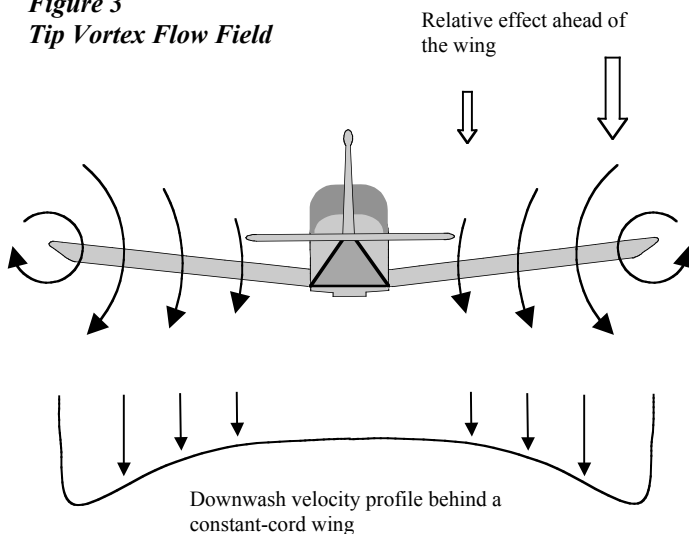
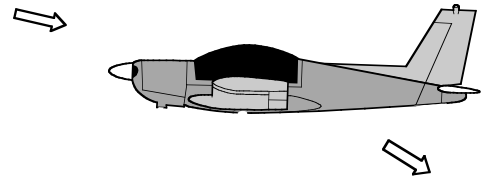


Figure 3
Tip Vortex Flow Field

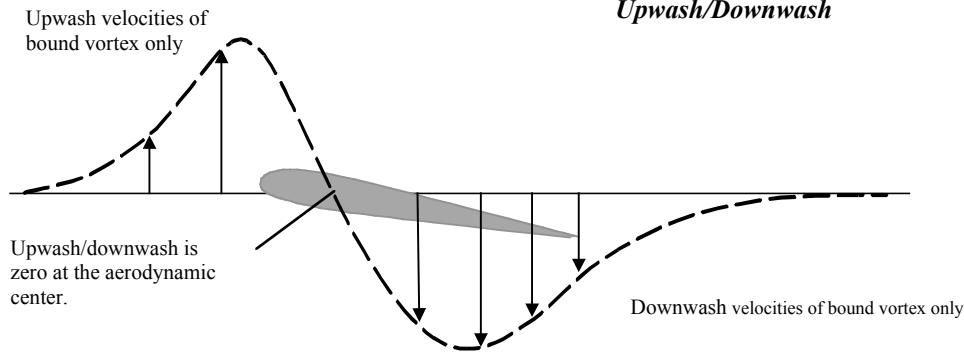


Air ahead of the wing begins descending in response to the vortex downwash.



Three-Dimensional Aerodynamics

Figure 4
Bound Vortex
Upwash/Downwash



The next few pages may be difficult going, but if you survive you'll have some insight into wing stall patterns.

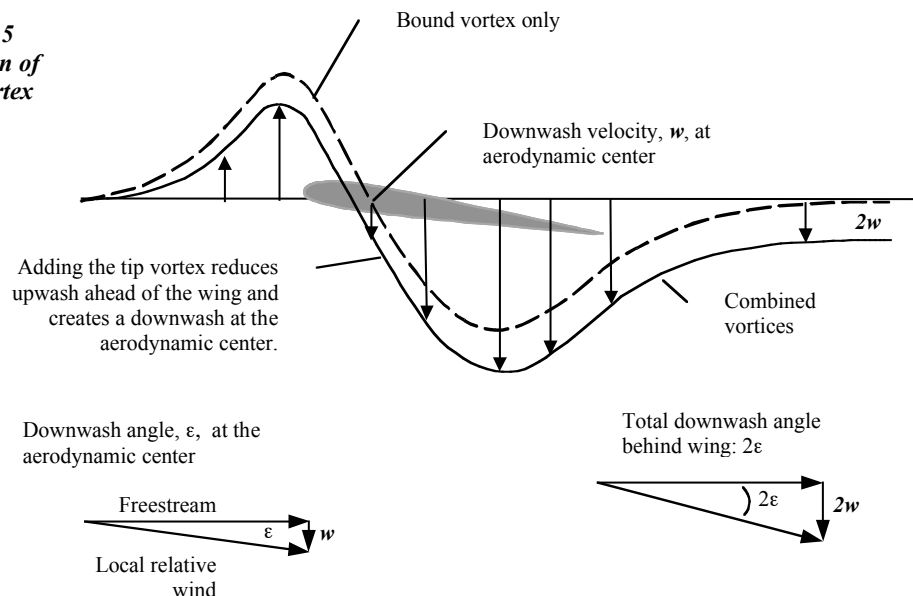
Figure 4 shows a common way of representing the components of the bound vortex around a given spanwise section of a finite wing, and Figure 5 shows what happens when the tip vortex is added to that circulation. Notice that the net upwash/downwash at the aerodynamic center is zero with the bound vortex alone. Adding the downwash from the wingtip vortex increases the vertical velocities of the total downwash behind the wing, and produces a *decrease in upwash velocities ahead of the wing, and a net downwash at the aerodynamic center.* (The aerodynamic center can be quickly defined as the location along the chord where changes in lift are considered to act. It's usually around 25 percent of the chord back from the leading edge. But

that's an abbreviated definition.)

The wingtip and bound vortex together produce a final, vertical downwash velocity, $2w$, behind the section, that's twice the velocity, w , of the downwash at the aerodynamic center. Adding the freestream and downwash vectors together gives you the downwash angle, ϵ , as shown at the bottom of Figure 5

Remember that the Figures 4 and 5 show circulation around a *section* of a finite wing. At another section along the span the circulation could be different. The tip vortex may have greater or less influence due to distance or planform, or the wing might be built with a twist or a change in section profile.

Figure 5
Addition of
Tip Vortex



Three-Dimensional Aerodynamics

Figure 6
Downwash Angle

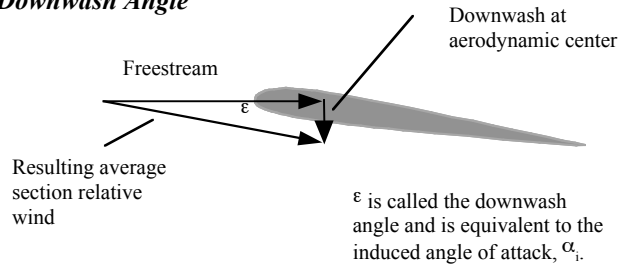
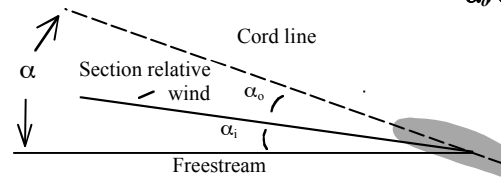


Figure 6 shows how the downwash behind the wing influences the effective angle of attack of a wing section. When you add the remote, freestream wind ahead of the section to the downwash at the section's aerodynamic center, the resulting vector is the section's average relative wind. This average relative wind, which is inclined to the freestream, is what the wing employs to create lift. Its inclination to the *freestream* is called the induced angle of attack, α_i . Its inclination to the wing *chord* is the local, average, section angle of attack, α_o . See Figure 7.

Once again, we can't talk about lift without talking about drag. *Because the lifting force is perpendicular to the local relative wind*, the inclination of the local relative wind, as shown in Figure 8, causes the lift vector to tilt back, opposite the direction of flight. The result is *induced drag*, as demonstrated in the figure by breaking the lift vector into horizontal and vertical components. Induced drag doesn't occur on a two-dimensional wing section: only on a real, three-dimensional wing with a tip vortex. Note that the angle ϵ between the freestream and the section relative wind is the same as the *induced angle of attack*, α_i , and also the same as the backward tilt of the lift vector.

The induced angle of attack, α_i , is directly proportional to coefficient of lift: double one and you double the other. But induced drag goes up

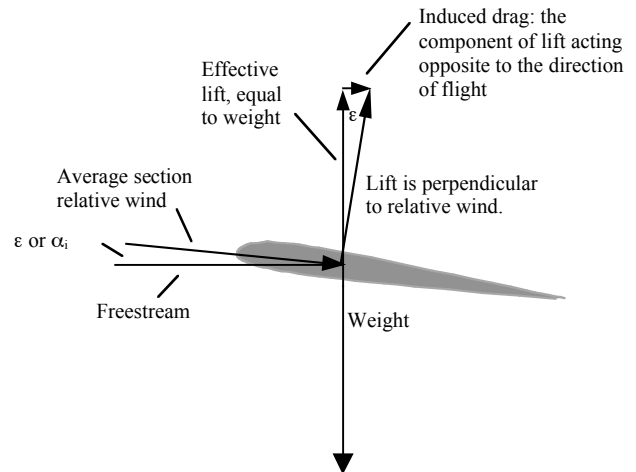
Figure 7
 α_o/α_i



A wing's angle of attack, α , is the sum of induced angle of attack, α_i , and section angle of attack, α_o . α_o generates lift; α_i tilts the lift vector and causes drag.

as the square of the lift coefficient: doubling the C_L gets you four times as much drag.

Figure 8
Induced Drag



Three-Dimensional Aerodynamics

α , the wing angle of attack, is the angle between the cord line and the freestream relative wind.

With no wing twist, $\alpha_{\text{tip}} = \alpha_{\text{root}}$.

α_o , the section angle of attack, is the angle between the cord line and section relative wind. Because of vortex effects:
 $\alpha_o \text{ tip} < \alpha_o \text{ root}$

α_i is the angle between the freestream and the section relative wind, and is the same as the inclination of the lift vector, ϵ , that's responsible for induced drag. Because of vortex effects:
 $\alpha_i \text{ tip} > \alpha_i \text{ root}$

w is the downwash at the section aerodynamic center. Because of vortex effects:
 $w \text{ tip} > w \text{ root}$

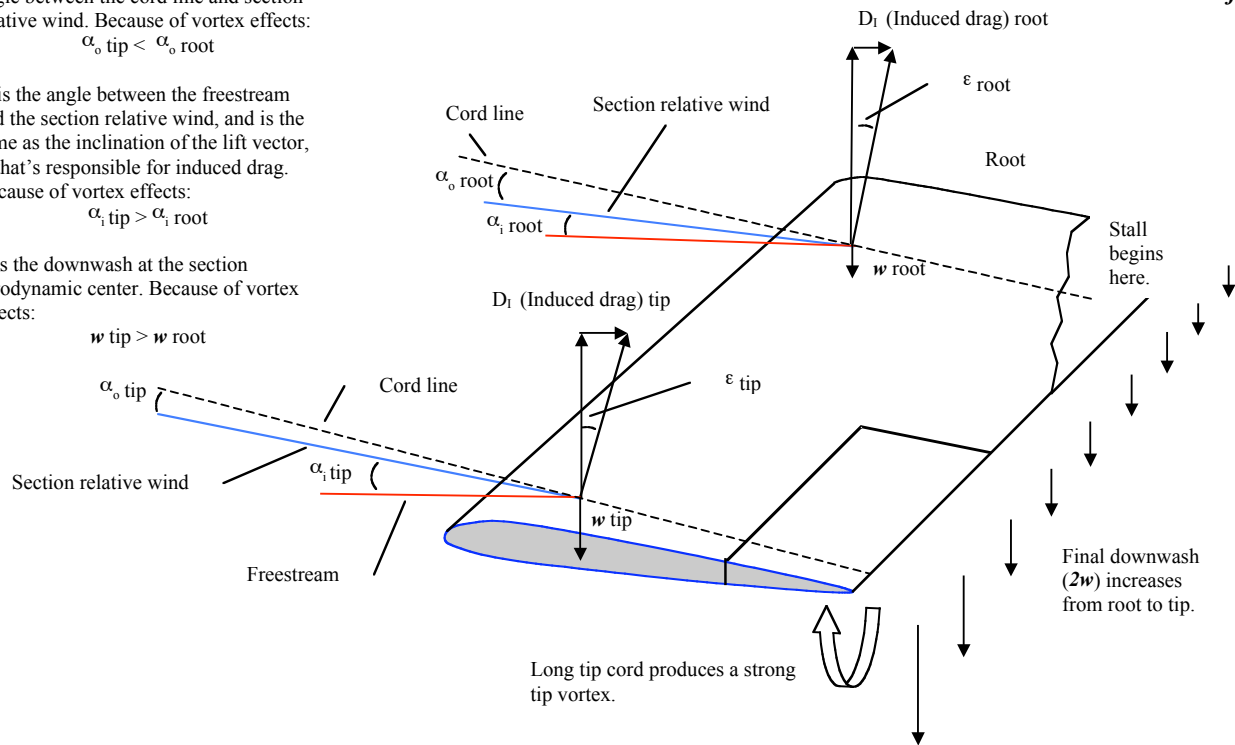


Figure 9
Rectangular
Wing
Planform

At this point, you may have lost your patience keeping α , α_i , α_o , and ϵ straight. Don't worry; the important concept is simply that the downwash behind the wing affects the nature of the upwash ahead, and thus the local angles of attack along the span.

Figure 9 struggles to show that even when the angle of attack, α (angle between chord line and freestream), of the wing as a whole remains constant, its component angles α_i and α_o can be different at different spanwise section locations. That's because the downwash can vary along the span behind the wing, depending on planform effects and on the relative influence of the wingtip vortex. Wing sections operating at

different local angles of attack, α_o , and thus at different coefficients of lift, can reach stalling angle of attack at different times.

A rectangular wing, like that of our trainers, produces a strong tip vortex and a total downwash that increases from root to tip (as Figure 9 illustrates). The greater downwash near the tip in turn reduces the outboard section angles of attack, α_o , relative to the inboard, for the reasons described above. Because the wing root operates at higher section angles of attack than the tip, the root is where the stall begins.

Three-Dimensional Aerodynamics

You'll observe this as you watch, and manipulate with the control stick, the spanwise movement of the tufts on the trainer's wing during stall entry. The tufts can't show you the downwash directly, of course, or section relative wind. But you will see the tufts responding to the accompanying changes in pressure pattern and to the expansion of the adverse gradient from trailing edge to leading edge and from root to tip, as section angles of attack increase and flow reversal and boundary layer separation start to occur.

Figure 10
Lift Curve Slope
Revisited

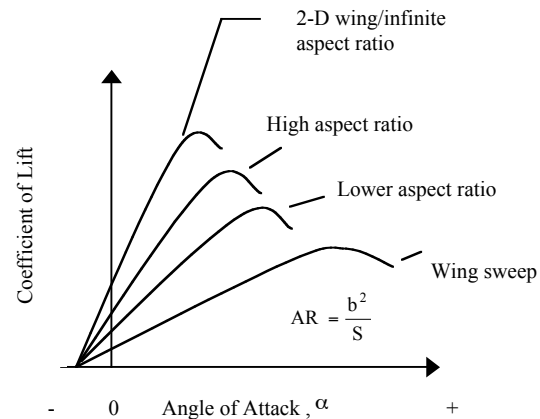
Aspect Ratio

At the start, we mentioned the effect of aspect ratio, AR , on the slope of the lift curve. Here's some additional explanation. The formula for aspect ratio is:

$$AR = \text{wingspan}^2 / \text{wing area}$$

Induced drag is inversely proportional to aspect ratio. Doubling the aspect ratio, for example, cuts induced drag in half. The smaller the aspect ratio (short wings) the faster induced drag will rise as we pull back on the stick and increase α and C_L . That's because as wingspan (and thus aspect ratio) decreases, the downwash from the wingtip vortex affects more of the total span.

Downwash distribution is the reason why low aspect ratio wings stall at higher overall angles of attack. Because the downwash from the tip vortex reduces the working, section angles of attack, α_o , over more of the wing, low aspect ratio wings need to operate at higher overall angles of attack, α , than longer wings to create equivalent lift. Therefore the slope of the lift curve in Figure 10 decreases with decreasing aspect ratio. Sweeping the wing also extends the influence of the vortex downwash inboard along the span, with similar effect.



Aspect ratio = wingspan (b) squared, divided by the wing area (S). Wingspan is measured directly from tip to tip.

Three-Dimensional Aerodynamics

Planform Differences and Stall Characteristics

Different wing planforms can produce significantly different downwash distributions behind the wing, and therefore different *lift distributions* along the span. You find the lift distribution by comparing section coefficients of lift, C_l , to the lift coefficient produced by the wing as a whole, C_L . The lift distribution determines the stall pattern.

When the downwash behind a constant-section, untwisted wing is uniform along the span, all sections of the wing will operate at the same section angle of attack, α_o , and section coefficient of lift, C_l . An elliptically shaped wing (like the one on your Spitfire) creates this sort of uniform downwash distribution.

Compared to a rectangular tip, the elliptical wingtip produces less total lift because of its reduced chord, and therefore a less intense tip vortex. The elliptical wing has a great advantage in generating the least induced drag compared to any other wing shape of the same aspect ratio. Since induced drag predominates at high C_L , the planform probably helped keep the Spitfire from losing energy in turns, where high g-loads require high lift coefficients. Elliptical wings are said to be difficult to build. As an alternative with nearly the same drag reduction characteristics, a tapered wing allows a compromise between drag and structural requirements.

Figure 11
 C_l / C_L

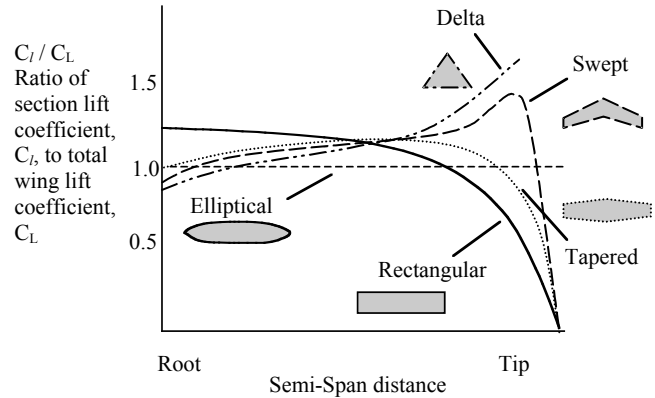
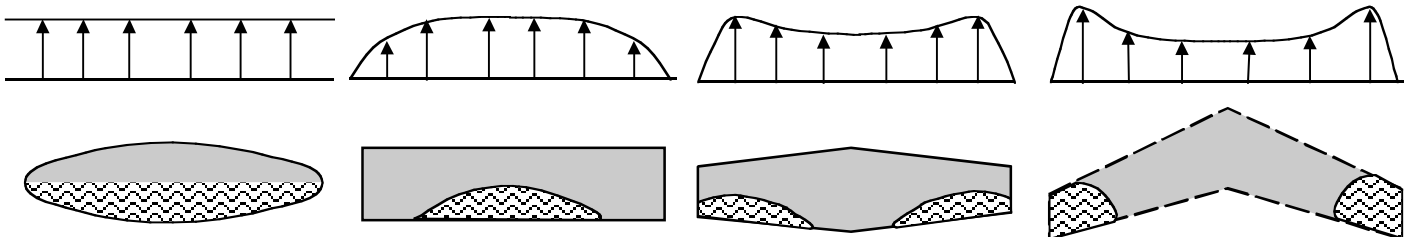


Figure 11 shows how the ratio between the section lift coefficient, C_l , and the coefficient of lift for the entire wing, C_L , varies between planforms. The elliptical wing has a constant ratio of 1.0. The lift distribution is uniform. As α increases, the sections all use up their lift potential at the same rate, and therefore will stall at about the same time. That can mean a sudden stall break, with little warning and ineffective ailerons.

The rectangular wing, however, starts with a C_l / C_L ratio higher than 1.0 at the root, where the section coefficients are greater than the wing

Figure 12
Stall Patterns
No Washout

Rise in local section C_l as α increases



Three-Dimensional Aerodynamics

coefficient as a whole. The ratio drops below 1.0 about two-thirds out, as the section coefficients become less than the wing's, and then goes to zero at the tip. As wing angle of attack, α , increases, the straight rectangular wing, with its skewed lift distribution, uses up its lift potential faster at the roots than at the tips. It stalls first at the roots.

The swept wing does just the opposite. It stalls at the tips because that's where it uses up its lift first. Figure 12 shows the relationship between stall pattern and the increase in local section C_l as α increases.

Although you pay a penalty in higher induced drag from the wingtips, the rectangular wing has optimal stall characteristics. The elliptical planform is the standard against which the efficiency of other wings is measured in terms of drag at subsonic airspeeds, but the rectangular wing sets the standard for behavior in stalls. Most of the gizmos that you find on other wings are designed to give them the benign stall characteristics and high- α lateral control more like that of a rectangular planform.

Stall warning can be better with a rectangular wing because the initial separation at the root can place the horizontal stabilizer in turbulent airflow, producing a warning buffet. This buffet is very evident in our training aircraft. When you see the wing root tufts start reversing you'll immediately feel the effect on the tail. In some aircraft the stick will shake against your hand as the elevator responds to the turbulence. That's the reversible control feedback that mechanical shakers are meant to simulate.

Roll control is naturally better with the rectangular wing as the stall approaches, because the ailerons work behind a lower section angle of attack and so remain in attached airflow longer into the stall entry. Geometric washout (twisting the leading edge of the wingtip down) and aerodynamic washout (changing the airfoil section toward the tip) are also used to adjust the lift distribution, keep the wingtips flying, and keep lateral control within bounds. Stall strips are used to adjust the spanwise stall pattern by tripping the root section into a stall at a lower angle of attack than would otherwise occur.

In out trainers, you'll be able to make a connection between the stall patterns that the tufts allow you to see and the resulting changes in aircraft lateral control.

Swept-wing Characteristics

A tendency toward tip stall happens when you radically increase wing taper, sweep, or both, without also introducing a compensating wing twist or a change in airfoil section along the span. Taper or sweep shift the vortex and the downwash inboard, causing the tips to work at higher section coefficients of lift, α_o .

Aerodynamic stall warning can deteriorate seriously when the tips reach stalling angle of attack before the rest of the wing, if the turbulence produced by the stalling tips passes outside the span of the horizontal stabilizer, preventing a warning buffet.

Because the tip sections of a highly swept wing can operate at higher section angles of attack (thus at lower upper-surface static pressures) than the inboard sections, static pressure over the top of the wing decreases from root to tip. The resulting spanwise pressure gradient produces an outward, spanwise flow that intensifies with increasing wing angle of attack. The geometry of a swept wing encourages this tendency because inboard areas of higher pressure are directly adjacent to outboard areas of lower pressure, as shown in Figure 14. The spanwise flow tends to

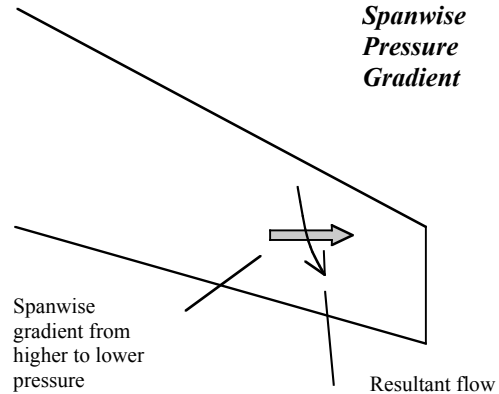
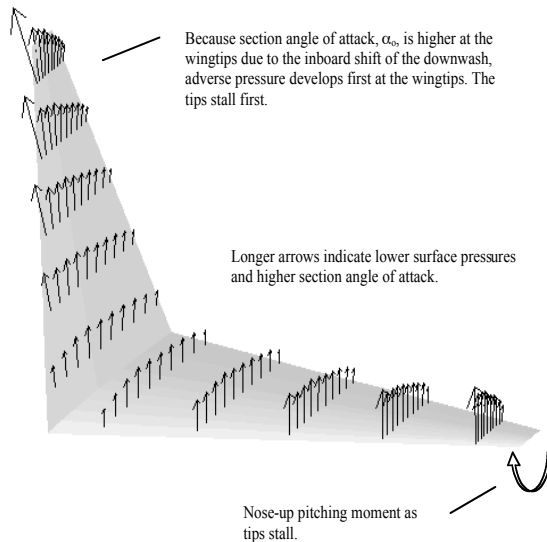


Figure 14
Spanwise
Pressure
Gradient

thicken the boundary layer toward the tips. The thicker boundary layer transfers less kinetic energy to the surface, and this lowers airflow resistance to the adverse pressure gradient along the wing chord, encouraging separation. On a swept wing the combination of higher tip section angles of attack, α_o , and a thicker, more easily separated boundary layer can cause the tips to tend to stall first. Stall fences along the wing chord, between the ailerons and wing root, were an early and often-seen solution.

Obviously, tip stall is bad for roll control, because of the airflow separation over the ailerons. And it's not good for pitch control, either. Due to the sweep angle, loss of lift at the tips will shift the center of lift forward. This shift causes a nose-up pitching moment, which can drive an airplane deeper into a stall or deeper into a high-g turn. The wing vortices also move inboard as the tips stall, thus increasing the downwash on the vertical stabilizer and the pitch-up tendency.

Figure 13
Surface Pressures



Flightlab Ground School

4. Lateral/Directional Stability

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Sideslips and Directional Stability, $C_{n\beta}$

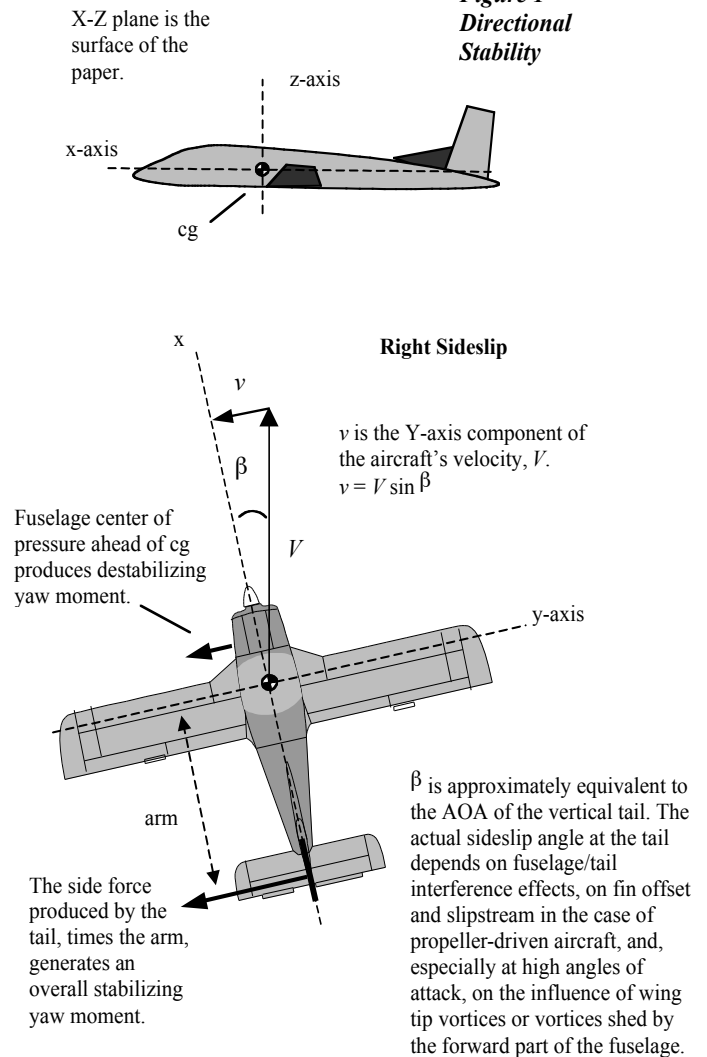
Most aerodynamics texts cover longitudinal (pitch axis stability) before tackling coupled lateral/directional behaviors. Since our flight program emphasizes those behaviors, we'll do things in our own order.

An aircraft is in a sideslip when its direction of motion (its velocity vector) does not lie on the x-z plane of symmetry. The top drawing in Figure 1 defines the x-z plane, and in the bottom drawing we're looking down the z-axis. The angle between the velocity vector, V , and the x-z plane is the sideslip angle, β (pronounced "beta"). In aerodynamics notation β is positive to the right, negative to the left. (Just so there's no confusion, a $-\beta$ sideslip to the left, for example, means that the nose is pointing to the right of the aircraft's actual direction of motion.)

Rudder deflections, wind gusts, asymmetric thrust, adverse yaw, yaw due to roll, and bank angles in which the effective lift is less than aircraft weight can all cause sideslips. In response, sideslips typically create both yawing and rolling moments. A stable aircraft yaws toward the velocity vector, but rolls away. These moments interact dynamically—playing out over time, most notably in the form of the disagreeable undulation called the Dutch roll. We cover the associated rolling moments a bit farther on, but concentrate on yaw around the z-axis here, pretending for the time being that it occurs in isolation.

The notation for the yawing moment coefficient is C_n (positive to the right, negative to the left). Remember that a *moment* produces a rotation about a point or around an axis.

Figure 1
Directional Stability

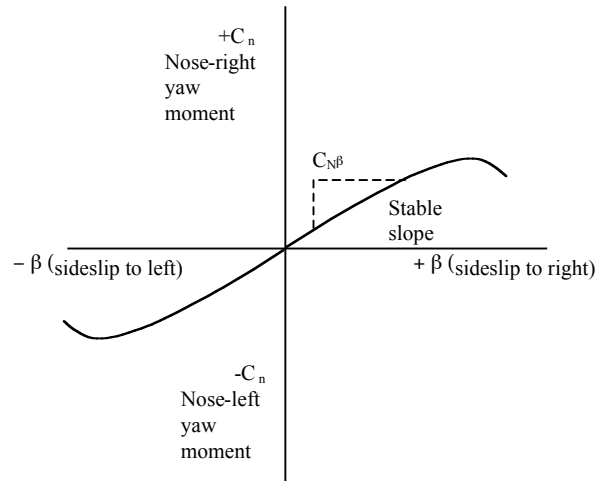


Lateral/Directional Stability

An aircraft has *static directional stability* if it tends to respond to a sideslip by yawing around its z-axis back into alignment with the relative wind. Another way to put it is to say that a directionally stable aircraft yaws toward the velocity vector, returning it to the aircraft's x-z plane of symmetry.

This is also called “weathercock” stability, in honor of a much simpler invention. Figure 2 shows that this stabilizing yaw moment is not typically linear, but tends to decrease at high β angles. In the figure, a positive slope (rising to the right) in the $C_{n\beta}$ curve indicates directional stability. The steeper the slope the stronger is the tendency to weathercock.

Figure 2
Directional Stability
Response



Lateral/Directional Stability

Not all parts of the aircraft contribute to directional stability. Alone, the fuselage is destabilizing. In subsonic flight, the center of pressure on a fuselage in a sideslip is usually somewhere forward of 25 percent of the fuselage length. Since the aircraft's center of gravity is typically aft of this point, the fuselage alone would tend to turn broadside to the relative wind in a sideslip. Notice in Figure 3 how the destabilizing contribution from the fuselage levels out as β increases.

Figure 3 breaks down the components of directional stability. A sideslip to the right ($+\beta$) produces a nose-right, stabilizing yaw moment for the entire airplane, but a destabilizing yaw to the left ($-C_n$) for the fuselage alone.

Of course, the vertical tail contributes most to directional stability. The yaw moment produced by the tail depends on the force its surface generates and on the moment arm between the tail's center of lift and the aircraft's center of gravity. (Therefore, a smaller tail needs a longer arm to produce a yaw moment equivalent to a bigger tail on a shorter arm. That being said, changing the c.g. location for a given aircraft, *within the envelope for longitudinal stability*, has little effect on its directional stability.)

The rate of the increase in force generated by the tail as β increases depends on the tail's lift curve slope (just as the rate of increase in C_L with angle of attack depends on the slope of the lift curve of a wing). Lift curve slope is itself a function of aspect ratio. Higher aspect ratios produce steeper slopes. (See Figure 13, top.)

The $C_{n\beta}$ directional stability curve for the fuselage and tail together reaches its peak when the tail stalls. You can see in Figure 3 that adding a dorsal fin increases the tail's effectiveness (and without adding much weight or drag). Because of its higher aspect ratio and steeper lift curve, the vertical tail proper produces strong and rapidly increasing yaw moments at lower sideslip angles, but soon stalls. But the dorsal fin, with its low aspect ratio and more gradual lift curve, goes to a higher angle of attack before stalling, and so helps the aircraft retain directional stability at higher sideslip angles. The dorsal fin can also generate a vortex that delays the vertical tail's stall.

Figure 3
Contributions to Directional Stability

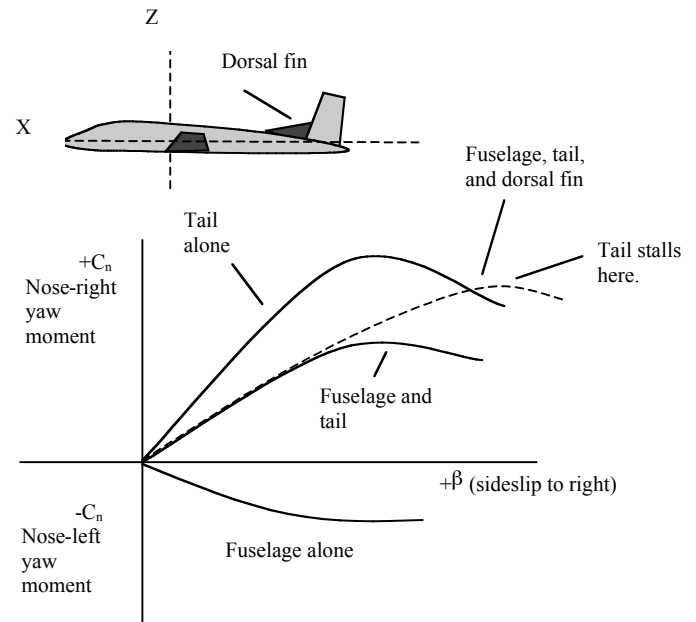
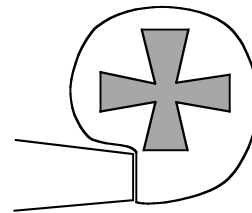


Figure 4
World War I Fokker Dr1 rudder



The Fokker Dr1 triplane provides an extreme example of a low-aspect-ratio tail (there's a rough approximation in Figure 4). Without a fixed vertical fin, the aircraft had low directional stability. The low-aspect-ratio rudder stalled at about 30-degree deflection. The combination gave the pilot the ability to yaw the nose around rapidly if necessary to get off a shot. But in straight-ahead flight the aircraft needed constant directional attention (a typical attribute of WW-I fighters).

Coming back to modern examples, it's appropriate to note that the lift curve slope of the vertical tail tends to go down at high Mach numbers, taking directional stability with it. This tendency is one reason why supersonic fighters need to compensate with such apparently oversized tails. Another reason is that the slope of the $C_{n\beta}$ stability curve also tends to go down at high angles of attack as the fuselage begins to interfere with the airflow over the tail. This is especially so with swept-wing aircraft that require higher angles of attack to achieve high lift coefficients. Directional stability is essential to prevent asymmetries in lift caused by sideslip that can lead one wing to stall before the other and send the aircraft into a departure.

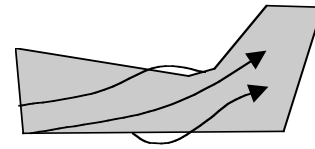
Propellers and Directional Stability

Propellers ahead of the aircraft c.g. are directionally destabilizing, mostly because of slipstream effects and P-factor (Figure 5). Our Air Wolf is an example of an aircraft that requires lots of directional trimming (or just rudder pushing) to compensate for propeller effects as angle of attack and airspeed change. In this respect it's quite unlike a jet, say, or an aircraft with counter-rotating propellers, which typically have no associated directional trim changes.

Note that as an airplane slows down, asymmetrical propeller effects cause it to yaw. If the pilot cancels the yaw rate, using rudder, while keeping the ball centered and the wings level, the aircraft will end up in a sideslip (to the left to generate the side force required to counteract the usual yawing effects due to a clockwise-turning propeller). Thus even a "straight-ahead" stall at idle power has a small sideslip component that may affect its behavior.

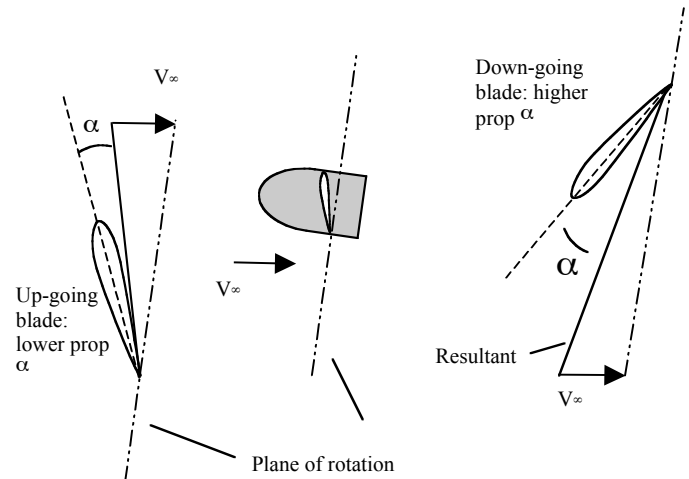
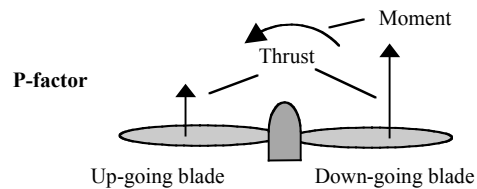
Figure 5
Slipstream
and P-factor

Slipstream



Spiraling slipstream produces a side force at the tail. The resulting yaw moment is most apparent at low airspeeds and high power settings—for example, during a go-around or at the top of a loop.

As aircraft α increases, P-factor causes the down-going blade to operate at a higher prop α than the up-going blade. The difference in thrust produces a yawing moment. A similar change in blade angle happens if the aircraft is in a sideslip, but produces a pitching moment. Left sideslip = pitch up; right sideslip = pitch down.



Dihedral Effect, $C_{l\beta}$

An aircraft with dihedral effect rolls away from a sideslip (away from the velocity vector). The term describes a single behavior with more than a single cause. Dihedral effect was observed first as resulting from actual geometric dihedral (wing tips higher than wing roots), but it's also produced by wing sweep, by a high wing location on a fuselage, and by forces acting on the vertical tail. For convenience, Figure 6 again illustrates sideslip angle, β , and sideslip velocity, v , velocity vector, V , plus the direction of roll.

During our flight program, we'll do *steady-heading sideslips* to assess the presence of dihedral effect. We'll press on a rudder pedal while applying opposite aileron, so that the airplane will be banked but not turning. We'll note the deflections necessary to keep the aircraft tracking on a steady heading, and we'll see what happens when we release the controls.

Steady-heading sideslips give test pilots information about the rolling moments a slipping aircraft generates and its lateral/directional handling qualities. We use them to illustrate the nature of yaw/roll couple and to demonstrate the effects of sideslip under various flap configurations, during aerobatic rolling maneuvers, and during simulated control failures. As you'll see, an aircraft can sideslip in any attitude—including upside-down.

The interaction between sideslip and dihedral effect forms the basis of an aircraft's *lateral stability*. Lateral stability can't appear unless an

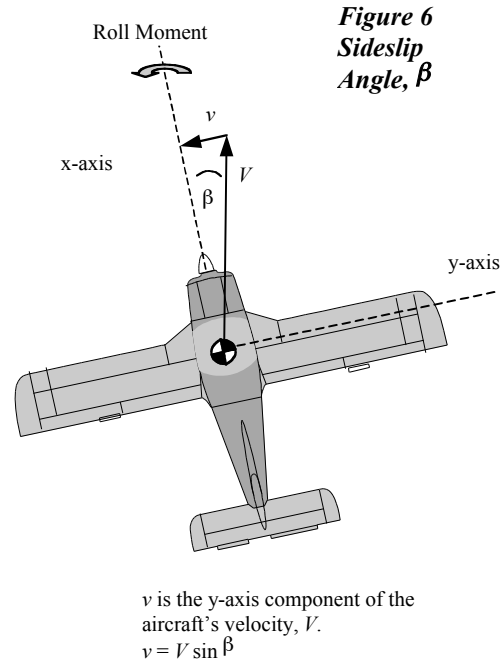


Figure 6
Sideslip
Angle, β

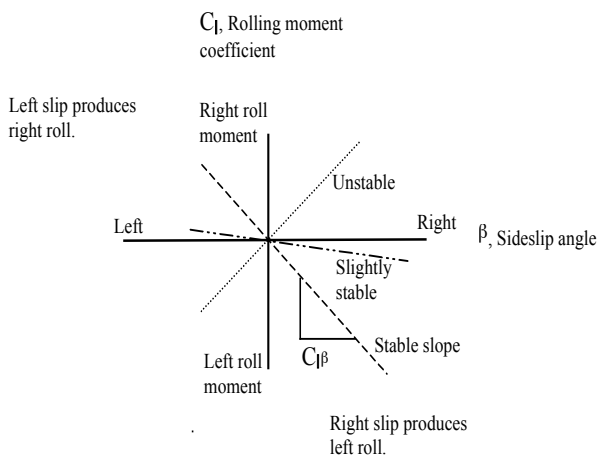
aircraft starts to sideslip first. An aircraft with positive lateral stability rolls away from the sideslip (velocity vector) that results when a wing drops, and that usually means back toward level flight (although an aircraft with dihedral effect can go into a spiral dive if the bank angle is high and other moments prevail).

In the notation used in Figure 7, sideslip angle is β (beta), and the rolling moment coefficient is C_l , so the slope of the curve of rolling moment due to sideslip is $C_{l\beta}$ (pronounced "C L beta").

Since it does roll off the tongue, if we lapse into this terminology you'll know what we mean. The figure shows that the slope must be negative (descending to the right) for stability when we follow the standard sign conventions, where aircraft right is positive, left is negative.

A laterally *unstable* aircraft tends to continue to roll toward the direction of sideslip (positive slope). Sweeping the wings forward or mounting them with a downward inclination so that the tips are lower than the roots (anhedral) produces this tendency. Sometimes anhedral is used to correct swept-wing designs having too much positive lateral stability at high angles of attack. Too much lateral stability can cause sluggish roll response (especially if there's also adverse yaw present) and a tendency toward the coupled yaw/roll oscillation of Dutch roll.

Figure 7
Lateral Stability



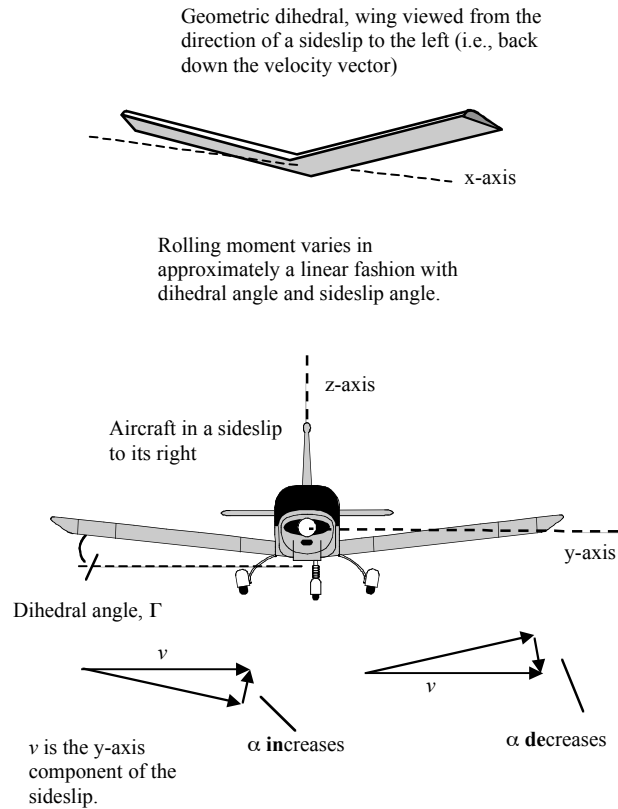
Lateral/Directional Stability

Geometric dihedral effect is easy to understand because it's easy to see how wing geometry and sideslip interact. Just stand on the flight line at a distance in front of an aircraft with geometric dihedral and pretend that you're looking right down the path of the relative wind. You may need to stoop a little to approximate an in-flight angle of attack.

Maintain that eye height above the ground and move back and forth in front of the aircraft, trying hard not to look too suspicious to possible representatives of the TSA. Notice how the angle of attack, α , of the near wing increases—you can see more wing bottom—while that of the far wing decreases as you change your position, as illustrated at the top of Figure 8. With anhedral, you'd see just the opposite.

Figure 8 also presents the same idea in another way. In the lower figure, the y-axis component of sideslip, v , is in turn broken down into two vector components projected onto the aircraft's y-z plane, one parallel to and one perpendicular to the wing. On the upwind wing, the perpendicular component acts to increase the angle of attack. It does the opposite on the downwind wing. The difference produces a rolling moment.

Figure 8
Sideslip, Dihedral
Angle, and Resulting
Change in α



Lateral/Directional Stability

Again, dihedral effect can also result from interference effects due to wing placement on the fuselage, from wing sweep, or from vertical tail height. Flap geometry and angle of deployment influence dihedral effect, as does propeller slipstream.

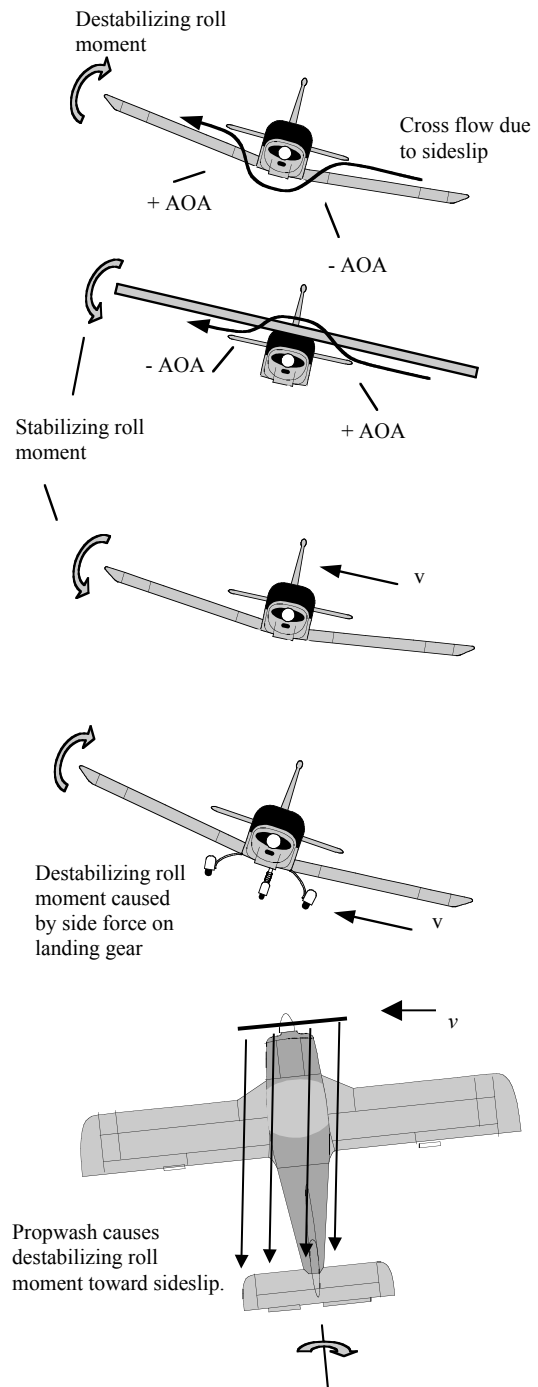
Figure 9 shows the contributions of wing position, tail height, landing gear, and slipstream angle to dihedral effect. Wing position guides the cross flow around the fuselage in a sideslip, altering the angles of attack on the near and far wings, and thus the relative lift. This is stabilizing on a high-wing aircraft. It's destabilizing on a low wing, which is why low-wing aircraft typically require more geometric dihedral. These fuselage effects are enhanced by smooth airflow over the wing-body junction. They're diminished by flow separation at the wing roots at the approach of a stall.

A vertical tail produces a side force during a sideslip. If the tail is tall enough, so that its center of lift is a good distance above the aircraft's center of gravity, the vertical moment arm can provoke a stabilizing roll response. Landing gear, below the c.g., is destabilizing.

The bottom illustration in Figure 9 shows how the angle of the propwash during a sideslip creates a destabilizing condition by increasing the airflow, and thus the lift, over the downwind wing. This generates a rolling moment into the sideslip. The destabilizing effect increases with the flaps down. It also increases at low airspeeds and high power settings, as the ratio of propwash velocity to freestream velocity increases and the propwash gains relatively more influence.

The propwash effect may vary somewhat, depending on the direction of the sideslip. Propeller swirl, as it's sometimes called, creates an upwash on the left wing root and a downwash on the right, leading to a difference in angle of attack between the wings and thus a rolling moment. For the aircraft at the bottom of Figure 9, clock-wise propeller swirl may initially generate a rolling moment to the right, which can suddenly reverse at high α , when the left wing stalls first because of its swirl-induced higher angle of attack. This is an important factor in spin departures, especially during the classic, career-ending skidding turn to final.

Figure 9
Sideslip-
induced Roll



Propwash effects don't occur in jets, but flap effects do. Flaps shift the centers of lift inboard on the wings, as illustrated in Figure 10. This shortens the moment arms through which the lift changes caused by sideslip act, and so sideslip-induced roll moments decrease.

We'll explore this effect during steady-heading sideslips by raising and lowering the flaps and watching the roll response. When the flaps go down, dihedral effect will diminish and the aircraft will start to roll in the direction of aileron input. (This demonstration is important in understanding the concept of *crossover speed*.)

Propwash increases flap effects because of the added airflow over the flap region of the up-going wing, but we can demonstrate with the prop at idle—it will just take more flap deflection.

Because wing taper also shifts the centers of lift inboard on the wings, a high taper ratio (tip chord less than root chord) decreases lateral stability. High aspect ratios move the centers of lift outboard, increasing lateral stability.

Geometric Dihedral and Coefficient of Lift, C_L

The strength of geometric dihedral effect does not depend *directly* on aircraft coefficient of lift (you'll see the reason for the italic treatment presently). The C_L/α curve for a cambered wing in Figure 11 is linear up to the stall, which means that for a given change in angle of attack (produced by a sideslip) there's a given incremental difference in coefficient, until the slope starts to decline near the stall. As a result, a given sideslip angle combined with a given dihedral angle, will generate a given difference in C_L . It doesn't matter if you start at low or high C_L , as long you stay on the straight line. That difference then produces a rolling moment that varies directly with speed.

If you can tolerate even more confusion, imagine that an aircraft with geometric dihedral is flying at its zero lift angle of attack (maybe during a pushover at the top of a zoom). If the airplane starts to sideslip, it will begin to roll as the angle of attack changes on each wing and a spanwise asymmetry in lift appears. Without geometric

Figure 10
Flap Effects

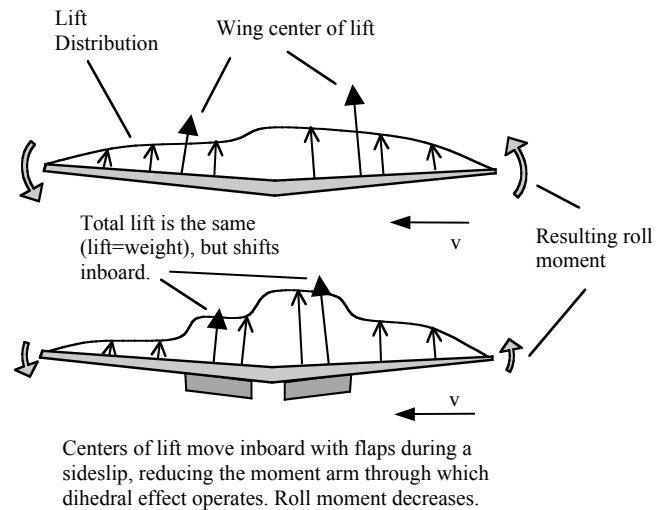
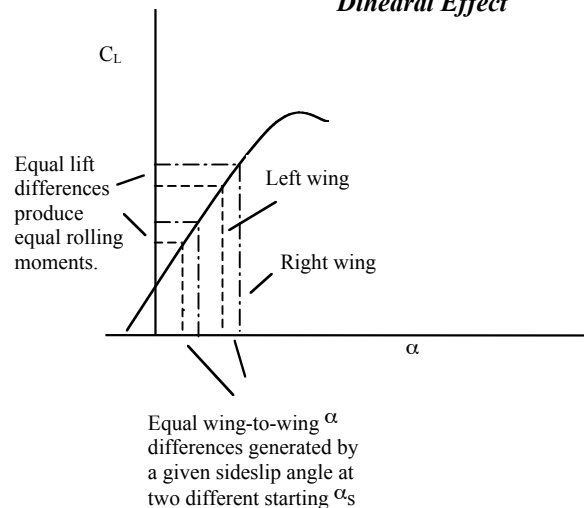


Figure 11
Geometric Dihedral Effect



dihedral, a purely swept-wing aircraft, at zero coefficient of lift, won't roll in the same situation, because the sideslip has no influence if lift is not already being generated.

Swept-wing Dihedral Effect

Figure 12 shows the contribution of wing sweep angle (Λ) to dihedral effect. It's almost enough to say that in a sideslip, because of the angle of intercept, the wing toward the sideslip "gets more wind" across its span, while the opposite wing gets less. But we can gain a better understanding of swept-wing characteristics by first breaking the airflow over the wing into normal and spanwise vectors. It's the normal vector (perpendicular to the leading edge on a wing with no taper, or by convention perpendicular to the 25% chord line on a wing with taper) that does all the heavy lifting, because *only the normal vector is accelerated* by the curve of the wing. There's no acceleration and accompanying drop in static pressure in the spanwise direction, because there's no spanwise curve.

When a swept wing sideslips, the relative velocities of the normal and spanwise vectors change. The spanwise component decreases and the normal component increases on the wing toward the sideslip, and so lift goes up; just the opposite happens on the other wing, and there lift goes down. A roll moment results. A directionally stabilizing yaw moment also results, because a difference in drag accompanies the difference in lift—but the effect is small compared to the stabilizing moment provided by the tail.

For a swept wing, the roll moment coefficient due to sideslip is directly proportional to the sideslip angle, to the sine of twice the sweep angle, and to the coefficient of lift.

Figure 12
Wing Sweep

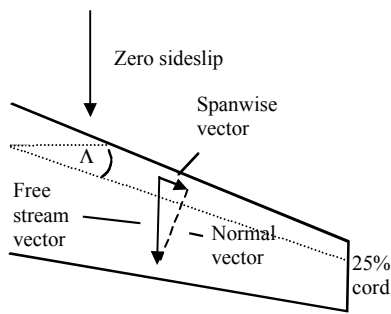
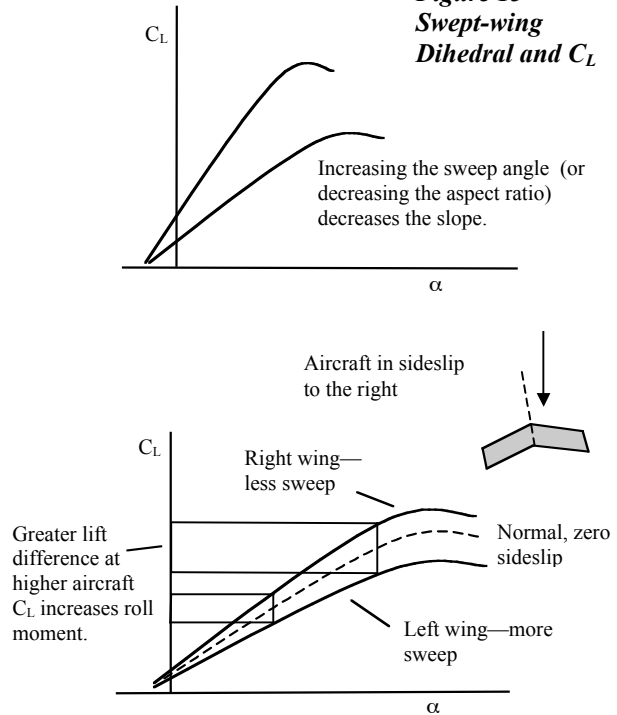
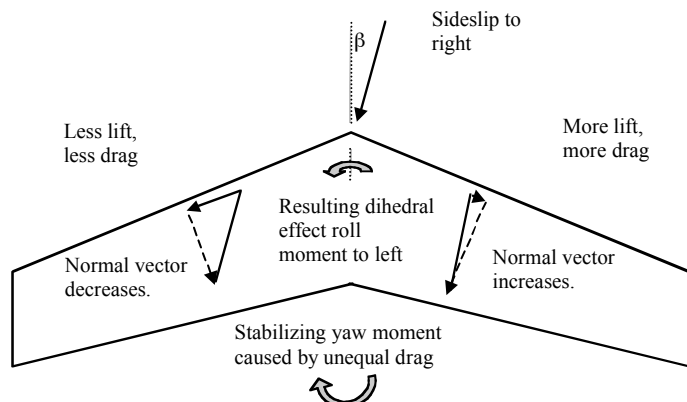


Figure 13
Swept-wing
Dihedral and C_L



The relationship between sideslip and sweep angles, and subsequent rolling moment can be anticipated just from looking at Figure 12, but the variation in rolling moment with C_L takes explaining. The easiest approach is to think of sideslip as changing the effective sweep angle of each wing, and thus the slope of their respective C_L/α curves. Sweep angle and slope are related as shown at the top of Figure 13. In a sideslip, as shown on the bottom, a swept-wing aircraft has two C_L/α curves: a steeper one than normal for the wing into the wind, and a shallower one than normal for the trailing wing. The difference between them creates the rolling moment. Note how the difference at any given β increases with α , and therefore with C_L .



Lateral/Directional Stability

Back in Figure 12, right, note the difference in spanwise drag during a sideslip. That difference is directionally stabilizing, and it's the reason why flying wing aircraft are swept.

Since wept-wing dihedral effect varies with lift coefficient, so does lateral stability. Aircraft with high sweep angles can have acceptable dihedral effect and lateral stability in normal cruise flight when C_L is low, but excessive dihedral effect at low speeds, or during aggressive turning maneuvers, or at high altitudes, where in each case C_L is necessarily high. Under those conditions, sideslips can produce strong rolling moments. This can allow a pilot to accelerate a roll rate by forcing a sideslip with rudder, but also increases the potential for Dutch roll oscillation and rudder misuse.

As mentioned, unlike a wing with geometric dihedral, a purely swept-wing will not roll in response to a sideslip unless it's already generating lift. There's no dihedral effect attributable to wing sweep at zero C_L .

You can see that a wing possessing both geometric dihedral and sweep has a kind of multiple personality (and usually a yaw damper).

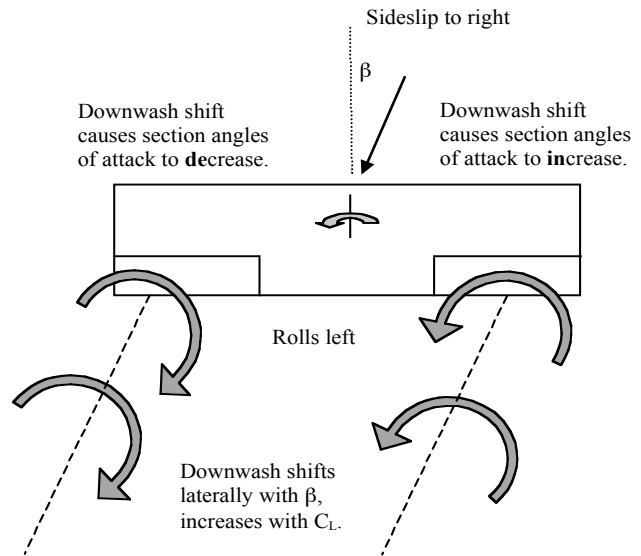
Straight Wings and Coefficient of Lift—Revisited

Despite the claim made earlier, straight-wing aircraft with geometric dihedral do exhibit a connection between increased C_L and increased dihedral effect.¹

If you go to the illustrations in our briefing materials on three-dimensional wings, you'll discover that the downwash caused by wing tip vortices alters the effective local angle of attack across the span. The greater the downwash, the lower the local effective angle of attack on the wing ahead of the downwash. (The angle of attack changes because the acceleration of air downward by the vortices actually starts to occur ahead of the wing. The air starts coming down even before the wing arrives.)

In a sideslip the vortex flow shifts laterally, as in Figure 14. This changes the overall downwash distribution, shifting it to the left in the case

Figure 14
Vortex Effects



illustrated, which in turn causes the average effective angle of attack of the left wing to be lower than it would from dihedral geometry alone. The average effective angle of attack on the right wing becomes higher. The result is a rolling moment to the left (a moment that would theoretically occur even if the wing had zero dihedral—as long as lift is being produced).

Since downwash strength is a function of C_L , pulling or pushing on the stick will affect roll moment due to sideslip in a manner similar to the swept-wing example already described. (Our trainers' rectangular planforms tend to promote strong tip vortices. Other straight-wing planforms with different lift distributions might not be as effective.)

Pushing and pulling on the stick during a sideslip also causes the aircraft to pitch around its y wind axis (as opposed to body axis), which introduces a roll as described in Figure 19. The effect would be in the same direction as the downwash phenomenon just mentioned, and the two might easily be confused.

From all the above, an under-appreciated yet nevertheless great truth of airmanship emerges: **For a swept or a straight wing, pulling the stick back tends to increase rolling moments caused by sideslip (and by yaw rate), pushing decreases them.**

¹ Bernard Etkin, *Dynamics of Atmospheric Flight*, Wiley & Sons, 1972, p. 305-306.

Sideslip and Roll Rate

With our particular emphasis on the aerodynamics of unusual-attitude recovery, here are the behaviors we want to be sure you understand:

(1) Increasing C_L (by pulling back on the control) will increase rolling moment due to sideslip and yaw rate. Decreasing C_L (by pushing forward) will decrease rolling moment due to sideslip and yaw rate. We'll explore the implications of this during our flight program. (See roll due to yaw rate, and y-wind-axis roll, farther on.)

(2) A laterally stable aircraft rolling with aileron *toward* the direction of a sideslip/velocity vector will experience a *decrease* in roll rate in proportion to the opposing rolling moment the sideslip produces. An aircraft rolling with aileron *away* from the direction of a sideslip/velocity vector will experience an *increase* in roll rate. You'll discover this effect when we start rolling the training aircraft through 360 degrees and begin using rudder-controlled sideslips to augment roll rates.

Figure 15 describes the link between sideslip direction and roll rate at two points during a 360-degree roll to the left, and Figure 16 plots roll rate against time, given differences in rudder use, dihedral effect, and directional stability.

Figure 15
Sideslip and
Roll Rate

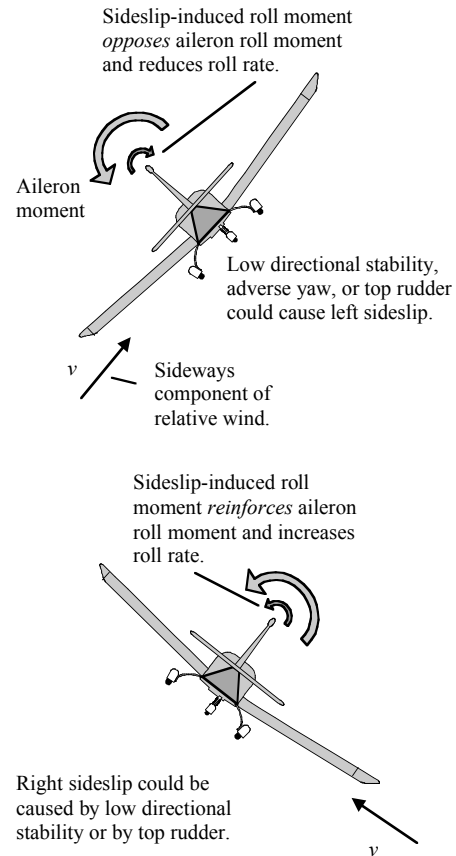
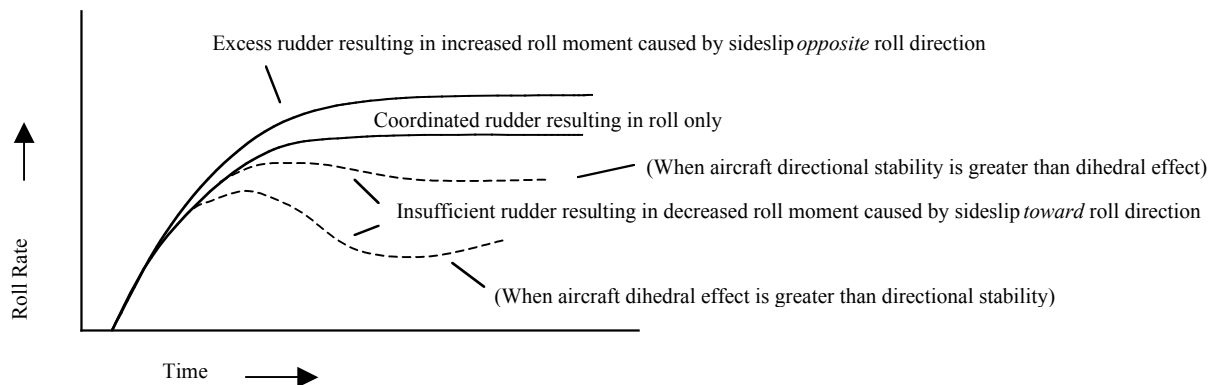


Figure 16
Dihedral Effect,
Rudder Use,
Roll Rate



Aerobatic Aircraft and Dihedral Effect

High-performance aerobatic airplanes usually have little or no geometric dihedral, and so very little lateral stability through dihedral effect. One can't always know what the designer had in mind, but the absence of dihedral allows aircraft to roll faster in the presence of opposing sideslips, and makes them easier to fly to competition standards because roll rate and rudder deflection remain essentially independent. It's possible to use the rudder to keep the nose up during the last quarter of a slow roll (when an aircraft that's rolling left, say, and going through the second knife edge is sideslipping to the right) without having to change aileron deflection to keep the roll rate from accelerating.

These desirable characteristics for smooth aerobatic flying actually make an aircraft less suitable for unusual-attitude training. Most aircraft do exhibit lateral stability, and the resulting characteristics are important to understand. For one thing, lateral stability allows you to roll an aircraft with rudder using normal directional input should you lose the primary roll control—the ailerons.

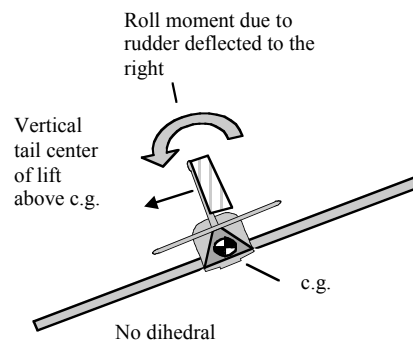
Absent dihedral effect and unaccompanied by aileron, rudder deflection alone in some aerobatic aircraft will produce a roll opposite the expected direction. For example, right rudder, instead of rolling the aircraft right by dihedral effect (and roll due to yaw rate), slowly rolls it to the left, as in Figure 17. *Roll due to rudder* is caused by the vertical tail's center of lift being above the aircraft's center of gravity. A moment arm results. The effect could be particularly evident in a zero-dihedral, low-wing aircraft, when a sideslip generated by rudder deflection also produces an accompanying, destabilizing roll due to cross flow. (Check back to Figure 9, top. Low wing is destabilizing.) The first time you try to unfold a map while using your feet to keep the wings level in an aircraft that behaves like this, you're in for a surprise.

If you actually lost your ailerons you might regain some positive dihedral effect and roll due to yaw rate by slowing down and increasing the coefficient of lift. Also, slowing down will raise the nose, and so place the tail lower and decrease the vertical distance between its center of lift and the c.g., reducing the moment arm. Perhaps the aircraft would then respond in the normal way. It may be possible (as in the Giles G-200, for

example) to control an aircraft by using roll due to rudder, but it's not the sort of thing that happens intuitively. Aileron failure is typically catastrophic in an aircraft without dihedral effect. That's one reason why preflight inspection of the lateral control system in a zero-dihedral aerobatic aircraft (for integrity of the linkages, and for items that could cause jams like loose change, nuts, bolts, screwdrivers, hotel pens—your mechanic has horror stories and probably a collection of preserved examples) is so important. The same, of course, goes for elevator and rudder systems.

Here's a related phenomenon: Next time you fly the swept-wing MiG-15, notice that rudder deflection produces a roll in the expected direction until you get past about Mach 0.86, but then the response reverses—left rudder causing the right wing to drop, for example. A sideslip, as pointed out in Figures 12 and 13, reduces the sweep of one wing and increases the sweep of the other, relative to the free stream. The reduction in the effective sweep of the right wing, caused by pressing the left rudder, can send the right wing past critical Mach number, causing shock airflow separation and a wing drop. If you're pulling g, the effect can happen at a lower speed because of the acceleration of the airflow over the wing caused by the higher angle of attack. Response to the rudder returns to normal at about Mach 0.95.

Figure 17
Roll due to
Rudder, $C_l \delta_r$



Roll Due to Yaw Rate, C_{l_r}

When an aircraft yaws, the wing moving forward has higher local velocity than the wing moving back. The higher the yaw rate, or the longer the wingspan, the greater the velocity difference becomes. Yaw rate produces a difference in lift and an accompanying roll moment, which disappears once yaw rate returns to zero. The roll moment varies with the square of the difference in speeds across the span (since the lift produced by a wing varies with V^2).

When you enter a sideslip by pressing the rudder, some percentage of the roll moment generated is caused by dihedral effect, and some by roll due to yaw rate. Once a given sideslip angle is reached and held and yaw rate disappears, dihedral effect provides the remaining rolling moment.

Like the dihedral effects described above, roll due to yaw rate increases with coefficient of lift, C_L . For rectangular wings, the value for the rolling moment coefficient per unit of yaw rate, C_{l_r} , is about 0.25 times C_L , on average. Wingtip washout, and/or flap deployment, reduces C_{l_r} .

An aircraft in a banked turn has a yaw rate. The outside wing has to travel faster than the inside. This can create a destabilizing, “over-banking” tendency and force the pilot to hold outside aileron during the turn. The situation gets worse as you slow down (or grow longer wings). *For a given bank angle*, yaw rate varies inversely with airspeed. So as you slow down and increase C_L , yaw rate also increases and roll due to yaw becomes more apparent. That’s why turning in slow-flight required so much opposite aileron to maintain bank angle and felt so weird back in primary training—and still does today.

An aircraft that requires lots of opposite aileron in response to yaw rate in a turn is likely to be spirally unstable if left to its free response. When a wing goes down and an aircraft enters a sideslip, dihedral effect will tend to decrease bank angle and roll the wing back up. But at the same time the aircraft’s directional stability tends to yaw the nose into the sideslip, generating a yaw rate and a rolling moment that increases bank angle. If that moment wins the contest, a spiral begins.

Figure 18
Aircraft Yaw Around Z Wind Axis

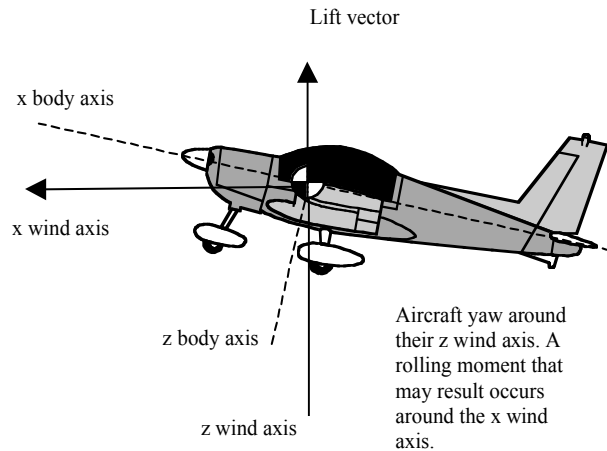
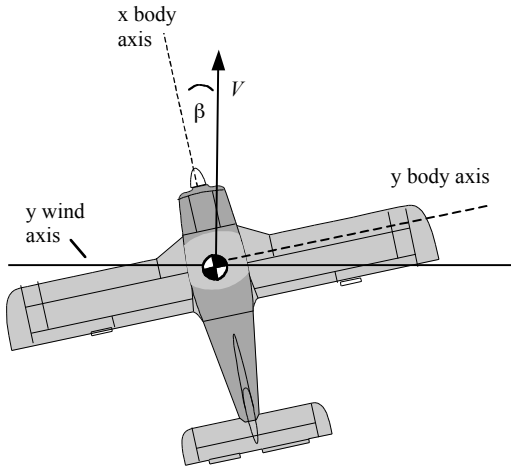


Figure 19
Aircraft Pitch Around Y Wind Axis



Geometrically, pitching around the y wind axis also produces a roll. In a sideslip to the right, as above, pulling the control back will cause a roll to the left; pushing forward causes a roll to the right. This is easier to visualize if you try it with a hand aircraft model. Note that the rolling effect is consistent with (operates in the same direction as) the other sideslip/yaw-rate rolling moments described in the text.

Dutch Roll

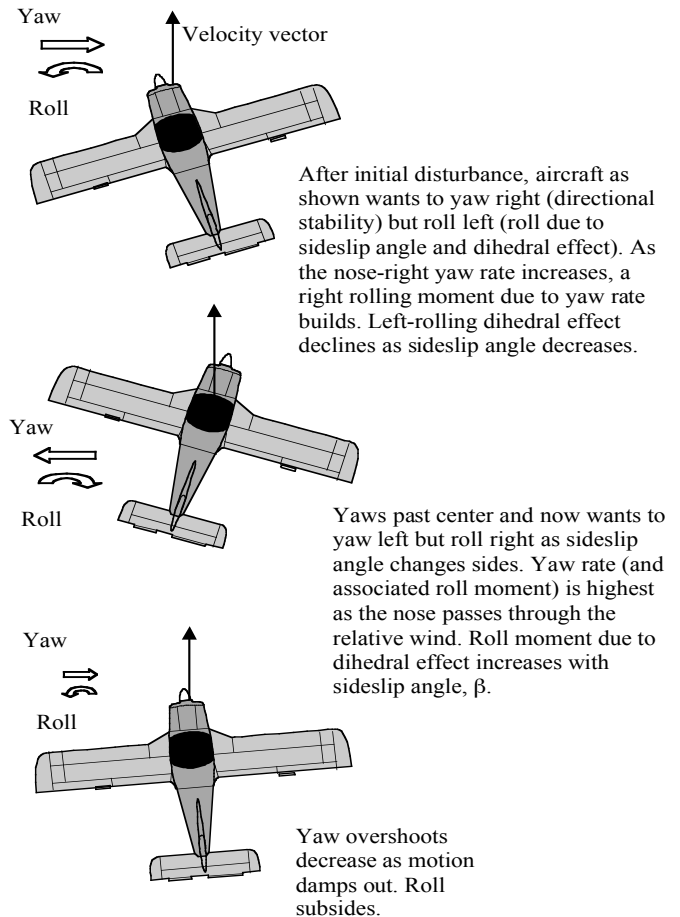
Directional stability, dihedral effect, and roll due to yaw rate all do battle in the dynamic phenomenon called Dutch roll. Dutch roll tendency appears in aircraft with high lateral stability as compared to directional stability. It's particularly a problem with swept-wing aircraft, in which lateral stability increases with angle of attack (i.e. coefficient of lift), as already described. Although not nearly as bad, our straight-wing Zlin has enough Dutch roll in turbulence to make the ride memorable.

In the Dutch roll, a disturbance in roll or yaw, whether pilot-induced or caused by turbulence, creates a sideslip. A sideslip shifting the velocity vector (relative wind) to the right, as in Figure 20, for example, leads to an opposite rolling moment to the left (through dihedral effect and roll due to yaw rate). But the aircraft's directional stability works to eliminate the sideslip by causing the nose to yaw to the right, back into the wind. However, momentum causes the nose to yaw past center (past zero β), and this sets up a sideslip in the opposite direction, which in turn sets up an opposite roll. The resulting out-

of-phase yawing and rolling motions would damp out more quickly if they occurred independently. Instead, each motion drives the other. Note that Dutch roll is the result of the fundamental tendency of a stable aircraft to roll away from but yaw toward the velocity vector whenever that vector leaves the aircraft's plane of symmetry.

Without a yaw damper to do it for them, it's difficult for pilots to control a Dutch roll because its period is short. It's hard to "jump in" with the required damping input at the right time. Pilots of swept-wing are frequently trained to keep off the rudders, check the roll with temporary, quick, on-off applications of aileron, and then recover to wings level. Another strategy is to use the

Figure 20
Dutch Roll



Lateral/Directional Stability

rudder—not to combat yaw but to keep the wings level.

The tendency to Dutch roll increases at higher C_L , because increasing the coefficient of lift increases both dihedral effect (especially swept-wing) and roll due to yaw rate. Dutch roll tendency also increases at higher altitudes, where aerodynamic damping effects diminish. Since aircraft must fly at high C_L at high altitudes, the problem compounds. Normally aspirated piston-engine aircraft upgraded with turbochargers for high-altitude flight sometimes end up needing larger vertical tails for better damping.

Reducing dihedral effect will ease the Dutch roll problem, but at the expense of reduced lateral stability.

Aircraft with greater directional than lateral stability tend to Dutch roll less, but also tend to be spirally unstable. Traditionally, the design compromise between Dutch roll tendency and spiral instability has been to suppress the former and allow the latter, because spiral dives—while potentially deadly—begin slowly and are easier to control than Dutch roll.

Lateral/Directional Stability

Flightlab Ground School

5. Longitudinal Static Stability

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Longitudinal Static Stability

Stability is a subject that gets complicated fast. Many factors contribute, yet the aerodynamics literature lacks an accessible, lucid account. The emphasis here—and in the Flightlab ground school texts on maneuvering and dynamic stability—is to give information that allows a pilot to observe an aircraft's stability characteristics in a thoughtful way, and to understand how those characteristics may vary under different conditions and from type to type.

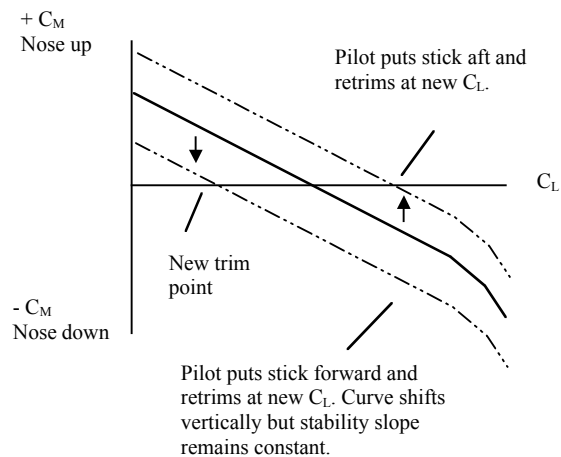
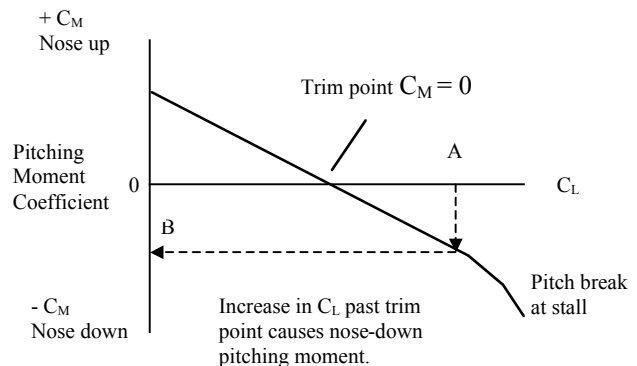
An aircraft has positive longitudinal *static* stability if its initial response in pitch, in 1-g flight, is to return to equilibrium around its trim point after displacement by a gust or by the temporary movement of the elevator control. (The term longitudinal *maneuvering* stability describes behavior in more than 1-g flight. *Dynamic* stability refers to response over time.)

When you trim an aircraft to fly at a given coefficient of lift, C_L , but then push or pull on the stick and hold it there in order to fly at a different C_L (or the equivalent angle of attack or airspeed) you're working against the aircraft's inherent stability. The aircraft generates a restoring moment that's proportional, if you don't retrim, to the force you feel against your hand. The faster that force rises with stick deflection, the more stable your aircraft.

Classical stability depends on the distance between the aircraft's center of gravity and a set of *neutral points* farther aft along the longitudinal axis—the larger the distance between c.g. and neutral point the higher the stability. We'll get back to neutral points later on.

An aircraft in trim is in an equilibrium state around its pitch, or y, axis. All the competing up or down moments (see Figure 4) generated by the various parts of the aircraft, and acting around its c.g., are in balance. In aerodynamics notation, a pitch-down moment carries a negative

Figure 1
Pitching Moment
versus C_L



sign; pitch up is positive. In equilibrium, all moments sum to zero.

Figure 1, top, shows the change in coefficient of moment in pitch, C_M , which results from a change in coefficient of lift for a statically stable aircraft. The longitudinal static stability curve crosses the C_L axis at the trim point, where $C_M = 0$. If the relative wind is displaced by a temporary gust or a pull on the stick, so that the

Longitudinal Static Stability

C_L of the wing goes up to point *A*, a negative pitching moment results, *B*, which restores the aircraft to its trimmed angle of attack, α , and thus C_L .

The bottom of Figure 1 shows how the stability curve moves vertically when you change elevator angle to fly at a different C_L . Note that the aircraft's stability remains the same (same slope), but the trim point shifts.

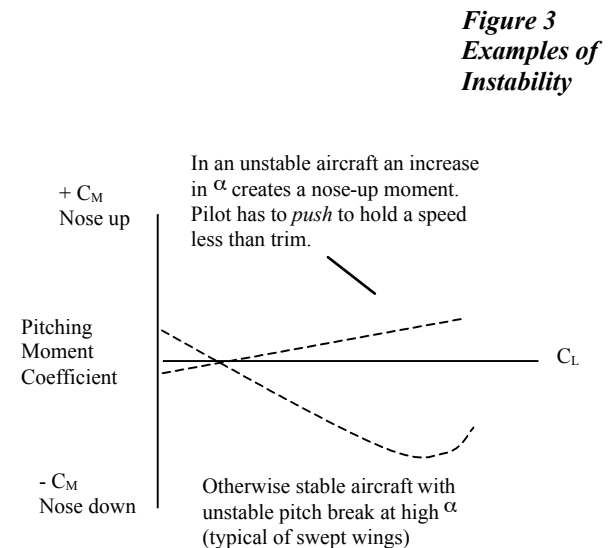
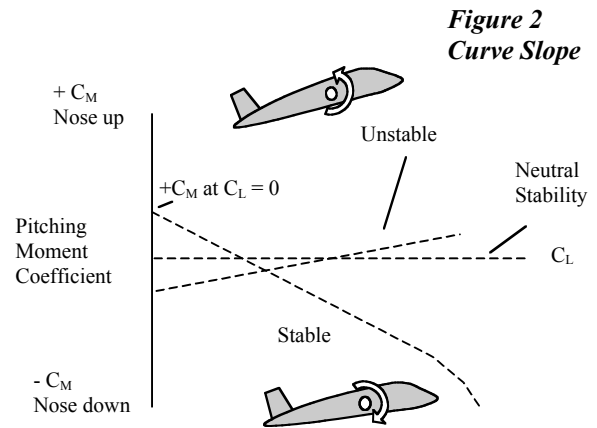
The stability (or $\Delta C_M / \Delta C_L$) curve typically takes a downward turn to a more negative slope as the aircraft passes the stalling angle of attack (Δ , pronounced "delta," means change). This is because the downwash at the tail decreases as the wing gives up lift (assuming a root-first stall and a receptive tail location), and because the pitching moment of the wing itself becomes more negative as its center of pressure suddenly moves rearward at the stall. The increase in downward pitching moment, $-C_M$, is helpful since it aids stall recovery. If such a *pitch break* (or *g-break*) occurs at the stall, it must be in the stable direction throughout the aircraft's c.g. envelope under the requirements of FAR Parts 23.201 and 25.201.

On the early swept-wing aircraft with a tendency to stall at the wingtips first—causing the center of lift to shift forward and the aircraft to pitch up—an initially negative, stable curve might actually reverse its slope at high C_L and produce an unstable pitch break.

A negative slope ($\Delta C_M / \Delta C_L < 0$) is necessary for positive static stability. The more negative the slope the more stable the aircraft. In addition, there must be a positive pitching moment, C_M , associated with $C_L = 0$.

The curve for a neutrally stable aircraft has a zero slope; so no change in pitching moment results from a change in angle of attack (Figure 2).

The $\Delta C_M / \Delta C_L$ curve for a statically unstable aircraft has a positive slope ($\Delta C_M / \Delta C_L > 0$). For normal certification, it must be necessary to pull in order to obtain and hold a speed below the aircraft's trim speed, and push to obtain and hold a speed above trim speed. A statically unstable aircraft doesn't obey this (Figure 3). Instead, a change in angle of attack from trim leads to a pitching moment that takes the aircraft farther



from equilibrium, and actually produces a reversal in the direction of stick forces.

The result of moderate instability might still be a flyable aircraft, but the workload goes up. Look at the positive, unstable slope in Figure 3. If you pulled back on the stick the aircraft would pitch up and slow. But if you then let go of the stick the nose would continue to pitch up, since a positive pitching moment would remain. It would require a *push* force to maintain your climb angle, not the mandated pull. If you pitched down and let go, the nose would tend to tuck under. You'd have to apply a *pull* force to hold your dive angle, not the mandated push. That's how the Spirit of St. Louis behaved. (The EAA's flying replica provides a fascinating example of the original's unstable flying

Longitudinal Static Stability

qualities. It's laterally and directionally unstable, as well. But it's not hard to fly—you just have to fly it all the time.)

Pilots experience longitudinal static stability most directly through the control force (and to a lesser extent the deflection) needed to change the aircraft's equilibrium from one airspeed trim point to another. The steeper the slope of the $\Delta C_M / \Delta C_L$ curve, the more force needed.

High performance, competition aerobatic aircraft tend to be somewhere on the stable side of neutral. Compared to other types, aerobatic aircraft can feel twitchy at first, partly because the light control forces associated with their shallow $\Delta C_M / \Delta C_L$ curves cause pilots to over control. But compared to aerobatic types, more stable aircraft can feel stiff and reluctant. It depends on where your most recent muscle memory comes from. FAR Part 25.173(c) requires that transport category aircraft have a minimum average stick force gradient not less than one pound for each six knots from trim speed. FAR Part 23.173(c) takes things more broadly, requiring only “that any substantial speed change results in a stick force clearly perceptible to the pilot.”

Figure 4 shows how the different parts of an aircraft contribute to longitudinal stability characteristics. The fuselage and the wing are destabilizing. Static stability depends on the restoring moment supplied by the horizontal tail being greater than the destabilizing moments caused by the other parts of the aircraft. If you require an aircraft with a wide center of gravity loading range, make sure to give it a powerful enough tail (large area, large distance from c.g., both) to supply the necessary restoring moments.

On conventional aircraft, once the design is set, static longitudinal stability and the control force necessary to overcome that stability are both functions of aircraft center of gravity location. Both decrease as the c.g. moves aft. Figure 5 shows how the $\Delta C_M / \Delta C_L$ curve changes with c.g. position.

Figure 4
Stability
Components

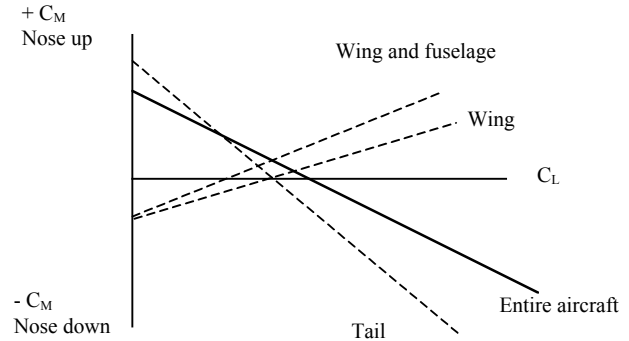
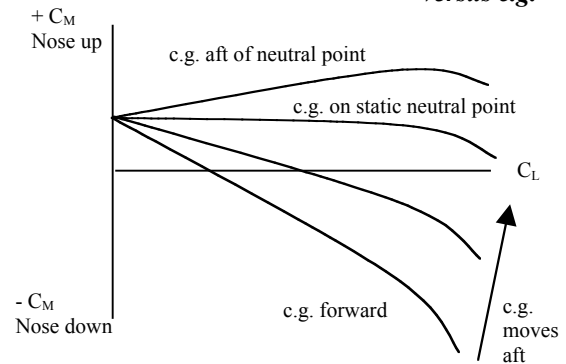


Figure 5
Stability
versus c.g.



Longitudinal Static Stability

Figure 6 shows how the curve for control force necessary to fly at airspeed other than trim varies with c.g. position. The forces necessary are greatest at forward c.g. Note that we're switching from a $\Delta C_M / \Delta C_L$ curve, which a pilot can infer but can't experience directly, to forces and speeds that he can.

The tendency of an aircraft to return to trim speed when the controls are released is friction and c.g. dependent. As the c.g. goes aft and the force returning the stick to the trim position becomes less powerful, friction effects become more apparent. The aircraft can appear to have nearly neutral stability within a given airspeed band when there's appreciable friction. If you displace the stick, let the aircraft establish a new speed, and then let go, friction may prevent the elevator from returning to its original position and the aircraft from settling back to its original speed.

The speed it does settle on is called the *free return speed*, which for Part 23 certification must be less than or equal to ten percent of the original trim speed. To determine free return speeds, trim your aircraft for cruise and then raise the nose, allowing speed to stabilize about 15 knots slower. Then *slowly*, so as not to provoke the phugoid, release aft pressure to lower the nose back down to trim attitude and *hold* it there, gradually releasing aft pressure as necessary. (Don't push, since this immediately wipes out the friction—the effect of which you're trying to measure.) When you've released all aft pressure, note the speed. Repeat the exercise with a push. First let the aircraft accelerate 15 knots, and then release forward pressure to bring the nose slowly back up to trim attitude. (Don't pull—friction, again) Hold that attitude and note the speed at which the necessary push force disappears. The numbers show your free return trim speed band, and may explain why you're always fussing with the trim wheel! A wide band makes an aircraft difficult to trim.

The trim speed band may become wider as the c.g. moves aft. Aft movement reduces stability, which in turn causes the slope of the control force curve to become less negative (Figure 6). Less return force is then generated to oppose the friction within the system.

Figure 6
Control force
versus c.g.

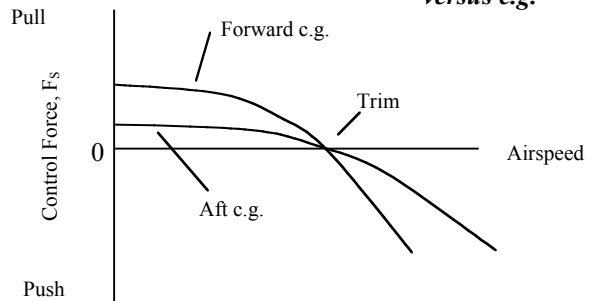
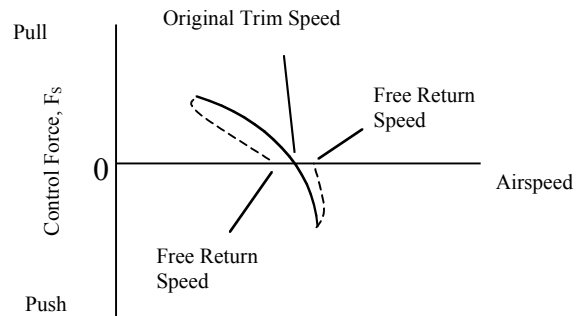
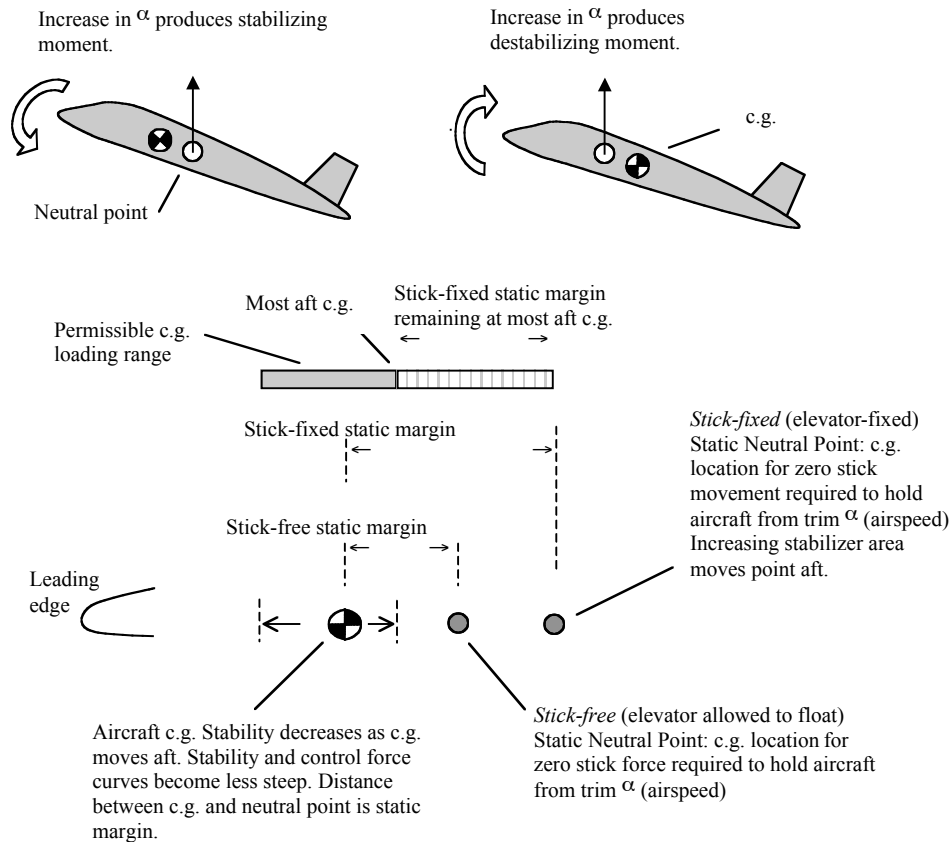


Figure 7
Free Return Speed



Longitudinal Static Stability

Figure 8
Static Neutral Points



Neutral Points

When the angle of attack of an aircraft changes, the net change in lift generated by the wings, stabilizer, and fuselage acts at the neutral point. The neutral point is sometimes referred to as the *aerodynamic center of the aircraft as a whole*, similar to the more familiar aerodynamic center of a wing. There's no moment change about the neutral point (or about wing aerodynamic center) as angle of attack changes—only a change in lift force.

In order for an aircraft to be longitudinally stable, the center of gravity must be ahead of the neutral point. Given that condition, the top left of Figure 8 shows what happens when a gust or a pilot input increases angle of attack, α , above trim. The increased lift, acting at the neutral point some distance from the c.g., generates a stabilizing, nose-down pitching

moment around the c.g. A stabilizing, nose-up pitching moment occurs if α goes down.

The aircraft on the right shows the unstable response when the c.g. lies behind the neutral point.

Static stability decreases as the c.g. moves aft, toward the neutral point. The $\Delta C_M / \Delta C_L$ curve becomes increasingly flat. If you shift the c.g. all the way back to the neutral point, there'll be a change in lift whenever α changes, but no moment change. With the c.g. at the neutral point, pitching moment, C_m , becomes independent of α . The aircraft will have neutral static stability. Since the aircraft no longer generates a stabilizing moment, the pilot feels no opposing force in the stick when he moves it to fly at a new C_L .

The aircraft becomes statically unstable when the elephant finally gets loose and moves the c.g. aft

Longitudinal Static Stability

of the neutral point. Once again there's a change in moment around the c.g. when α changes, but now it's destabilizing.

On a statically stable aircraft, the distance between the most permissible aft c.g. and the neutral point (both of which are expressed as percentages of the mean aerodynamic chord of the wing) is known as the *static margin*. The greater the static margin, the greater the stability becomes (and thus the more negative the slope of the stability curve).

Actually, as Figure 8 indicates, there're two static stability neutral points: *stick-fixed* (elevator and trim tab held in the prevailing trim position), and *stick-free* (hands off, elevator allowed to float in streamline as the angle of attack at the tail changes). In flight-testing, stick-fixed stability determines the amount of control and elevator *movement* needed to change airspeed (or C_L , or α) from trim. Stick-free stability determines the required *force*. We'll amplify this below.

Stick-fixed Neutral Point

With a powered, irreversible control system the elevator usually doesn't float unless something broke, and so only the stick-fixed stability normally matters. (However, sometimes a programmed, artificial float is introduced to cure stability problems. Also, a control system can revert in case of hydraulic failure. The Boeing 737 reverts to a reversible system following hydraulic failure. Its predecessor, the 707, was reversible to begin with.)

At a given center of gravity position, an aircraft's *static stick-fixed stability is proportional to the rate of change of elevator angle with respect to aircraft lift coefficient* (aircraft lift coefficient includes the combined wing and fuselage lift effects). In other words, the more stable the aircraft is (the larger the static margin) the farther you have to haul back or push on the stick. As you bring the c.g. back, less stick movement is needed to produce an equivalent change in C_L and airspeed—and less spinning of the trim wheel is necessary to trim out the resulting forces. If the c.g. is brought back to the *stick-fixed* static neutral point, the change in stick position needed to sustain a change of airspeed is zero. Once you've moved the stick to attain a

new angle of attack, you can put it back to where it was before.

Reportedly, the Spitfire has just about neutral stick-fixed static stability in all flight modes. The DC-3 is stable in power-off glides or at cruise power but unstable at full power or in a power approach at an aft c.g.

Stick-free Neutral Point

The *stick-free* static neutral point is the c.g. position at which the aircraft exhibits neutral static stability (slope of the $\Delta C_M / \Delta C_L$ stability curve = 0) with the elevator allowed to float. In other words, it's the position where pitching moment, C_M , is independent of C_L with the stick left free.

Your intuition may tell you that *stick-fixed* static stability is likely to be greater than the elevator-floppy situation of stick-free, because of the fixed elevator's greater efficiency in producing restoring pitching moments. The actual difference between fixed and free in an aircraft with reversible controls (with reversible controls, wiggling the control surface wiggles the stick) depends on elevator control system design, in particular the control surface hinge moments. Aerodynamic balance used to reduce hinge moments, and thus reduce the force a pilot has to apply to deflect the elevator, also reduces floating tendency—and therefore increases the stick-free static stability margin. The stick-free neutral point usually lies ahead of the stick-fixed point. Just how far ahead depends directly on how much the elevator tends to float.

Figure 6 showed how the longitudinal stick force, F_S , necessary to move an aircraft off its trim point decreases as the center of gravity moves aft. This is the logical result of the accompanying decrease in static stability. When the aircraft's c.g. lies on the stick-free neutral point, no change in *force* is needed to change airspeeds.

Conventional handling qualities require that the aircraft c.g. lie ahead of the stick-free static neutral point. If c.g. moves *behind* the neutral point, control forces reverse. A pull force becomes necessary to hold the aircraft in a dive; a push force becomes necessary in a climb.

Flightlab Ground School

6. Longitudinal Maneuvering Stability

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Maneuvering Stability

Longitudinal maneuvering stability is really just static stability with an additional factor: pitch rate. An aircraft in accelerated (curved) flight—whether pulling up, pushing over, or turning—has a pitch rate. Figure 1 shows the simple case of an aircraft in a pull-up. The aircraft pitches about its c.g. The tail sweeps along behind, on its arm, l_T . The tail's motion creates a change in its relative wind and thus in tail angle of attack, α_T . The change in tail angle of attack due to pitch rate produces an opposing pitching moment, known as *pitch damping*.

The change in tail angle of attack, $\Delta\alpha_T$, due to pitch rate is shown in the formula below, where q is pitch rate in radians per second (one radian equals 57.3° ; and 0.1 radian/second is approximately 1 RPM). l_T is the distance between aircraft c.g. and the aerodynamic center of the tail. V_T is the velocity of the tail (taken tangentially to the aircraft's flight path).

Thus the faster you pitch, and/or the farther back your tail, the greater the change in α_T , but it's all inversely proportional to speed, V_T , as the formula shows.

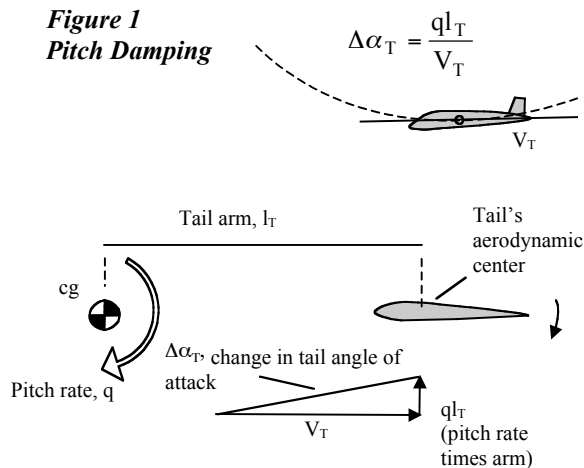
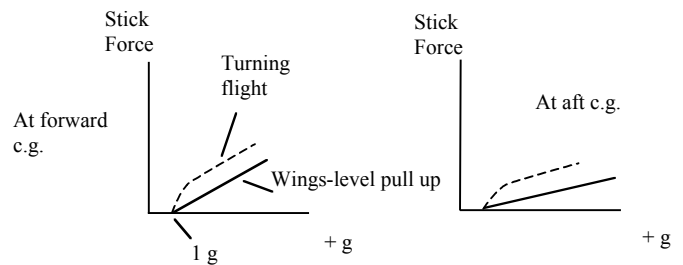


Figure 2
Stick force-per-g gradient versus c.g.



The actual tail angle of attack will also depend on the increased downwash produced by the wing as its lift coefficient rises in the pull-up, and a proper formula would take that into account.

Because of pitch damping, an aircraft is actually more stable in maneuvering flight than in flight at 1-g. Remember, we assess stability in terms of the force needed to displace the aircraft from equilibrium (trim). We assess static stability in terms of the push or pull on the stick necessary to change the coefficient of lift, C_L , and to produce airspeeds different than trim, while flying at 1-g. In maneuvering flight at more than 1-g, pitch damping increases the stick force we have to apply to displace the aircraft from equilibrium. How rapidly stick forces will increase as we increase g depends on the maneuvering characteristics for which the aircraft was designed, and its c.g. location. We can examine an aircraft's *stick-fixed* (elevator position-per-g) and the really more germane—since it's what the pilot feels—*stick-free* (stick force-per-g) maneuvering characteristics.

Figure 2 shows how the gradient, or slope, of stick force-per-g depends on the location of the aircraft c.g. Forward c.g. increases an aircraft's

Longitudinal Maneuvering Stability

maneuvering stability, and therefore stick forces become heavier. As you move the c.g. back, stick forces required to pull g go down. (The stick *position*-per-g curve behaves similarly. As c.g. moves aft, the deflection required to pull g goes down.)

Stick force-per-g also varies directly with wing loading (aircraft weight divided by wing area). Highly wing loaded aircraft may need the help of a powered control system to keep forces in check. Raising the wing loading has the same effect as moving the c.g. forward.

Stick force-per-g is a particularly important parameter and one of the basic handling quality differences between aircraft designed for different missions. When we maneuver an aircraft, we tend to evaluate its response in terms of the *force* we apply to the stick rather than the change in stick *position*. We know the stick has returned to the equilibrium trim position, for example, when the force disappears (at least ideally—friction and other factors can get in the way). And when we move the c.g. well aft in an aircraft—or take that first aerobatic flight—it's the reduction in stick forces we probably notice first.

Fighters and aerobatic aircraft require lower forces-per-g than do normal or transport category aircraft because their g envelopes are wider and the total stick force necessary at high g would otherwise be too great for the pilot to sustain. So a fighter operating at up to 9-g or more needs a shallower force-per-g gradient than a transport expected to operate at no greater than the 1.5-g approximately required for a 45-degree-bank level turn. The fighter's shallow force-per-g gradient would be devastating in a transport because the pilot could easily overstress the aircraft. The transport's steeper gradient would have the fighter pilot pulling with both hands while pushing on the instrument panel with his feet.

The importance of stick force-per-g in fighters became apparent during World War II. It was decided that the upper limit should be about 8 lb/g to keep the pilot from tiring in a fight, with a lower limit of 3 lb/g to prevent overstressing the aircraft and losing by default.

Overstress is the big worry; so FAR Part 23.155 specifies the *minimum total* control force necessary to reach an aircraft's positive limit

maneuvering load factor (g limit). It's based on aircraft weight and the type of control. For wheel controls the minimum force has to be at least 1% of the aircraft's maximum weight or 20 pounds, whichever is greater, but doesn't have to exceed 50 pounds. For stick controls, minimum force for maximum g has to be at least max weight/140, or 15 pounds, whichever is greater, but doesn't have to exceed 35 pounds.

To figure out what that would mean in terms of required average *minimum* control-force-per-g gradient, you can take the design load limit of the airplane (6-g's for our trainers), subtract 1-g to get the maximum g-load actually applied, and then divide that into the minimum total force required by regulation. For the Air Wolf (6-g's and 2900 lbs. maximum aerobatic weight):

$$\frac{2900 / 140}{5} = 4.1 \text{ lb/g minimum allowable stick force}$$

A Cessna 172's yoke force is greater than 20lb/g. A wings-level, 1.7-g pull-up in a Boeing 777 requires 135 pounds. The Boeing is certified under FAR Part 25, which actually doesn't contain sustained maneuvering control force requirements.

The FARs doesn't specify *maximum* stick-force-per-g, but the military does, depending on the type of aircraft.

Aircraft with shallow stick force-per-g gradients can feel dramatically sensitive if your muscle memory expects greater forces. Even experienced aerobatic pilots stepping up to higher performance aerobatic aircraft usually find themselves pulling too hard, detaching the boundary layer, and buffeting the aircraft—especially in the excitement of aerobatic competition. This is seen from the ground as an abrupt flattening in the arc of a loop, and from the cockpit as a sudden g-break. But after one becomes accustomed to those shallow gradients, the lower performance aerobatic aircraft one trained in can seem disagreeably reluctant to maneuver. The physical effort now feels out of proportion to the result.

On the other hand, pilots of early swept wing fighters had to worry about "g-limit overshoot" because of the forward shift in the center of lift as the tips began to stall. The F-86E Sabre Aircraft Operating Instructions cautioned pilots

Longitudinal Maneuvering Stability

against “A basic characteristic toward longitudinal instability under conditions of high load factor, which ... results in a tendency to automatically increase the rate of turn or pull-up to the point where the limit load factor may be exceeded.” Fortunately, this was preceded by lots of warning buffet.

As noted, pitch damping depends on pitch rate. Pitch rate depends not just on how hard you pull, but also on the kind of maneuver you’re pulling in. *At a given load factor, n* , (where n = lift/weight) a level turn actually requires a higher pitch rate than a wings-level pull-up.

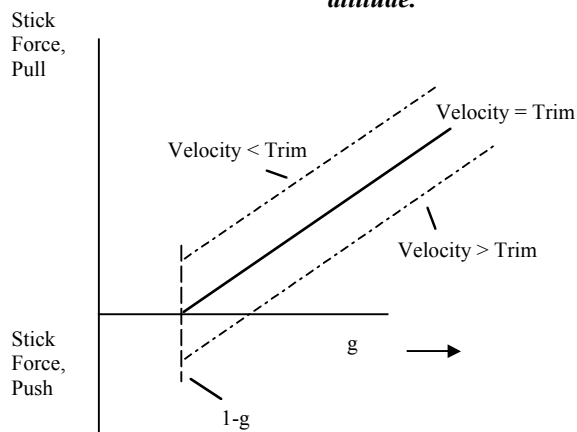
For a level (constant altitude) turn at a given velocity, pitch rate is a function of $n - 1/n$, but for a wings-level pull-up it’s the smaller function of $n - 1$. That greater pitch rate in the level turn means more pitch damping. As a result a 2-g turn, for example, requires more stick force than a 2-g pull-up. Accordingly, a high-performance turn takes more pilot muscle than a loop entry at the same load factor. See the dotted versus the solid lines in Figure 2.

Our trainers have reversible controls (wiggle an elevator by hand and the stick wiggles as well). In aircraft with reversible controls, at any given altitude and c.g., the gradient of the stick force-per-g curve is independent of airspeed. Figure 3 shows how the gradient remains constant as airspeed shifts from trim. The figure also shows how the absolute stick force needed to obtain a given g will depend on the relationship between trim speed and actual airspeed. For example, when the aircraft is flying slower than trim, static stability leads to a nose-down pitching moment, which adds to the pull force a pilot has to hold to maintain a given g . But when flying faster than trim, static stability leads to a nose-up pitching moment that decreases the pull force necessary to maintain a given g . Because of the change in absolute stick force necessary to hold a given g at speeds slower or faster than trim, test pilots try to maintain trim speed when examining stick-force-per-g in “windup turns.” Otherwise the data would plot an inaccurate stick force-per-g gradient.

The stick force needed to pull a given g remains the same at any trim speed. Say the trim speed rises. Because the elevator’s effectiveness increases with airspeed, you don’t have to deflect it as much to produce a given pitch rate and load factor as you do at lower speeds. Less deflection

would mean *lower* forces, except that control surface hinge moments—which are what the pilot feels through the control system gearing—also increase with airspeed. The decrease in required deflection is canceled out by the increase in hinge moment, and the stick force required for a given g load is the same at all trim velocities (at a constant altitude and c.g.). This holds as long as compressibility effects associated with high Mach numbers don’t become a factor. Compressibility tends to produce an increase in stick force-per-g.

Figure 3
Stick force-per-g gradient is constant at constant cg and altitude.



Longitudinal Maneuvering Stability

Damping versus Altitude

While static stability is not a function of altitude, maneuvering stability is. Stick force-per-g goes down as you go up. That's because damping decreases along with the decrease in air density as you climb.

At least that's the short explanation. Actually, in responding to a given control input an airplane doesn't care about altitude, it cares about airspeed. Compressibility effects aside, for a given input it will generate the same pitching (or rolling or yawing) moment at a given EAS (equivalent airspeed, meaning calibrated airspeed corrected for compressibility) regardless of whether it's flying down low or up high. But the damping this moment has to overcome is a function of altitude, because damping is a function of TAS (true airspeed, or equivalent airspeed corrected for density altitude), as Figure 4 explains. TAS goes up as altitude increases.

The figure shows that for a given pitch rate, q , the velocity component generated by the movement of the tail, ql_T , is the same regardless of altitude. But since true airspeed is higher at altitude, the vectors add up to less change in tail angle of attack, and so less damping.

This is why an airplane will feel more responsive and less stable at altitude, or perhaps even lower down on a hot, high-density-altitude day. The reduction in damping also applies to an aircraft's directional and lateral stability. Stability augmentation systems, like yaw dampers, earn their keep up high.

Tail Volume

Stability depends on the restoring moment supplied by the horizontal tail being greater than the destabilizing moments caused by the other parts of the aircraft. One factor is the tail-volume coefficient, \bar{V} . This is the product of the distance between the aircraft c.g. and the tail's aerodynamic center, l_T , times the tail area, S_T . The result is then divided by the mean aerodynamic chord of the wing, \bar{c} , times the wing area, S .

$$\bar{V} = \frac{l_T S_T}{\bar{c} S}$$

In other words, the tail volume coefficient relates the area of the tail and its distance from the c.g.

Figure 4
Damping and
TAS

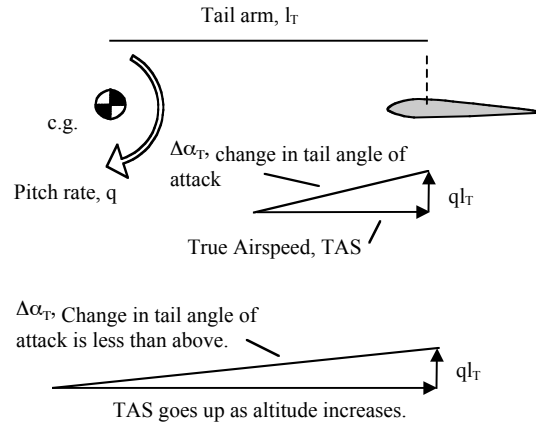
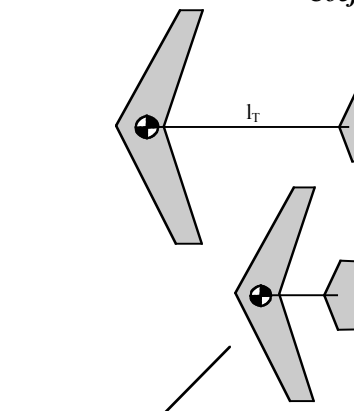


Figure 5
Tail Volume
Coefficient



Same tail volume coefficient as above, but shorter l_T . Less pitch damping makes the aircraft more maneuverable.

to the chord and area of the wing. It suggests how effective the tail is going to be at producing pitching moments. You can achieve a given tail volume for a wing of a given size either by having a small tail on a long fuselage, or a large tail on a short fuselage (Figure 5).

Longitudinal Maneuvering Stability

Since *pitch damping is a function of the square of the tail's lever arm, l_T^2* , the farther back your tail is the greater the opposing aerodynamic damping generated when you start pitching it around to maneuver. The design criterion for rapid maneuvering is a big tail on a short fuselage—a hallmark of modern fighter design. Transports have proportionately smaller tails on longer fuselages.

Neutral Points Again

Figure 6 adds the stick-fixed *maneuver* neutral point and the stick-free *maneuver* neutral point to the stick-fixed and stick-free *static* neutral points discussed in the ground school briefing “Longitudinal Static Stability.” The aft shift of the corresponding maneuver points reflects the stabilizing effect of pitch damping. Because damping goes down with altitude, the maneuver points actually sneak forward as you climb.

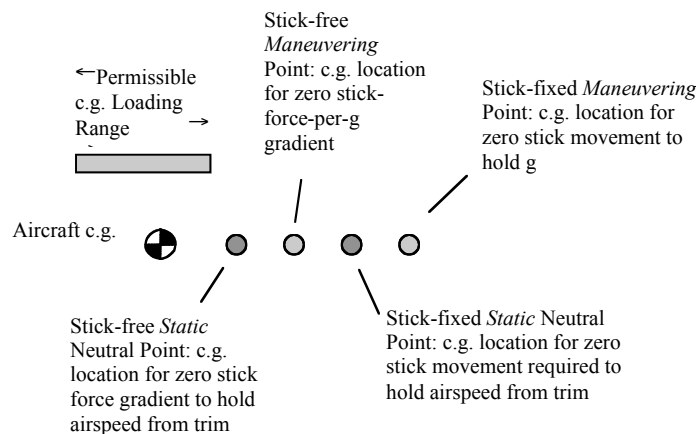
The stick-free maneuver point is the c.g. position at which the gradient of stick force-per-g becomes zero. The more rearward stick-fixed

maneuver point is the c.g. position at which stick movement-per-g becomes zero.

If we had a weight on rails and could move the c.g. rearward during flight, the first thing we'd notice is a reduction in control force necessary to change α and thus airspeed from trim (static stability), accompanied by a reduction in stick force needed to pull g (maneuvering stability). Short of shifting the c.g., a knowledgeable instructor can simulate this for a student by manipulating the trim.

As tail volume increases, the neutral points move aft. This in turn increases the aft c.g. loading range.

Figure 6
Stick-fixed and free
Neutral Points



Typically for inherent stability and good handling qualities for an aircraft with reversible controls, maximum permissible aft c.g. must be ahead of all static and maneuvering neutral points, and forward of the point for minimum allowable stick-force-per-g. Maximum forward c.g. is determined by control authority need to raise the nose to C_{Lmax} , or by the maximum allowable stick-force-per-g.

Longitudinal Maneuvering Stability

Flightlab Ground School

7. Longitudinal Dynamic Stability

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Introduction to Stability

Stability is the general term for the tendency of an object to return to equilibrium if displaced.

Static stability is an object's *initial* tendency upon displacement. An object with an initial tendency to return to equilibrium is said to have *positive* static stability. For those blessed with a conventional pilot's education, the concept of stability normally evokes the textbook image of a marble rolling around in something like a teacup, as shown in Figure 1.

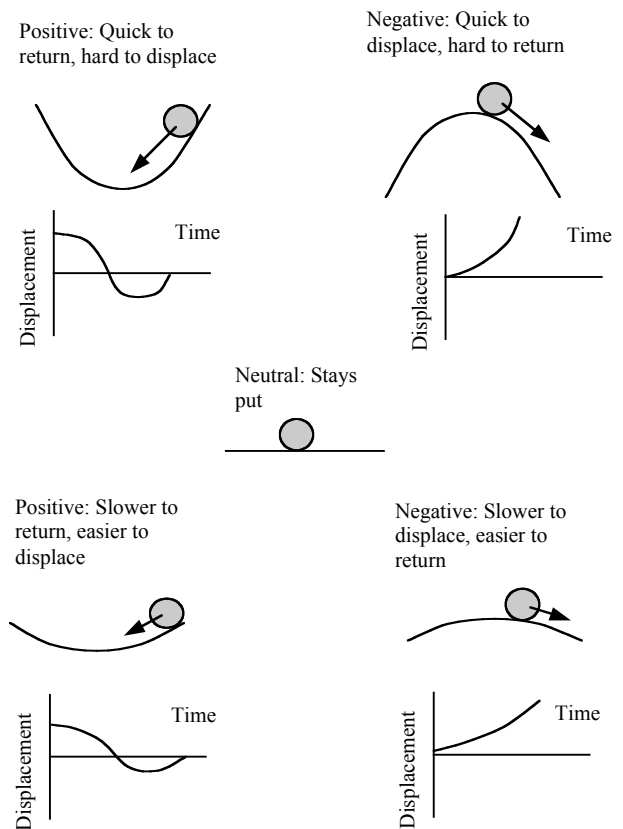
An airplane can't be trimmed unless it has longitudinal (around the y axis) static stability—in other words, unless pitching forces tending to equilibrium are present. But the greater an aircraft's static stability (thus the greater the forces tending to equilibrium) the more resistant the aircraft is to the displacement required in maneuvering. For a given aircraft, the most important factor in determining longitudinal static stability is c.g. position. Moving the c.g. aft reduces static stability.

Dynamic stability, our real subject here, refers to the time history that transpires following displacement from equilibrium, as shown in Figures 1 and 2.

Aircraft can either have *inherent* aerodynamic stability (the typical case), or *de-facto* stability, in which stability requirements are met with the aid of a control system augmented with sensors and feedback. For example, in order to achieve maximum maneuverability, the F-18 lacks inherent stability, and can't be flown without some operational brainpower on board in addition to the pilot. The Boeing 777 has *relaxed* inherent longitudinal static stability, which produces efficiencies in cruise from a more rearward c.g. and a physically lighter tail structure than otherwise possible. Boeing transport aircraft have conventional downward-lifting tails that, like all such tails, in effect add weight to the aircraft by virtue of the "down-lift"

they generate (and also drag, the by-product of that lift). The main wing has to produce additional lift in compensation, and consequently produces more drag itself, which costs money at the gas truck. Moving the c.g. aft reduces the necessary down-force. The 777's digital flight computers make up for the resulting longitudinal stability deficit—but the aircraft still has to have sufficient inherent stability to be flown safely and landed should the digital augmentation go bust. The monster Airbus A380 employs an aft center of gravity for the same reason. It can pump fuel aft to shift the c.g.

Figure 1
Static Stability



Longitudinal Dynamic Stability

Figure 2
Dynamic Stability

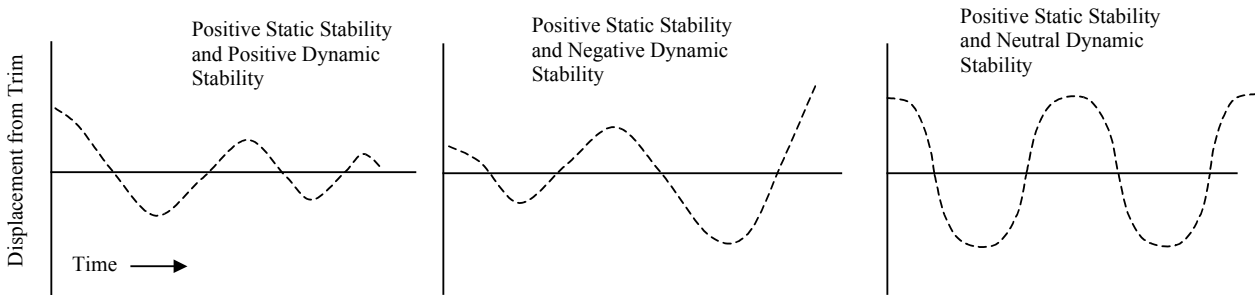


Figure 3
Positive Dynamic Stability

Dynamic Stability: Short Period and Phugoid

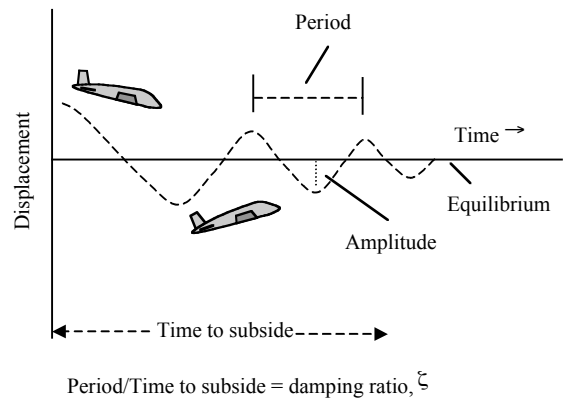
Figure 3 illustrates positive longitudinal dynamic stability: a series of damped oscillations of constant period, or frequency, and diminishing amplitude, that bring the aircraft back to the trimmed condition after a displacement.

Period is time per cycle. *Frequency*, which is inversely proportional to period, is cycles per unit of time. *Amplitude* is the difference between the crest or the trough and the original equilibrium condition.

Damping is the force that decreases the amplitude of the oscillation with each cycle. The *damping ratio*, ζ , is the time for one cycle divided by the total time it takes for the oscillation to subside. The higher the damping ratio, the more quickly the motion disappears.

Damping defines much about the character of an aircraft. If damping is too high, an aircraft may seem sluggish in response to control inputs. If damping is too low, turbulence or control inputs can excite the aircraft too readily; its behavior appears skittish.

There are two modes of pitch oscillation: the heavily damped *short period mode* (damping ratio about 0.3 or greater), followed by the

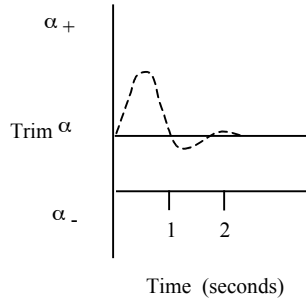


lightly damped, and more familiar, long period, *phugoid* mode. When you maneuver an airplane in pitch by moving the stick forward or back, you initially excite—and essentially just ride through—the short period mode. If you were then to let go or to return the stick back to the trim position, the aircraft would enter the phugoid mode. Instead, you normally hold the pressures necessary to prevent a phugoid from occurring.

Short Period

The short period mode is excited by a *change in angle of attack*. The change could be caused by a sudden gust or by a longitudinal displacement of

Figure 4
Short Period



the stick. Figure 4 shows the variation in angle of attack, α , over time. The aircraft quickly overshoots and recovers its original angle of attack, or its new angle of attack in the case of an intentional pilot input and a new stick position. The motion of the tail causes most of the damping, although other parts of the aircraft can contribute to damping (or to oscillation). There's negligible change in altitude or airspeed by the time the mode subsides. During the short period oscillation the aircraft pitches around its c.g.

Positive damping of the short period is important because catastrophic flight loads could quickly build from a divergent oscillation—suddenly the airplane has oscillated into parts. The short period mode is also an area in which pilot-induced-oscillations, PIO, can occur, because the typical lag time in pilot response is about the same as the mode's period (approximately 1-2 seconds). As a result, by the time a pilot responds to an oscillation his control input is out of phase, and he ends up reinforcing rather than counteracting the motion he's trying to correct.

At some point during our flights, we can perform a *frequency sweep* with the stick to try to isolate the aircraft's short period natural frequency, ω_n . (As a child you pumped a swing in rhythm with its natural frequency to make it go higher and terrify your mother.) We'll do this by moving the stick back and forth over a constant deflection range of perhaps three or four inches, but faster and faster until we find the input frequency that places us 90 degrees out of phase—meaning that the stick is either forward or back when the nose is on the horizon (although it can be hard to tell). We're then at the undamped short period natural

frequency—undamped because we're driving it with the stick. Then we'll abruptly return the stick to neutral when the aircraft is at its trim attitude, and observe the damping of the short period oscillation. It subsides very quickly, as in Figure 4.

The frequency sweep is not occupant friendly, but it's a good way to assess an aircraft's pitch acceleration, or "quickness." The high pitch acceleration—the ability to quickly change angle of attack—is one of the first things you'll notice when transitioning to high-performance aerobatic aircraft. You can think of an aircraft's natural frequency in terms of its ability to "follow orders"—how rapidly you can tell it to do one thing, then tell it the opposite, and still have it respond. The higher the natural frequency, the more response cycles you can coax from it per unit of time. As we do our sweep, you'll notice that past a certain point you can't coax any more. Then the faster you move the controls back and forth the less the aircraft responds. It's as if the aircraft figures that you can't make up your mind, and that you need to be ignored.

An aircraft with a low natural frequency may seem initially unresponsive to control input. A pilot may then over control, using a large initial input to get things going, only to find that the aircraft's final response is excessive. If the natural frequency is too high, the aircraft will feel too sensitive in maneuvering and too responsive to turbulence.

Aircraft with low short period damping ratios tend to be easily excited by control inputs and turbulence, and the resulting oscillations take longer to disappear. Aircraft with high short period damping can be slow to respond—they're sluggish, and the control forces seem high.

(We'll also look at our trainer's quickness in roll. The notion of a natural roll frequency doesn't really apply, because an aircraft isn't supposed to oscillate in roll. Oscillatory response is characteristic of "second-order" systems. First-order systems, like a rolling aircraft, are exponential and non-oscillatory. We'll do some "roll sweeps," anyway. You'll discover a similar fall-off in response.)

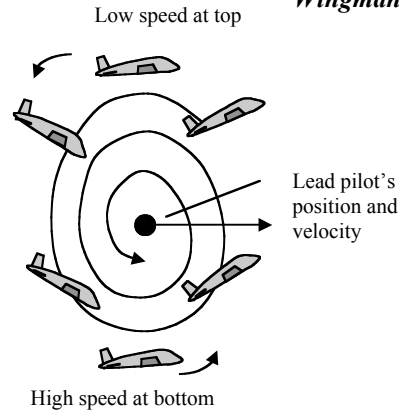
Long Period—Phugoid

The lightly damped, long period, or phugoid, oscillation can take minutes to play out. But it doesn't get to very often. Unlike the short mode, the phugoid period is long enough that the pilot can intervene easily and return the aircraft to equilibrium. We typically demonstrate the phugoid by pitching the nose up (thus exciting the short period mode) and allowing the aircraft to decelerate and stabilize some 15-20 knots below trim. Then we positively return the stick to its original trimmed position. The positive return overcomes any friction in the elevator system, and this keeps us from imposing an overall descent or a climb onto the phugoid. Usually it doesn't matter if you then hold the stick or let it go, since the difference between stick-fixed and stick-free is minor in the long period mode. But for consistency in response we want to keep the wings level. By using rudder for that job, we can avoid inadvertent pitch inputs. (On our flights we'll often enter a phugoid more theatrically, perhaps as the recovery from a spiral dive.)

From the nose-high attitude, the nose will begin to drop through the horizon into a descent, then pitch up and climb back up as speed increases. It then repeats the cycle, overshooting its original, trimmed airspeed/altitude point by less and less each time. *During the phugoid the aircraft maintains essentially a constant angle of attack, α , while cyclically trading altitude and airspeed (potential and kinetic energy) until it again regains equilibrium as in (Figure 3).* The pitch rate and the variation in maximum pitch attitude will diminish with each oscillation. Pitch attitude at the very top and bottom will be approximately the same as the original pitch attitude at trim. Minimum airspeed will occur at the point of maximum altitude, and maximum airspeed will occur at the point of minimum altitude.

The phugoid oscillation is typically damped and convergent, but it can be neutral, or even divergent, and the aircraft will still be flyable, because of the ease with which the pilot can bring the long period under control (you're controlling the phugoid whenever you hold altitude). But poor damping does increase the workload and complexity of the scan for instrument pilots when flying by hand, because the effort needed to hold altitude increases. Poor damping also makes it harder to trim an aircraft.

Figure 5
Phugoidal
Wingman



The undulating lines back in Figure 3 suggest how the phugoid would appear to a stationary observer. Figure 5 shows the same from the point of view of another pilot flying level in formation, watching a “phugoidal” (“phugoiding?”) wingman. The aircraft appears to rise and fall as airspeed changes produce lift changes. Excess airspeed at the bottom produces lift greater than weight and a resulting *upward* force. Diminished airspeed at the top produces lift less than weight and a resulting *downward* force. Remember, α stays the same.

As a result of the airspeed changes an aircraft in the phugoid would also appear to move back and forth, falling behind at the top of the cycle and scooting forward at the bottom, but less and less each time as the motion damps out.

Drag effects, rather than tail movement, damp the phugoid. Raising parasite drag increases damping. With both the short period and the phugoid mode, an aft shift in c.g., close to the neutral point, will begin to produce an increase in period and a decrease in damping (for *neutral point*, see ground school “Longitudinal Static Stability”).

Propellers add a damping factor absent with jets. If brake horsepower is constant, propeller thrust increases as airspeed decreases, and vice versa. This adds a forward force at the low-speed top of the phugoid and a restraining force at the high-speed bottom. This changing thrust/airspeed relationship helps reduce the speed variation from trim and thus helps damp the motion.

The phugoid is sensitive to coefficient of lift, C_L . At slow speeds, thus at high C_L , both the period and the damping decrease. At high speeds, thus at low C_L , both period and damping increase.

Regulations

FAR Part 23.181(a) requires that the short period oscillation must be “heavily damped” with the control free and fixed. FAR Part 23.181(d) requires that “Any ... phugoid oscillation ... must not be so unstable as to increase the pilot’s workload or otherwise endanger the aircraft.”

Part 25.181, for large aircraft, says the same thing about the short period, but leaves the phugoid unmentioned.

The common element in the regulations is the recognition that a pilot can readily control the long phugoid mode, and it’s not a crucial factor in flying qualities.

In regulatory practice, “heavily damped” means in no more than two cycles. Test pilots for the Raytheon Premier I took the aircraft to 35,000 feet to evaluate short period behavior in gusts. After pitching up and releasing the controls (stick-free), they found that the aircraft took approximately 2.5 cycles and 5 seconds to return to level flight. The FAA agreed that this presented no safety issues, but refused to wave their criteria (2 cycles and 4 seconds). The designers fixed things by adding wedges to the trailing edge of the elevator to change the hinge moments, making the elevator’s response to vertical gusts more neutral and bringing the aircraft into line with FAA requirements. All of this happened after an earlier modification had slightly reduced the friction in the elevator control system, which in turn reduced the damping ratio. The strange protuberances you see on aircraft often have complex histories.

Longitudinal Dynamic Stability

Flightlab Ground School

8. Maneuvering Loads, High-G Maneuvers

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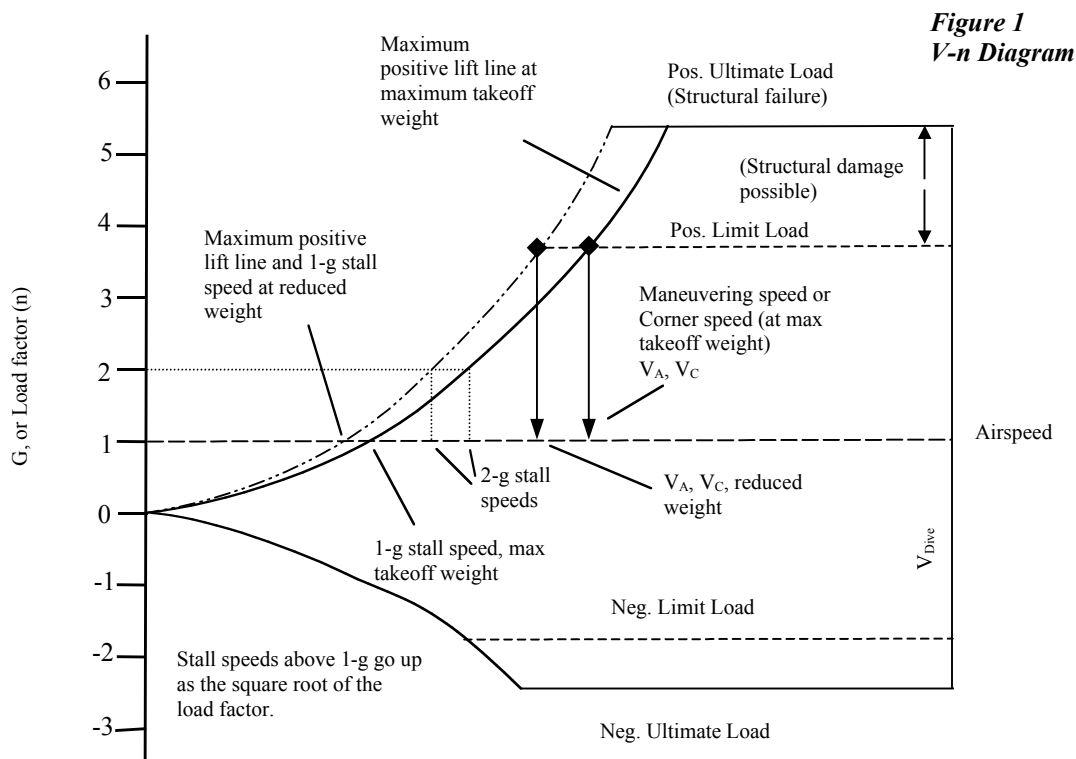
Maneuvering Loads and the V-n Diagram

The V-n, velocity-versus-load diagram, Figure 1, describes the relationship between an aircraft's speed, its longitudinal (pitch axis) maneuvering capability, and its structural strength. The positive-g, maximum lift line indicates how aggressively, at any airspeed, we can apply aft pressure to pitch an aircraft to change its flight path without stalling the wings or doing damage through excessive loads. The maximum lift line shows how our excess margin of nose-up pitch control (in other words, the load factor, or g, available in reserve) diminishes as we slow down, disappearing finally at the 1-g stall. At that point, in a normal aircraft, we can only pitch down.

The limits represented by the parabolic maximum lift line are also physiological, and

dramatically so. If you pull too hard, climb the lift line too high, and stay there too long, the blood starts leaving your brain. Your face becomes strikingly woeful in the video; your vision collapses from gray to black. Then consciousness shuts down. When the blood returns and the lights come on, your short-term memory is an empty hole. Amnesia is common enough in centrifuge trials that the USAF believes that many fighter pilots who experience g-induced loss of consciousness (G-LOC) never realize it.

Each V-n diagram is for a specific aircraft weight and wing configuration (lift devices in or out): see Figure 2. Indicated airspeed is generally used since it corrects IAS for position errors caused by the placement of the pitot and static sources, and by gauge errors within the airspeed indicator



Maneuvering Loads, High-G Maneuvers

itself. An aircraft will stall at the same calibrated airspeed regardless of altitude. If the gauge error depends only on airspeed, the aircraft will stall at the same indicated airspeed, regardless of altitude.

The maximum lift line, or $C_{L_{max}}$ boundary, takes its parabolic shape from the fact that lift is a function of velocity squared (because lift is proportional to dynamic pressure, q , which is itself proportional to V^2). You can draw the lift line based purely on an aircraft's 1-g stall speed at a given weight. At least you can for speeds to about Mach 0.3. Above that, compressibility effects take over, $C_{L_{max}}$ declines, and the slope of the curve decreases.

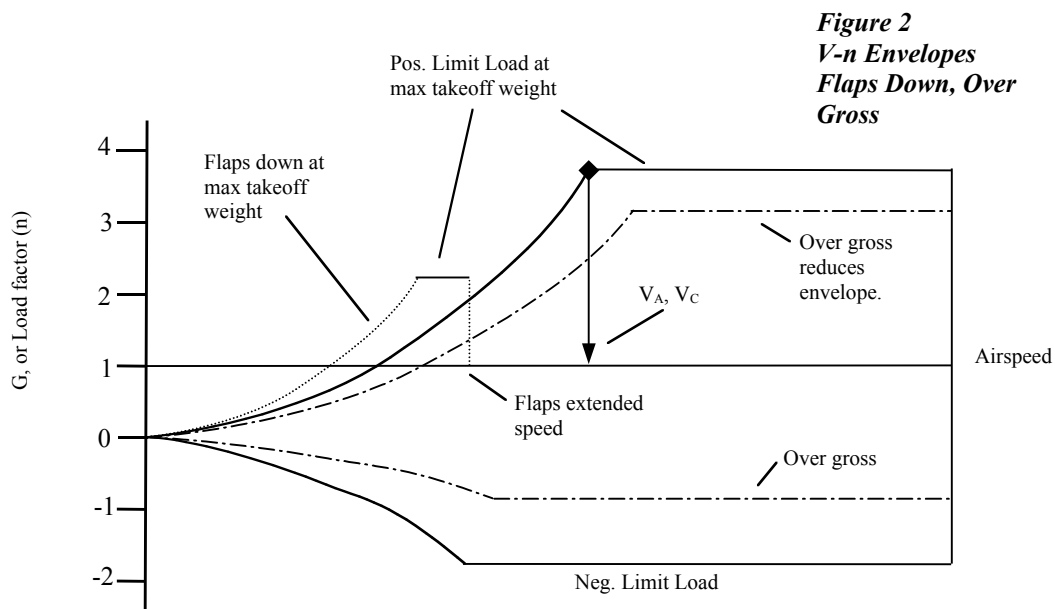
Load factor, n , ($n = \text{Lift}/\text{Weight}$) is what's read on the g meter. In normal, 1-g equilibrium flight, lift equals weight. In 2-g turning or looping flight, the aircraft produces lift equal to double its weight. Some of that extra lift goes to generate a centripetal force that accelerates the aircraft toward the center of an arc. Flight at more than 1 g is always associated with a pitch rate.

As you increase your pitch rate at a given airspeed, your g-load increases until you reach the maximum lift line and stalling angle of attack. Actually, before you hit the lift line you usually hit a buffet boundary, as airflow separated from the wing and fuselage starts

belaboring the tail. In aircraft with personality issues, the buffet boundary might be severe, or the aircraft might have a pitch-up tendency or a wing rock before reaching maximum coefficient of lift, $C_{L_{max}}$, in which case the operational boundary is defined by those characteristics rather than by an actual stall break.

The lift line represents the maximum load factor obtainable at the corresponding velocity. In a conventional aircraft you can't fly to the left of the line because the wing will stall first. The aircraft unloads itself. You might exceed the lift line briefly by a quick charge, since dynamic effects can allow airfoils to sustain lift momentarily at greater than normal stalling angle of attack, if angle of attack is increased at a high rate per second. But then you'd just fall back into the envelope as the momentary, extra lift disappears.

Stall speed goes up by the square root of the load factor. So at 2 g, for example, stall speed goes up by a factor of 1.4 (since $\sqrt{2} = 1.4$).



Maneuvering Loads, High-G Maneuvers

Maneuvering Speed, V_A

As defined by the V-n diagram, maneuvering speed, V_A , is the maximum speed at which an aircraft *in symmetrical flight at the specified flight weight and configuration* will stall (unload) before exceeding limit load and sustaining possible structural damage. Aircraft are therefore aerodynamically g-limited by the lift line up to maneuvering speed, and structurally g-limited by the load line above it. Maneuvering speed is also the maximum speed for turbulent air penetration, although a speed somewhat less—fast enough to avoid stall yet slow enough to diminish the loads experienced—is usually recommended. (In an aircraft subjected to a sharp vertical gust of given intensity, the increase in structural load—and thus the acceleration the pilot feels—varies directly with airspeed.)

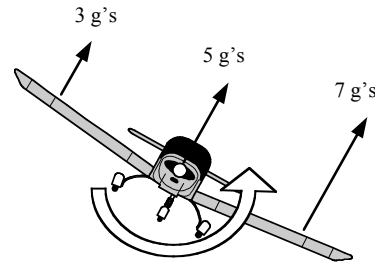
At speeds above roughly Mach 0.3, C_{Lmax} begins to decrease. Mach number depends on altitude, so indicated V_A increases with altitude because you have to go faster to generate equivalent lift at the lower C_{Lmax} .

Symmetrical flight means the aircraft isn't rolling and isn't yawed. The load is symmetrical across the span. That's not the case in a rolling pull-up, however, where the rising wing experiences a higher load than the wing going down (the rising wing is lifting more because of the camber change; the descending wing lifting less). The g meter in the fuselage reads only the average load, as in Figure 3.

Rolling pull-ups became a problem with the F4U Corsair gull-wing fighter in World War II. Reportedly, pilots would roll with aileron as they pulled out after a ground attack run, hoping to place the aircraft's protective armor plating between them and the answering ground fire. They sometimes went past limit load in the roll and came home with bent wings along with the usual shell holes.

V_A and limit load (as measured at the fuselage) therefore decrease if the aircraft is rolling. The rolling motion could come from aileron deflection, or from aggressive rudder input causing a roll couple (as in a snap roll). Aircraft flight manuals that specify a maximum limit load for rolling pull-ups typically place it at two-thirds to three-quarters of the symmetrical limit load. If you settle on a conservative two-thirds, a

Figure 3
Asymmetrical
Loads



Asymmetrical Load during Rolling Pull-up

6-g aerobatic aircraft has a rolling pull-up (and snap roll) limit of 4 g. To keep things in round numbers, the “rolling” V_A , as calculated for the aircraft weight, would be about twenty percent less than the symmetrical V_A .

By the same logic a large aircraft certified under FAR 25.337(b) with the minimum allowed limit load of 2.5 would be restricted to a 1.65-g rolling pull-up, assuming that Mach buffet, caused by the transonic acceleration of the airflow over the wing as angle of attack is increased, doesn't occur first.

Unload before rolling if you're in a high-g situation and need to level the wings.

The above notwithstanding, maneuvering speed is usually defined—without regard to asymmetrical loads—as the maximum speed at which full or abrupt combined control movements can be made without damaging the aircraft. The FAA's AC 61-23C, “Pilot's Handbook of Aeronautical Knowledge,” says that “any combination of flight control usage, including full deflection of the controls, or gust loads created by turbulence should not create an excessive air load if the airplane is operated below maneuvering speed.” According to the Navy, “Any combination of maneuver and gust cannot create damage due to excess airload when the airplane is below the maneuver speed.”¹

¹ Hurt, H. H. Jr., *Aerodynamics for Naval Aviators*, Aviation Supplies & Academics, Inc. 1965. p. 339. I understand that the FAA copied Hurt.

Maneuvering Loads, High-G Maneuvers

The NTSB has pointed out that this broader definition, although widespread among pilots, is incorrect. Engineers consider each axis separately in designing for the air loads accompanying an abrupt, full control input at maneuvering speed. “Full inputs in more than one axis at the same time and multiple inputs in one axis are not considered in designing for these [V_A] flight conditions.”²

The particular “multiple inputs” that prompted NTSB comment were the rudder reversals leading to a yaw over swing followed by a final reversal that destroyed the vertical tail of American Airlines Flight 587 on November 12, 2001. (Under FAR 25.351, rudders are tested for sudden displacement in a single direction at a time, and then returned to *neutral*, at speeds up to design dive speed.)

So here’s a conservative, inclusive, legalistic mouthful: ***Maneuvering speed, V_A, is the maximum speed, at a given weight and configuration, at which any one (and only one) flight control surface can be abruptly and fully deflected—not to include rapid control surface reversals—without causing aircraft damage.***

Simple Formulas

These formulas help define the relationships between aircraft weight, speed, and load.

(1) 1-g Stall Speed vs. Aircraft Weight:

Knowing the 1-g stall speed, V_S, at any weight gives you the 1-g stall speed for any other weight:

$$\sqrt{\frac{\text{New Weight}}{\text{Known Weight}}} \times (\text{Known } V_S) = \text{New } V_S$$

(2) Stall Speed and Load Factor: Stall speed goes up as the square root of the load factor, n. To find the accelerated stall speed, V_{Sacc}, for a given load factor:

$$V_{Sacc} = V_S \sqrt{\text{Load factor, } n}$$

(3) Maneuvering Speed, V_A. Given the 1-g stall speed, to determine an aircraft’s maneuvering

speed at maximum takeoff weight for upright flight in its category, use the formula above and substitute V_A for V_{Sacc}. Insert a load factor of:

- 3.8 for Normal & Commuter but see FAR Part 23.337(1).
- 4.4 for Utility
- 6 for Aerobatic
- FAR Part 25.337(b), 2.5 minimum

(4) Maximum Aerodynamic Load Factor for a Given Airspeed:

The highest load factor you can pull at a given airspeed is based on the 1-g stall speed, V_S, at the aircraft’s actual weight. You can use this to plot the lift line in the V-n diagram:

$$\left(\frac{\text{Airspeed}}{V_S} \right)^2 = \text{Load factor, } n$$

(5) Maneuvering Speed vs. Aircraft Weight:

Like other V speeds calculated on the basis of aircraft weight, maneuvering speed, V_A, goes down as aircraft weight goes down. If the aircraft is under max gross takeoff weight, the allowable limit and ultimate limit loads don’t change (so interpret the g meter as usual). Only the corresponding V speeds change as the maximum lift line shifts toward the left. Although the total lift force that the wing has to develop at limit load is less at lower weights, and the stress on the wing is less, individual aircraft components still weigh the same. Things like engine mounts, battery trays, luggage racks, chandeliers (it happens), and landing gear up-lock systems may not be designed to withstand more than their component weight times limit load. At lower gross weights that load can be reached at lower speeds because the wing doesn’t have to produce as much lift. Since it doesn’t have to work as hard, it won’t stall until after the limit load is exceeded.

To calculate V_A at reduced aircraft weight:

$$\sqrt{\frac{\text{New Weight}}{\text{Max Takeoff Weight}}} \times (\text{Max Takeoff } V_A) = \text{New } V_A$$

² NTSB Safety Recommendation, November 10, 2004.

Corner Speed

V_A is also known as *corner speed*, V_C , especially by fighter pilots, for whom it has tremendous tactical significance. V_C is the speed for maximum instantaneous turn performance without exceeding structural limits.

“Instantaneous” is used because an aircraft might not have the thrust necessary to sustain V_C under the elevated induced drag of maneuvering at high angle of attack. Sustained corner speed has a lower value.

Turn rate goes to maximum at corner speed.

That’s because turn rate is proportional to n/V_T (n is load factor; V_T is true airspeed). Combinations of high g and low airspeed favor turn rate. Corner speed is the lowest airspeed at which maximum structural g is possible. Flying at maximum structural g at any speed in excess of V_C causes turn rate to decrease.

A high turn rate is obviously important to fighter pilots because it allows them to achieve firing solutions in a turning fight.

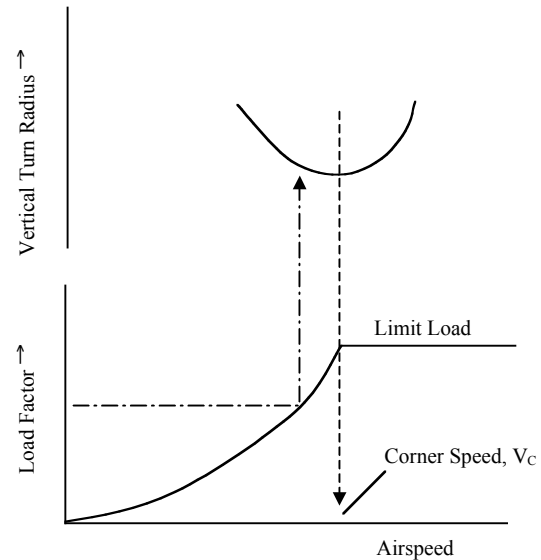
Turn radius goes to minimum at corner speed.

Turn radius is proportional to V_T^2/n . Therefore radius is minimized by high g and low airspeed. Again, corner speed is the lowest speed for the highest allowable structural g .

The top of Figure 4 suggests how the radius decreases as load factor rises. It decreases quickly at first, but then the rate of change per g slows down. Note that flying at maximum structural g at any speed in excess of V_C causes the turn radius to increase.

Low wing loading (aircraft weight/wing area) favors maneuverability. At a given C_L , minimum turn radius and maximum rate come when the aircraft is light. Higher air density (thus lower altitude) also favors maneuverability.

Figure 4
Pull-up Turn Radius
versus Corner Speed



Pull-ups

Corner speed is spoken of in discussions of turning flight, but remember that turning isn’t limited to the horizontal plane. The pull-up you may find yourself in during a nose-low unusual-attitude recovery is a vertical turn. Here, achieving minimum radius may be crucial. Figure 4 shows the relationship between corner speed and turn radius in a pull-up.

The strategy for a low-altitude, maximum-performance, minimum-radius, limit-load pull-up is to pull to and maintain C_{Lmax} (indicated by initial buffet, angle of attack indicator, stick shaker, fly-by-wire g limiter, unacceptable wing rock) until reaching corner speed, then remain at limit load until recovery.

The problem is blasting through V_C , (or starting the recovery past V_C) so you’ll want to have the drag devices out, pending approval from the POH/AFM. In propeller aircraft, that includes power back and flat pitch for more drag. Lowering the landing gear might blow off the doors or lead to a partial extension, but that could be a good trade. In a jet, what you do with power could depend on the pitching moment associated with power change. With fuselage-mounted engines, throttles would normally come back. But retarding power on an aircraft with

Maneuvering Loads, High-G Maneuvers

wing-pylon-mounted engines creates a *nose-down* pitching moment. Some speed brakes do the same. The POH/AFM is the guide. At low altitude, Mach buffets and Mach-related trim effects presumably would not be a factor.

Critics of the use of corner speed as part of recovery procedure point out that the speed varies with aircraft weight, and there's the "potential that pilots could fixate on obtaining and maintaining corner speed, while delaying or overlooking implementation of other recovery techniques, and result in [*sic*] unnecessary loss of altitude during a nose low recovery. Exposing pilots to the concept of corner speed and radius of turn as a basis for understanding why it may be necessary to increase speed in order to recover from a nose low, low altitude upset is beneficial. However, incorporating a corner speed into recovery procedure, we feel is inappropriate."³ Sounds like a sensible objection.

Student behavior suggests that the most common error is to be too gentle on the aircraft in the initial part of a dive recovery. For fear of overstressing the aircraft, pilots are reluctant to add normal acceleration (g's) to longitudinal acceleration (the aircraft's increasing speed), so they bring in the g slowly. But the induced drag created by the increased lift necessary for normal acceleration also acts as a brake on longitudinal acceleration. ***Pull smoothly—no yanking into an accelerated stall that actually lowers pitch rate—but if ground avoidance is at stake don't hesitate in getting to the maximum g (i.e., maximum pitch performance and minimum radius) the flight condition allows.***

Rolling is a limiting flight condition. If necessary, ***level the wings before a pull up. The asymmetrical load caused by aileron deflection, added to a pull-up load, can overstress the wing.*** Again, an aircraft's V_A and g-meter limit load decrease when rolling. And as pilots generally don't recognize, ***high adverse yaw generated by large aileron deflection while pulling could lead to high sideslip angles and bending stresses on the vertical tail.***

³ Attachment H, *Correspondence from Airplane Manufacturers to American Airlines and Response*. Exhibit Items from the Public Docket, NTSB Public Hearing American Airlines Flight 587 Belle Harbor, New York, October 29-November 1, 2002. (Link at www.nts.gov/events/2001/AA587/exhibits)

A wings-level pull-up is also more efficient, since the entire load is applied to lifting the nose to the horizon, and not partly to turning.

Pull-ups and Phugoids

The hands-off phugoids we fly at the beginning of our flight program demonstrate that a longitudinally stable aircraft will try to pull out of a dive by itself. The altitude consumed will depend on the true airspeeds and load factors attained.

At a given g at any instant, the radius of either a pilot-induced or a pure phugoid-induced pull-up varies with the square of the airspeed. As a result, for example, if you enter twice as fast, but your load factors remain identical, you'll consume four times the altitude.

(The g that actually matters in maneuvering performance is "radial g," explained farther on. Radial g depends both on the load factor seen on the g meter and on aircraft attitude.)

The phugoid-generated load factor depends on the design and balance characteristics of the control system, but more essentially on the difference between the airspeed attained and the trim speed. Remember that during the phugoid the aircraft maintains a constant angle of attack. At a constant angle of attack, lift goes up as the square of the increase in airspeed. For example, if we trim for 100 knots in normal flight (1 g) and reach 200 knots in a phugoid dive recovery, airspeed will be double the trim speed and the load factor will hit a theoretical 4 g. If we accelerate to 140 knots, it's a 1.4 increase in airspeed over trim. $1.4^2 = 2$; thus a load factor of 2 g.

A pilot can overstress an aircraft in a dive by a pull on the stick in addition to the aircraft's natural phugoid. Again, the load generated by the phugoid depends on trim speed versus airspeed. The required pull, or g-limiting push, depends on how this load compares to limit load.

The classic disaster pattern consists of the horizontal stabilizers failing downward first if the pilot pulls too hard. When they fail, the aircraft suddenly pitches nose down, and the wings fail *downward* because of the sudden negative load.

Lift Vector, Radial G, and the Split-s

In a level turn, as shown at the top of Figure 5, the tilted lift vector has two vectoral components, a vertical one equal to and opposite aircraft weight, and a horizontal one pointing toward the center of the turn. While the pilot feels (and the g meter reads) loads in the direction of the tilted lift vector, the horizontal, centripetal force that's actually turning the aircraft—its *radial g*—has a lower value.

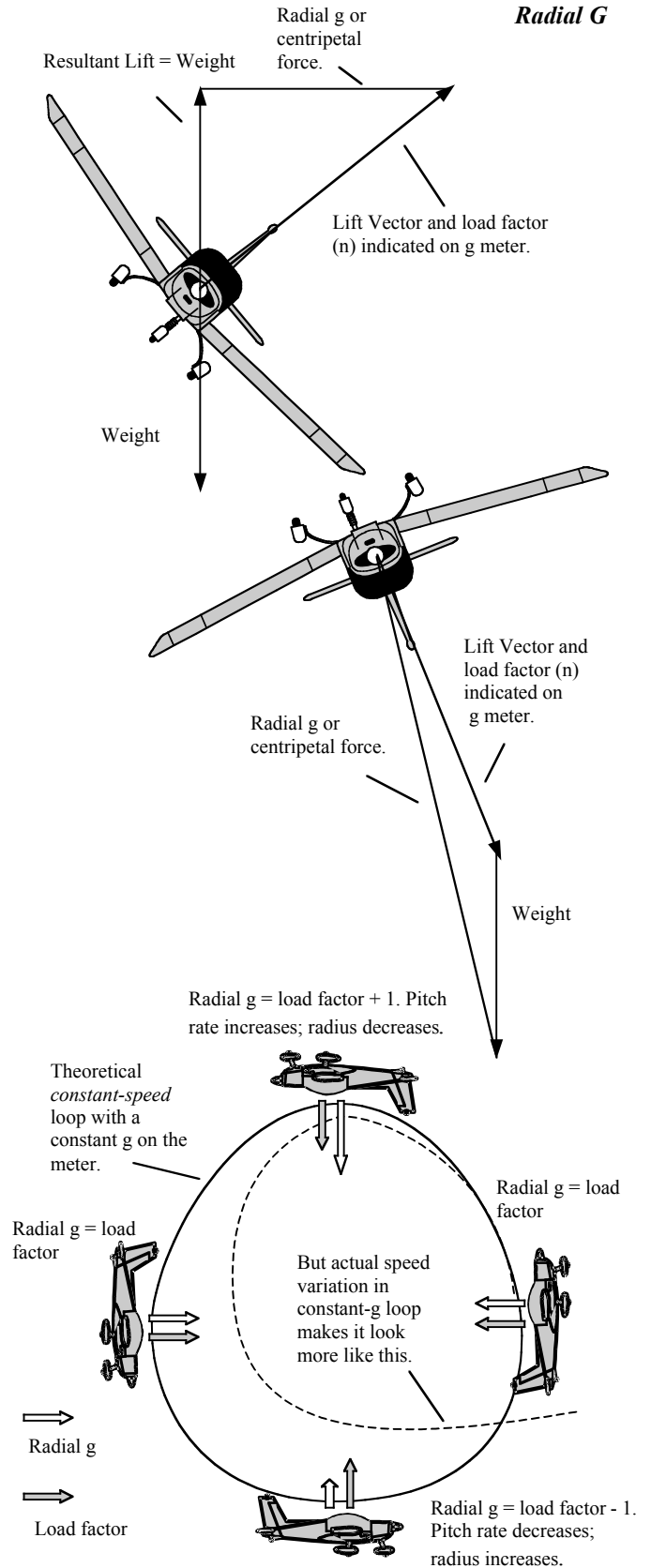
As bank angle increases in coordinated, constant-altitude flight, radial g grows. Past 90 degrees of bank, the lift vector starts pointing toward the earth, and radial g gets a boost from gravity. The result can be up to a 1-g gain in radial g in inverted flight at the top of a loop.

For a given load factor (g on the meter), pointing the lift vector above the horizon decreases radial g and pitch rate; pointing it below the horizon increases radial g and pitch rate. The increased radial g available in inverted attitudes can help win dogfights, but it's a trap for untrained pilots. It's why, at a given airspeed and applied g, positive (nose toward your head) pitch rates when flying inverted are higher than positive pitch rates when flying upright, and why pulling back on the stick as a reaction to the confusion of inverted flight so quickly brings the nose down and the airspeed up. The resulting split-s entry (half loop from inverted), especially if provoked by an inexperienced pilot who releases his aft control pressure out of contrition once the nose starts down, then changes heart and pulls some more, can quickly take the aircraft outside the envelope of the V-n diagram. That's when it rains aluminum.

In a nose-down, inverted unusual-attitude recovery, the most important thing is to get the lift vector pointed back above the horizon. Except at extreme nose-down attitudes, that means rolling upright rather than pulling through in a split-s. In brief: ***When inverted, push to keep the nose from falling further. Roll the lift vector skyward with full aileron while removing the push force as you pass through knife-edge. Then raise the nose.***

Just so you know, maximum structural instantaneous turn performance happens while pulling maximum g, at corner speed, inverted.

Figure 5
Radial G



Maneuvering Loads, High-G Maneuvers

Flightlab Ground School

9. Rolling Dynamics

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For Training Purposes Only

The Aircraft in Roll

The dynamics of an aircraft in roll are surprisingly complex, given the apparent simplicity of the maneuver. Of course, one person's complexity is just another person getting started. At the U.S. Navy Test Pilot School, for instance, "The classic roll mode is a heavily damped, first order, non-oscillatory mode of motion manifested in a build-up of roll rate to a steady state value for a given lateral control input."¹ Well, ok, that sounds right.

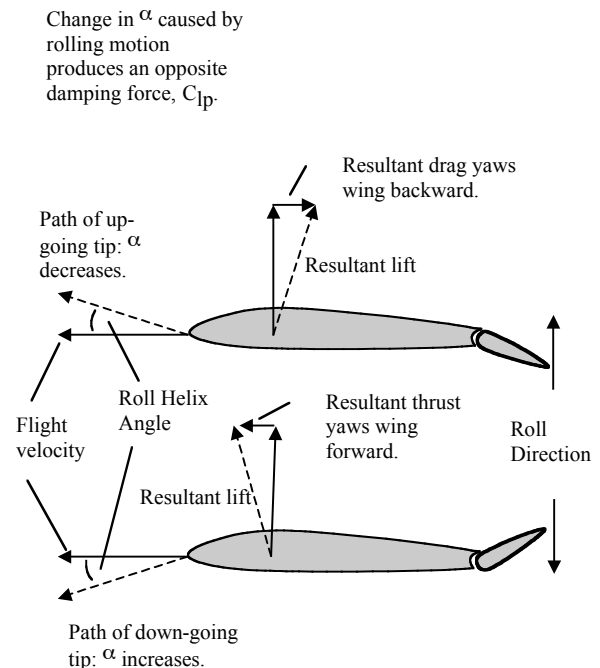
Our *Maneuvers and Flight Notes* training guide describes piloting technique during aerobatic or unusual attitude rolling maneuvers. Here the emphasis is on the general characteristics of aircraft response.

A roll starts with the creation of an asymmetric lift distribution along the wingspan. In the case of aileron roll control, deflecting an aileron down increases wing camber and coefficient of lift; raising the opposite aileron reduces camber and coefficient of lift. The resulting spanwise asymmetry produces a rolling moment.

As the aircraft begins to roll in response to the moment produced by the ailerons, the lift distribution again begins to change. The rolling motion induces an angle of attack increase on the down-going wing, and an angle of attack decrease on the up-going wing (Figure 1). This creates an opposing aerodynamic moment, called roll damping (or rolling moment due to roll rate, C_{lp}). Roll damping increases with roll rate (and varies with other factors we'll get to). When the damping moment produced by the roll rate rises to equal the opposing moment produced by the ailerons, the roll rate becomes constant.

In Figure 1 you can see that as the airplane rolls, the lift vector tilts to accommodate itself to the new direction of the relative wind, creating new vectors of thrust and drag. As a result, the rolling motion produces adverse yaw all by itself, a yawing moment that goes away when the roll stops. This yaw due to roll rate, C_{np} , is in addition to the adverse yaw created by the displaced ailerons, and increases with coefficient of lift. Depending on wing planform, at aspect ratios above 6 or so, adverse yaw due to roll rate actually becomes more significant than that due to aileron deflection.

Figure 1
Roll Damping, C_{lp}
Yaw due to Roll Rate, C_{np}



¹ U.S. Naval Test Pilot School Flight Test Manual: Fixed Wing Stability and Control, USNTPS-FTM-No. 103, 1997. p. 5.55.

Adverse Yaw, $C_n \delta_a$

Aerodynamic coupling effects keep rolling from being a one-degree-of-freedom proposition. Rolling moments come with yawing moments attached, and those yawing moments affect roll behavior.

Induced drag increases when an aileron goes down, decreases when an aileron goes up. The result is usually an adverse yawing moment, opposite the direction of roll. In the absence of a sufficient counteracting yaw moment—supplied in part by the aircraft’s inherent directional stability, in part by aileron design, and in the remainder by coordinated rudder—the aircraft will begin to sideslip. The velocity vector will shift from the plane of symmetry toward the roll direction if too little coordinating rudder is applied, and shift opposite the roll direction if the rudder gets too emphatic an in-turn boot. In a perfectly coordinated, ball-centered roll and turn, with adverse yaw properly countered by rudder deflection, the “instantaneous” velocity vector remains on the plane of symmetry, as Figure 2 describes.

The rudder deflection necessary to handle adverse yaw depends on the ratio of yaw moment to roll moment the ailerons produce. While the ratio is basically a function of the aileron system design, it increases with coefficient of lift, C_L . This means that as airspeed goes down, the need for rudder coordination becomes greater. The nature of induced drag rise at high angles of attack is the major reason, since induced drag increases as the square of the coefficient of lift. As the drag curve becomes steeper, a given aileron deflection produces a greater difference in induced drag across the span, and the yaw/roll ratio increases. Differential or Frise ailerons, initially designed to reduce aileron *forces*, also reduce adverse yaw by increasing the drag of the up-going aileron.

Another factor is the reduction in directional stability caused by the disrupted fuselage wake at angles of attack approaching stall. Because energy is removed from the free stream, more rudder deflection is needed as weathercock stability goes down in the tired-out air.

Configuration is also important. Partial-span flaps cause an aircraft to fly at a more nose-down angle for a given overall coefficient of lift. As a

result, the aileron portion of the wing experiences a relative washout (leading edge down) and generates a lower local coefficient of lift than when the flaps are up. That lower local coefficient translates into less adverse yaw. Flaps also reduce dihedral effect, so the sideslip that does occur has less effect on roll.

Spoilers

Spoilers are generally thought to produce proverse, roll-direction yaw, but they can cause adverse yaw. Spoilers increase profile drag. They also decrease induced drag, since they kill lift. When the increase in profile drag predominates, as it does at high speed, spoilers can generate proverse yaw. At low speeds, when induced drag is more important, they can generate adverse yaw, since the induced drag on the wing going down, the one with the deflected spoiler killing lift, is less than on the wing going up, where the spoiler remains tucked away.

Spoilers are useful in situations when aeroelastic aileron reversal could have been a problem (B-52, and just about all of the swept-wing, high aspect ratio transports that followed), or when it’s necessary to extend the wing area available for flaps. They have an advantage over ailerons of producing powerful rolling moments at high angles of attack, but the disadvantage of lesser moments at low angles. The classic problem with spoilers is a possible nonlinear response as their location moves forward on the wing. Small deflections may generate no roll, or even a temporary reversed roll response. (As the spoiler first rises, the tripped airflow can reattach to the wing. This results in an effective increase in camber and therefore in lift. Spoiler movement has to be nonlinear with control wheel or stick movement—so that the spoilers can quickly pop up high enough to defeat any tendency for the airflow to reattach.) Many designs use spoilers and ailerons in combination, with the ailerons providing both rolling moment and control feel, and a possible way of overcoming nonlinear spoiler response.

If you’re stuck in coach, the most entertaining window seat on a Boeing is just back of the trailing edge, where you can watch the slot-lip spoilers being used for bank control when the flaps are extended. When the spoilers rise, the slots above the flaps open up. The change in pressure pattern reduces the lift gained from flap

Rolling Dynamics

deployment and causes the aircraft to roll. Deployed symmetrically, the spoilers provide aerodynamic braking.

A pilot who looks up to find himself flying inverted in a spoiler-equipped aircraft has a quandary, since spoilers become more effective at higher coefficients of lift (higher α). Does that mean the pilot should pull while inverted, to increase roll response, at the risk of altitude loss and airspeed gain from the resulting nose-low attitude? It's hard to find someone with a satisfactory answer. Aggressive use of the rudder might be warranted to help roll the aircraft using dihedral effect and roll due to yaw rate.

Turn Coordination

Usually, we roll in order to turn. Steep turns deserve to be regarded as unusual attitudes, not just because of the high bank angles but also the high-gain response those angles require when you're trying to be perfect. The concentration level goes up when you fly a steep (45-degree plus), coordinated turn, while holding altitude.

We've defined coordination during roll in terms of keeping the velocity vector on the plane of symmetry. While the ailerons are deflected, that means using rudder to correct for adverse yaw and yaw due to roll rate—companion phenomena whose relative magnitudes can be difficult to figure out, but then you don't have to figure: just push the rudder to center the ball.

Once the bank is established, the ailerons move to the position necessary to maintain the bank angle. Rudder into the turn is often needed to counteract yaw damping, C_{nr} , caused by the fuselage and tail resisting the yaw rate and by the outside wing moving faster than the inside wing and producing more drag. That might be the predicament shown in the center aircraft at the bottom of Figure 3. An over-banking tendency requires aileron deflection against the turn—possibly causing proverse yaw (since the inside aileron is down), which of course modifies the rudder requirement.

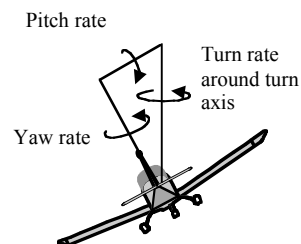
The gyroscopic precession of the propeller creates a force parallel to the vertical turn axis. Therefore, precession causes the nose to move perpendicularly to the horizon, regardless of bank angle. For a clockwise propeller as seen from the rear, that means nose down turning

right, nose up turning left. At high bank angles, when the aircraft's y-axis approaches alignment with the turn axis, more rudder deflection may be needed to counter precession. Step on the ball.

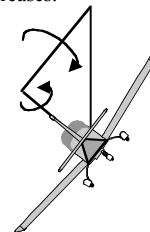
Banked turns are combinations of yaw and pitch (Figure 2). Coordination (keeping the velocity vector on the plane of symmetry) means establishing both the yaw rate and the pitch rate appropriate for the bank angle.

As bank angle increases, pitch rate becomes increasingly sensitive. Pitch rate controls load factor, and **for a constant-altitude turn, the required load factor goes up exponentially with bank angle**. Getting the pitch rate/load factor right at high bank angles is difficult because the load requirements change so rapidly with even small changes in bank angle. Because the load factor goes up exponentially, so do the stick forces, at least in aircraft with reversible elevator controls.

Figure 2
Relative Yaw and
Pitch Rates.
Constant-
Altitude Turn

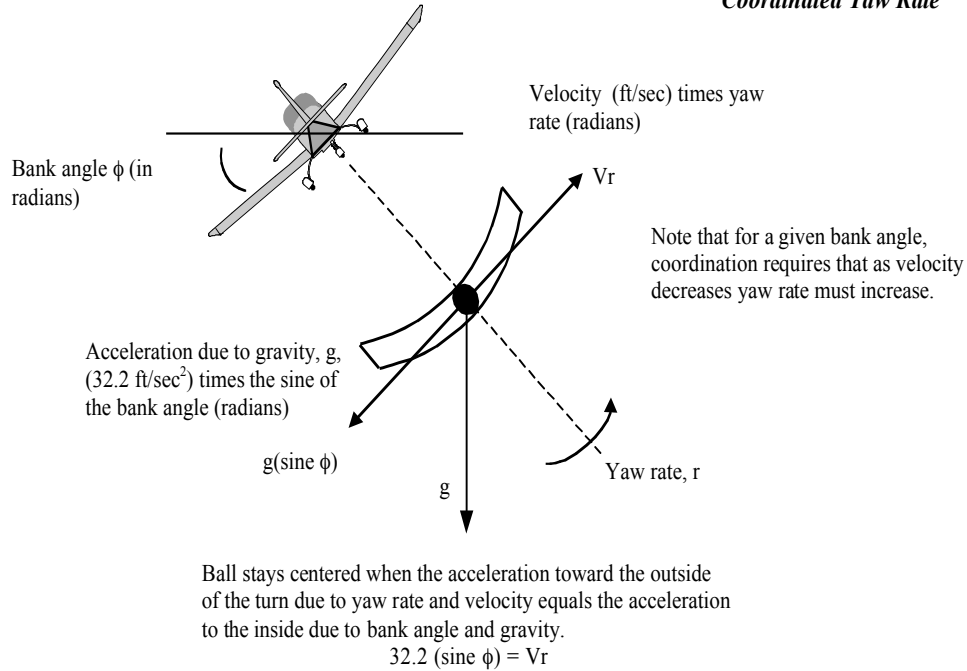


As bank increases, pitch rate increases, yaw rate decreases.

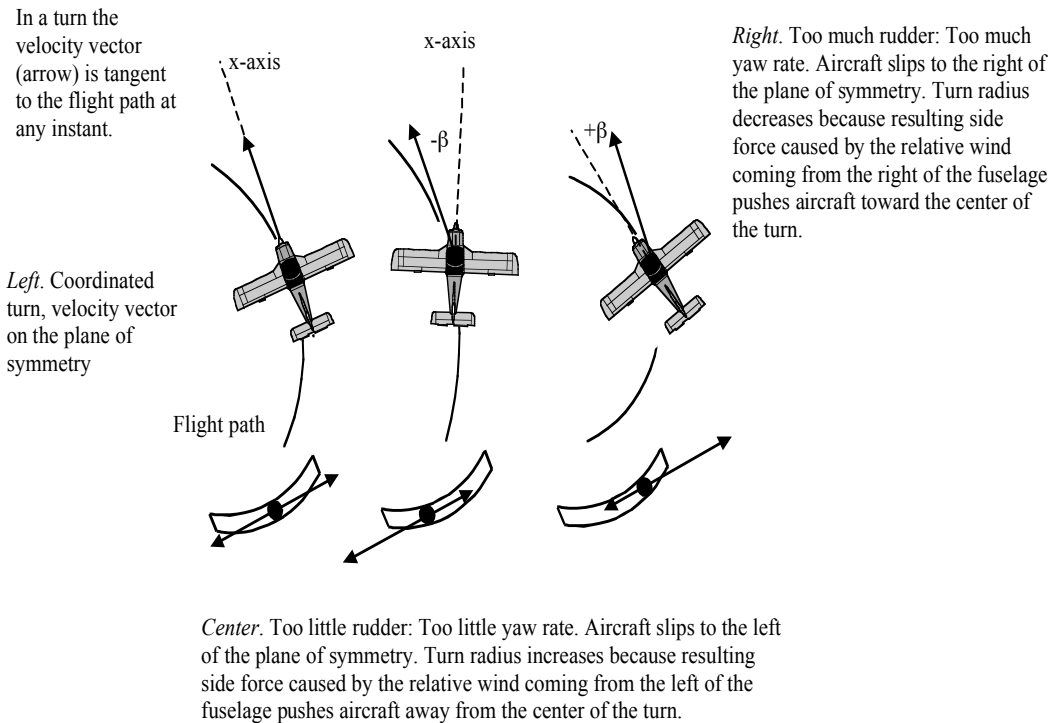


Rolling Dynamics

Figure 3
Coordinated Yaw Rate

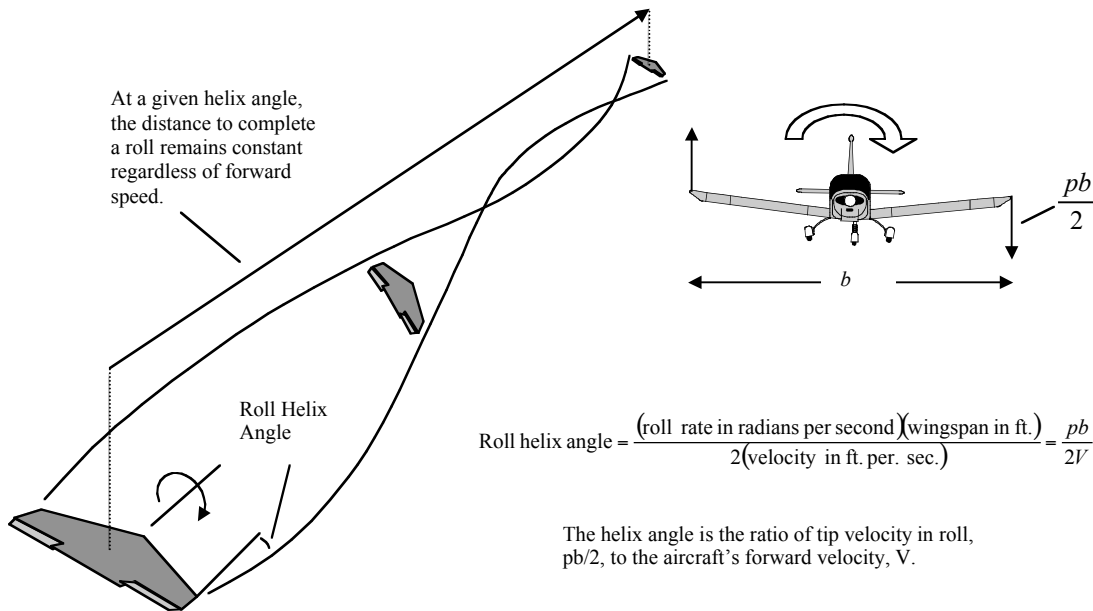


“Stepping on the ball” controls yaw rate.



Rolling Dynamics

Figure 4
Roll Helix Angle



Roll Helix Angle

As an airplane rolls, its wingtips follow a helical path through the sky, like the shape of a stretched spring. You see the helix at airshows when the pilot fires up the tip smoke. The angle between the resultant flight path of the wingtip and flight path of the aircraft is called the *roll helix angle* (Figure 4). The roll helix angle increases with increasing aileron displacement. Maximum attainable helix angle depends on aircraft design and mission. But on a given aircraft a given aileron deflection always builds to a given roll helix angle.

For any aileron deflection (roll helix angle), coordinated roll rate, p , varies directly with true airspeed. “Coordinated” means there’s no sideslip affecting the rate. For the statement to be true, there must also be no aero-elastic effects (wing bending caused by aileron deflection at high speeds).

As the aircraft’s forward velocity increases, it will maintain the helix angle—by virtue of rolling faster. As a result, for a given helix angle an aircraft will complete a roll in the same forward distance traveled, regardless of airspeed. Slippage aside, the helix angle is like the pitch of

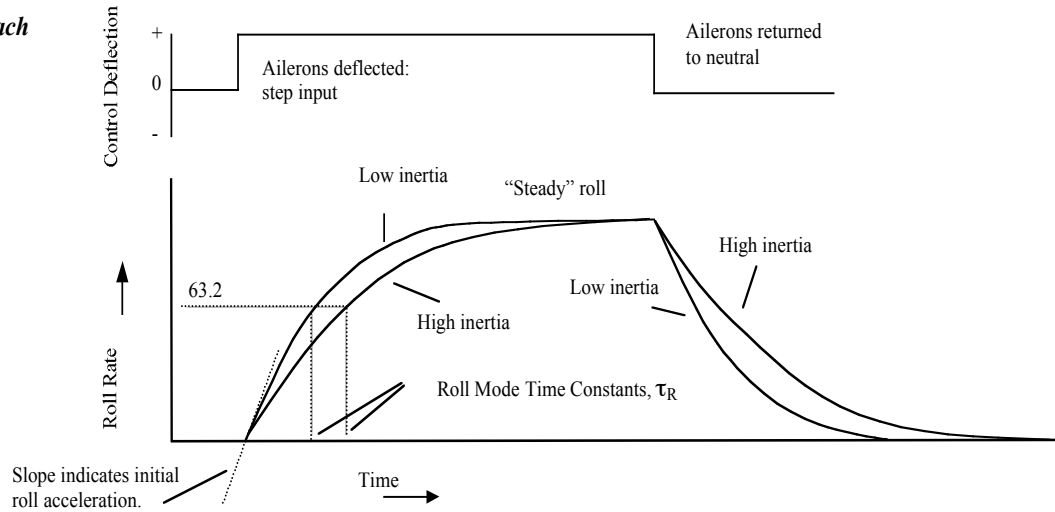
a screw of given length. Regardless of rpm, it takes the same number of turns to fasten it down.

When you know the helix angle, wingspan, and aircraft velocity, you can solve the formula in Figure 4 for roll rate. The helix angle provides a way of establishing minimum acceptable roll rates for different aircraft (about 0.09 minimum for fighters; 0.07 for transports). But it doesn’t account for roll inertia, so it’s only a partial description of rolling character and is no longer used as a certification or acceptance measure.

Timed bank changes are used instead. The FAA’s requirements are listed in FAR Parts 23.157 and 25.147 (e).

Rolling Dynamics

Figure 5
Time to Reach
Roll Rate



Roll Acceleration, Time Constant

Roll acceleration (and thus how quickly the aircraft reaches the final roll rate for a given aileron deflection) depends on how much rolling moment the ailerons produce versus the moment of inertia about the roll axis the ailerons have to overcome. We're assuming the necessary rudder coordination, and thus no inadvertent moments due to sideslip:

$$\frac{\text{Rolling moment due to aileron deflection}}{\text{Moment of inertia about the roll axis}} = \text{Rolling acceleration}$$

The moment of inertia about the roll axis, I_{xx} , depends on how mass is distributed in the aircraft. If there's lots of fuel in the wings, some engines hanging out there, and maybe full tip tanks, roll inertia will be higher than if most of the mass were confined to the aircraft's fuselage.

Figure 5 shows the effect of inertia on roll acceleration and deceleration. Span, wing planform, and the rolling moment due to the aileron "step" deflection are the same for both curves. Only the moment of inertia, I_{xx} , is different. Notice the difference in initial slope between the two curves, and how maximum roll acceleration (not rate) happens at the initial control input, before damping forces have a chance to build. Notice the difference in the time required for reaching the steady rate in the two

inertia cases, and for the roll to stop when the ailerons are neutralized.

The roll mode time constant, τ_R , is the time it takes to achieve 63.2 percent of the final roll rate, in seconds, following step input. If you could maintain the initial acceleration (i.e. no damping to slow things down) the airplane would reach the target roll rate in only 63.2 percent of the time actually required. In theory, the rolling aircraft "remembers" this constant. Because of damping, it takes the same amount of time to achieve the next 63.2 percent of the final roll rate, then the next 63.2 percent after that, and so on. At least theoretically, the asymptotic curve keeps trying but never flattens out. After five time constants the roll rate will be at 99.5% of the final value. Close enough.

The greater the moment of inertia versus the aileron authority, the longer the time constant will be. Two aircraft may have the same maximum roll rate, but the one with the greater time constant will take longer getting to it *and longer to stop rolling when the ailerons are returned to neutral*. Therefore inertia characteristics, and not just maximum roll rates, need to be taken into account when comparing the rolling performance of different aircraft. In a given aircraft, roll rate can magically increase with increasing change of angle. Roll rate measured from a 45-degree bank to an opposite 45-degree bank may be lower than if measured from, say, 60 degrees to 60 degrees. That's because the time spent accelerating is a smaller fraction of the total.

Rolling Dynamics

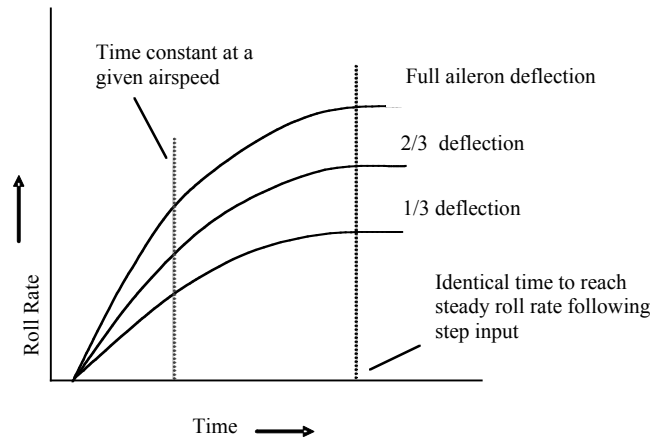
It's difficult for a pilot to measure the time constant without special equipment, because there's no easy visual reference on roll initiation, and it's usually less than a second (and imperceptible for a fast roller). Since the time constant is the same to stop a roll as it is to start one, and the visual references are clearer, you can try to measure the time to stop instead. (It helps if there's minimal freeplay in the control system.) Begin with a 45-degree bank angle and make a coordinated roll to upright using an immediate, step aileron deflection (the amount of deflection doesn't matter, since the time constant is the same, see Figure 6). Hold that aileron input until the wings become level with the horizon, then instantly neutralize the controls and watch for any additional roll. 63.2 percent of the time it takes for any remaining roll to subside is the time constant due to roll inertia. You might think that the more aileron you use and the faster you roll to upright the greater your overshoot past level. But it doesn't work that way, because the faster you roll the greater the aerodynamic damping available to stop things when you neutralize the controls.

The idea that an aircraft that accelerates quickly into a roll can stop just as quickly takes aerobatic students by surprise. In performing 360-degree rolls, most will start out leading the recovery by too much and stopping short of wings-level. (That's normal, but students who over-roll and stop past wings level are obviously behind the aircraft.)

At a given altitude, roll mode time constant varies inversely with true airspeed (TAS). That's true to experience—the faster you go, the quicker you can accelerate into a roll. But at a constant TAS, the time constant increases with altitude. The air is less dense, and for a given TAS there's less dynamic pressure available to overcome inertia. There's also less damping as altitude increases, so it takes longer for the roll rate to settle.

Airplanes with noticeable time constants (as caused by high roll inertia and/or low roll damping, and limited aileron control power) require that pilots learn to “shape” their control inputs, first using large initial deflections for maximum acceleration and then reducing the deflection once the desired rate is achieved. Then they have to check the airplane's roll motion with opposite, anticipatory aileron inputs when capturing a bank angle or returning to level

Figure 6
Time to Reach
Roll Rate



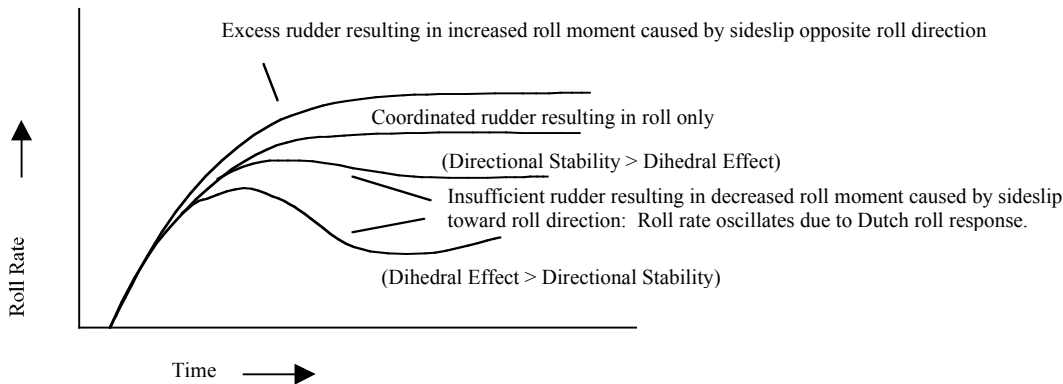
flight. The wheel or stick becomes an acceleration controller. Pilots can adapt, but the workload increases. Because of its huge x-axis roll inertia, the B-52 has this kind of response.

On the other hand, aircraft with short time constants tend to feel quick and responsive. Because they accelerate quickly, the stick becomes essentially a rate controller. Within bounds, that's what pilots prefer.

The FARs don't specify time constant requirements, but, for the military, MIL-STD-1797A 4.5.1.1 sets the maximum τ_R between 1 and 1.4 seconds, depending on aircraft mission and phase of flight.

In an aerobatic aircraft, because of the rapid roll acceleration, you can sometimes get the impression that the aircraft's steady roll rate is faster than it really is. We feel acceleration much more profoundly than rate, especially as passive recipients. Studies have shown that pilots tend to estimate ultimate roll rate based on initial acceleration. One of the malicious joys of instructing from the backseat in a true high-performance tandem aerobatic trainer is watching your student's head snap sideways when you demonstrate maximum acceleration point rolls. A given roll rate can seem much faster (and not such great fun) when you're the pilot-not-flying, because you're not performing the initiating control inputs that prepare the rest of your body for the ride.

Figure 7
Dihedral Effect,
Rudder use,
Roll rate



Roll Rate

Figure 6 shows a time history, from the initial acceleration to the point where acceleration stops and a constant rate is achieved, for rolls using three different aileron instantaneous step deflections at the same airspeed. One thing it reveals is that at a given airspeed it doesn't take an airplane any longer to reach its highest, full-deflection roll rate than it does to reach lesser rates using lower deflections.

Figure 7 shows the effects of sideslip on roll rate. Roll moments caused by sideslip are a function of effective dihedral and of both sideslip angle and angle of attack. (See Flightlab Ground School, Lateral/Directional Stability) The two dashed lines in Figure 7 show an uncoordinated, aileron-only bank, with adverse yaw allowed to do its worst. In a laterally stable aircraft, sideslip produced by adverse yaw reduces roll rate because of the opposing rolling moment from dihedral effect. Rolling in one direction while yawing in another can also set off Dutch roll oscillation, seen in the figure as an oscillation in roll rate over time. Note that the worse case, when rolling without coordinating rudder, comes when dihedral effect is high and directional stability is low.

For geometrically similar airplanes, roll rate varies inversely with span (cutting the span in half gives twice the rate). The reason is that roll damping varies directly with span. At any given roll rate, the longer the span the faster the

wingtip moves, and therefore the greater the damping caused by the larger roll-induced change in angle of attack. This explains the short wingspans of aircraft designed to roll fast.

Roll damping is also an inverse function of true airspeed. Because TAS increases with altitude, roll damping decreases as you climb—as does directional and longitudinal damping. (See Damping versus Altitude in “Longitudinal Maneuvering Stability.”)

At high angles of attack approaching $C_{L,max}$, roll damping begins to decrease as the wing's C_L curve begins to level out (Figure 8). Turbulence or yaw rate causing a wing to drop can then force the angle of attack of the tip section past the point of stall. Now the coefficient of lift, instead of rising as it normally does as the wing descends, starts falling down the post-stall side of the lift curve, and damping disappears. The transformation of damping into autorotation is the essence of spin departure. Quickly reducing the angle of attack usually restores roll damping, and lateral control, before a real spin can get underway.

Muscle Versus Roll Rate

Aileron systems are designed primarily in terms of the lateral control required at speeds near stall—a function of aileron size. At high speeds, roll rate is a function of the available aileron deflection.

As mentioned earlier, *for a given aileron deflection (thus roll helix angle), coordinated roll rate, p , varies directly with true airspeed.* Roll rate also depends on how big a gorilla is driving. In an aircraft without boosted or powered flight controls, *the control force felt by the pilot increases as the square of the true airspeed.* As a result, aileron forces go up faster than roll rates, and ultimately the force required for maximum deflection can exceed the pilot's muscle power.

For example, a Spitfire had a maximum roll rate of around 105 degrees per second at about 175 knots EAS. A clipped-wing Spitfire made it to about 150 degrees per second at the same speed. A P-51B Mustang's roll rate peaked at only about 90 degrees per second at around 260 knots EAS. When these airplanes went slower, maximum-performance roll rates decreased due to the slower TAS. When they went faster, roll rates decreased because the pilot couldn't fully deflect the controls, as Figure 9 illustrates. The roll rate of the Japanese Zero went down

Figure 8
Loss of Roll
Damping past Stall

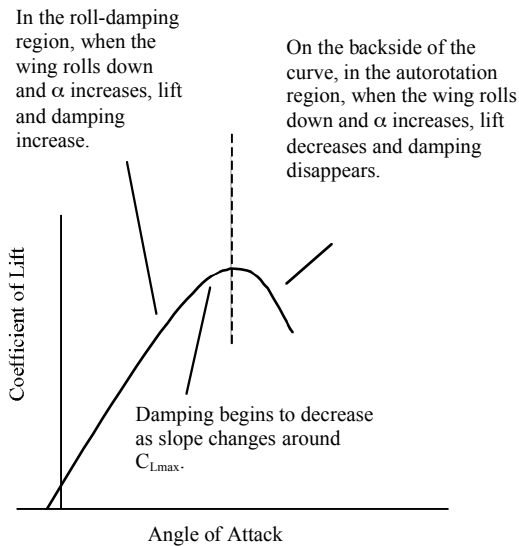
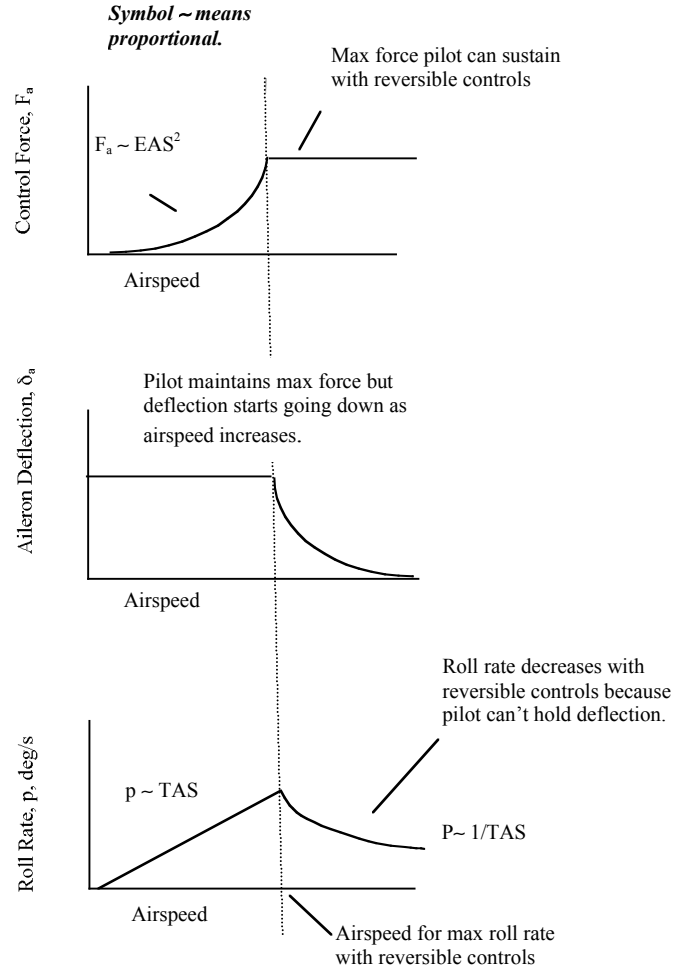


Figure 9
Roll Rates versus
Airspeed, Muscle-
Powered Reversible
Controls



drastically at high speed because of aileron reversal caused by wing twisting (see below).

By way of comparison, if a contemporary, high-performance aircraft designed for top aerobatic competition rolls less than 360 degrees per second, at maximum sustained level flight speed, it's considered a slug.

Rolling Dynamics

In testing for certification under FAR Part 23.157, aircraft are required to roll from a thirty-degree banked turn to a thirty-degree bank in the opposite direction within time limits specified for aircraft weight and configuration. Under FAR Part 25.147 (e), “Lateral control must be enough at any speed up to V_{FC}/M_{FC} to provide a peak roll rate necessary for safety, without excessive control forces or travel.”

Aeroelastic Aileron Reversal

At high speeds, aeroelastic deformation also puts a cap on roll rates. The down aileron produces a twisting moment on the wing, which forces the leading edge to deflect downward, reducing the angle of attack (Figure 10). This reduces lift and consequently rolling moment. Roll rate then starts going down and at a certain speed, V_R , when the decrease in lift due to twisting equals the increase in lift due to aileron deflection, the ailerons will no longer create a normal rolling moment. Beyond this speed “aileron reversal” occurs. A down-going aileron then produces a down-going wing.

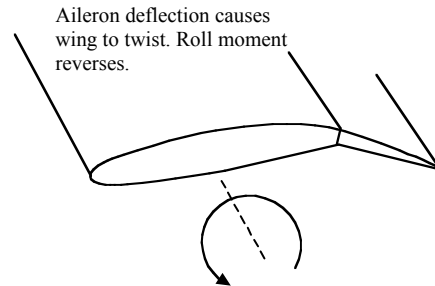
One of the cures for aileron reversal, not surprisingly, is to increase the torsional stiffness of the wing (at the expense of added weight). On swept wings it’s necessary to increase the bending stiffness because the geometry of a swept wing causes it to twist as it bends. Moving the ailerons inboard or extending their span inboard also helps raise V_R on a swept wing. Spoilers are another option, as mentioned.

Comparing Roll Performance

You first need to specify flight regime in order to make useful roll performance comparisons between our aerobatic training aircraft and larger transports—for example the roll rates at approach speed and configuration versus cruise. Because of yaw/roll coupling, you also need to consider sideslip and yaw rate contributions based on aircraft dynamics and pilot technique. The question is complicated by all of the derivatives that have to be plugged in.

The people who create simulation algorithms have the derivatives plugged in. Comparisons of roll rates (and control forces) made between your aircraft and our trainers based on the performance of your aircraft’s *simulator* should

Figure 10
Aileron Reversal



be useful—especially if the simulation occurs within the boundaries of the angle of attack, α , and sideslip, β , envelopes supported by your aircraft manufacturer’s flight-test data. Rolls through 360 degrees can be modeled reliably, as long as they happen within α/β boundaries, even if the subject aircraft has never been tested in full rolls itself. Combined high angles of attack and high sideslip angles may not be well supported, however, because they’re usually not flight-tested for aircraft not receiving spin certification, and their nonlinear effects make reliable modeling difficult. During the unusual-attitude portion of your simulator training (if indeed there is such), ask to observe roll rates at different airspeeds, configurations, and altitudes—and especially with different contributions from the rudder. Then, assuming you passed the check and won’t be called a troublemaker, go ahead and ask where the test data stops and the extrapolation begins.

Flightlab Ground School

10. Spins

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For Training Purposes Only

A Short Sermon

There's a distinction between feeling safe and being safe. Unfortunately, we can experience the former without actually achieving the latter. Most of the decisions people make about safety rely on the feeling of protection—a feeling that comes from the sense of a buffer between themselves and any dangers likely to occur. It's been pointed out that the reason some people prefer sport utility vehicles, despite the poor accident record, is that being surrounded by all that metal and padding simply feels safer. The impression is that an accident will be survivable. The fact is that an SUV accident will also be more likely because of poor handling qualities. Drivers are less likely to get into accidents in smaller cars that are more easily maneuvered out of danger. In the SUV case, people apparently assume that accidents are inevitable and therefore seek a physical buffer. In the small-car case, people accept more responsibility for their own welfare. They don't really feel safe in their smaller cars, but the absence of that feeling makes them drive more safely, anticipate potential trouble sooner, and so actually be safer in the end. Their skill is the buffer.

The problem of feeling safe versus being safe obviously applies to flying in general and to spin training in particular. Airplanes, even giant ones, are like small cars. They aren't designed to make you feel comfortable about the notion of hitting things. They're meant to be maneuvered back to safety. People who argue against spin training usually do so by relying on statistics showing that most stall/spin accidents start too close to the ground for recovery. In such cases, knowing how to recover from a spin wouldn't help. The conclusion they draw is that flight training should rely on stall avoidance as the way to spin avoidance—that stall avoidance is the buffer. Aerodynamically, they're right: stall avoidance *is* the way to spin avoidance. But spin training is itself the best way to produce unswerving loyalty to stall avoidance, because it's the only way for a pilot to experience what happens when you take the buffer away. Its real purpose is to reinforce

the buffer and render emergency spin recoveries unnecessary. Spin training shouldn't make a pilot feel complacent while maneuvering an aircraft—or, for that matter, feel safe. It should make him better at anticipating the trouble in store if airspeed gets low and the precursors of autorotation appear (perhaps during an emergency landing following engine failure). Not feeling safe is what motivates people to act safely. Training shows them when to be wary and how to behave. An otherwise well-schooled pilot who hasn't experienced spin training might feel safe, but have less real ability to look ahead and refrain from doing the wrong thing—less ability to keep the buffer intact.

We cover spin theory in this briefing, and examine some of the characteristic differences between aircraft types.

A Little History

Lieutenant Wilfred Parke, of the Royal Navy, made the world's first spin recovery, on August 25, 1912. We'll note here that while Parke was desperately improvising, Geoffery de Havilland was watching anxiously from the ground. Sometime between late April and late November of 1914, de Havilland became the first to enter an *intentional* spin, recovering using the technique Parke had discovered of rudder opposite the spin direction. That this planned attempt only occurred some two years after "Parke's Dive," as it came to be called, underscores the wariness that remained. Until Parke's nick-of-time revelation, pilots had always held rudder into the direction of a turn to prevent sideslip—a practice mistakenly carried over into spins.¹ Parke died in the unexplained crash of a Handley Page monoplane soon after his pioneering spin recovery. Geoffery de

¹ Wing Commander Norman Macmillan, articles on the early history of spins, *Aeronautics* magazine, July, December 1960, September 1961.

Spins

Havilland went on to build the series of pioneering aircraft that carry his name.

Of course, spins went on to become standard civilian training maneuvers—and then not, at least not in the U.S. after 1949, once the regulators changed their minds. We'll jump forward some decades after Parke and begin at the point where “jet-age” spin history begins. This will help us place the spin characteristics of our training aircraft in better context—since our aircraft are pre-jet-age, if you will, at least in a functional if not a chronological sense.

Wing Planform and Aircraft Mass Distribution

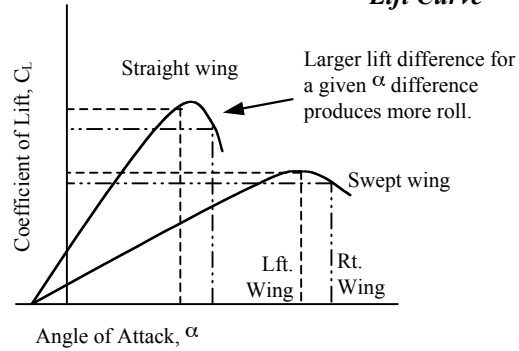
After World War II, a new generation of jet fighter aircraft appeared with swept wings and with their mass distributed more along the fuselage axis, and less along the span (fuselage loaded). This changed for the worse the governing aerodynamic and inertial relationships that determined their stall/spin behavior. Modern corporate jets are the descendents of these early fighters; just as modern jet transports are the descendents of early swept-wing bombers.

Swept wings allowed the early jets to achieve high speeds by delaying transonic drag rise. But the swept-wing solution for high-speed flight introduced problems in the high- α regime, where control was jeopardized by the swept wing's tendency to stall first at the tips. This caused a forward shift in the center of lift and a pitch-up. It also destroyed aileron authority. If one swept tip stalled before the other, the resulting asymmetry could send the aircraft into a departure leading to a spin.

The hefty-looking chord-wise stall fences you see on early swept-wing fighters, like the Korean War MiG-15, were an attempt to control the span-wise airflow that encourages tip stall. (Fences are still used to manage spanwise airflow and stall pattern.) During its development the rival North American F-86 Sabre was given leading-edge slats to improve its high- α behavior, and the horizontal stabilizer was re-positioned away from the downwash of the high- α wing wake to improve nose-down pitch authority.

Figure 1 shows that swept wings stall at higher angles of attack than straight wings. There's

Figure 1
Lift Curve



typically also a more gradual change in slope around the peak of the lift curve, and so the stall is less defined. Figure 1 suggests that when a swept-wing aircraft stalls asymmetrically, its wings reaching different angles of attack, the lift difference, and thus the autorotative rolling moment, is small. But because induced drag rises quickly with angle of attack, asymmetrical yaw moment may be large. If directional stability is weak, this can produce mostly yaw acceleration on departure in swept-wing jets. (However, a thin airfoil with a sudden, leading-to-trailing-edge stall pattern will typically accelerate in roll. The lift curve peak is sharp, and differences in wing contour or surface texture usually cause one wing to stall first. See “Two-Dimensional Aerodynamics.”)

Departure yaw can come from aileron deflection. Adverse yaw was a big problem on the North American F-100-series swept-wing jets. Deflecting the ailerons could cause roll reversal at high α . Instead of rolling away from it, the aircraft could yaw toward the wing with the down aileron—the resulting sideslip and roll due to yaw rate sending it into a departure against the ailerons. At high α , aircraft had to be rolled with rudder to prevent aileron-induced “lateral control departure.”

The redistribution of mass toward the fuselage was also important. Once departure occurs and a spin develops, in a fuselage-loaded aircraft inertial characteristics can cause the spin attitude to flatten or tend toward oscillation. Anti-spin aerodynamic yawing moments generated by rudder deflection can be insufficient for recovery. To break the spin, the pilot (or flight control computer more recently) often needs to deflect the ailerons into the spin to generate anti-spin *inertia* yawing moments to help the rudder

Spins

along. (Described farther on, inertia moments operate on the same principle as the propeller gyroscopics you're familiar with, but the rotating mass is the aircraft itself.)

The piston-engine fighters of World War II behaved differently than the new jets. They had straight wings, with stall patterns often more favorable for aerodynamic warning and lateral control (but not always—there were many aircraft that announced a stall by suddenly dropping a wing). The lift curves for straight wings typically have well-defined peaks (Figure 1). This can help promote well-defined stalls and prompt recoveries. But there can be strong rolling moments if the wings stall asymmetrically, and therefore predominantly roll acceleration on spin departure. Usually the piston fighters departed to the left because of engine torque and local airflow differences produced by the slipstream. You can observe departure characteristics by watching the old training films. (Sociologically entertaining, as well. Times were different. For an informative collection of videos, see www.zenoswarbirdvideos.com/)

Our trainers exhibit straight-wing spin behavior. The rectangular-wing Zlin's departure characteristics are dominated by wing-root-first stall patterns at high α —patterns you'll see when we stall a tufted wing. The tapered-wing SF260's stall pattern is shifted outboard, which makes the aircraft more susceptible to a sudden wing drop. Their inertial characteristics come from a fairly equal distribution of mass in fuselage and wings (pitch inertia only a little higher than roll inertia—close to the $I_{yy}/I_{xx}=1.3$ neutral value discussed later). They need a bit of yaw to shift the stall pattern asymmetrically, respond positively in autorotative roll, and then pick up the yaw rate as the spin gets organized. In the departure and early incipient stage, before the yaw rate begins to develop and while spin momentum remains low, neutralizing the controls is often all that's necessary to recover lift symmetry and break autorotation.

Training: What's Possible

The spin training available to civilian pilots is limited to aerobatic, straight-wing, piston-engine singles, like ours. This raises the obvious question of how such training corresponds to the kind of spin behavior a pilot might experience in an aircraft with a different wing planform or

distribution of mass. (Corporate jets are often swept-wing and fuselage-loaded, for example.) Does a stick-pusher make the issue irrelevant, or can it fail and suddenly reveal the reasons it was installed in the first place? In addition, when aircraft are not flight tested for spins, on the assumption that a spin is a very unlikely event in type, their behavior can only be predicted. Prediction is complicated because the relevant aerodynamic stability derivatives, which are linear when the aircraft experiences small perturbations (the engineer's term) from steady flight, become nonlinear when perturbations are large. They can't be extrapolated from static conditions in a wind tunnel; they depend too much on the history of the unsteady airflow that precedes them. Dynamic wind tunnel testing is possible,² but only flight tests can really confirm spin characteristics and recovery techniques.

As a result of training in aircraft possibly quite different from their own, pilots taking spin training have to think in general terms. This is reasonable, however, because generic departure awareness—focused on the general principles of spin avoidance rather than on the peculiarities of a specific aircraft—works across the board: ***Aircraft depart into spins when lateral and/or directional stability break down in the stall region, the wings develop asymmetrical lift and drag along the span, and the asymmetry draws the aircraft into autorotation.*** The solution to avoidance is to deprive this combination of its key ingredient—operation in or near stall, especially in uncoordinated flight, when the aircraft takes on a yaw rate and sideslip that can provoke lift/drag asymmetry.

In recovery from a spin departure, rudder application is also generic: ***Always, full rudder opposite the spin direction.*** You can learn this in any spin-approved aircraft. ***Following the rudder, stick neutral or forward of neutral*** is nearly generic, although the timing, amount of deflection past neutral, and the elevator stick force necessary can vary among airplanes. The details should always be determined from the POH/AFM before first-time spin practice. For aircraft with lots of their mass in the wings, the elevator can actually be a more effective *anti-yaw* recovery control than the rudder, as we'll see.

² Visit www.bihrl.com

Spins

Spin-recovery technique depends on the ability of these two primary anti-spin control surfaces, rudder and elevator, to generate large enough aerodynamic anti-spin moments. Sometimes they can't, and that's when recovery procedures need to generate persuasive anti-spin inertia moments to help the aerodynamics along. This is complicated stuff in the telling (and predictive rather than proven for aircraft not spin-tested) but it essentially boils down to how the pilot handles the *ailerons*. ***In addition to anti-spin rudder and elevator, fuselage-loaded aircraft may require aileron into the direction of the spin.***

Check the aileron instructions for your aircraft. If an aircraft has not been certified for spins, there's no requirement to list a hypothetical procedure in the handbook.

Regulations and Recoveries

The flight testing of both military and civil aircraft is done according to intended use and likely user—the user being a pilot who is assumed to have only average skills in aircraft type and who might be slow to react or might misuse controls (the guy test pilots refer to solicitously as “your average Joe-Bag-of-Donuts”). In other words, testing is for intended use with some abuse. For uniformity, both the military and the FAA prefer standardized spin recovery techniques, but neither actually requires a specific set of inputs.

FAR Part 25, for large aircraft, doesn't include spin certification, because spins are not intended use and aircraft are expected to behave in a manner making them very unlikely. The military echoes this. Under the military acceptance standards (MIL-STD), “All classes of airplanes shall be extremely resistant to departure from controlled flight, post-stall gyrations, and spins. The airplane shall exhibit no uncommanded motion which cannot be arrested promptly by simple application of pilot control.”³ Only training aircraft that might be intentionally spun and Class I and IV aircraft undergo spin tests. (Class I includes small airplanes such as light utility, primary trainer, light observation. Class IV includes high-maneuverability airplanes such as fighters, interceptors, attack, and tactical reconnaissance.)

³ MIL-F-8785C, 3.4.2.2.1

Appendix 3-D in the *Airplane Upset Recovery Training Aid*⁴ shows the α/β flight-testing envelope for a number of transport aircraft. You can see the variation in tested parameters between aircraft. In no cases are high angle of attack and high sideslip conditions explored simultaneously. Stall tests are done at zero sideslip to prevent spins.

Back to smaller aircraft: Our ground school text, “Certification Requirements,” contains the civil aircraft FAR Part 23.221 spin requirements. In addition, “The Flight Test Guide for Certification of Part 23 Airplanes” (FAA Advisory Circular AC-23-8A)⁵ provides interpretation and procedures. Together they describe the minimum acceptable spin characteristics for each aircraft category. For the normal category, in particular, meeting the requirements actually means leaving much about the aircraft's spin characteristics still unknown. The normal-category, one turn spin recovery requirement is intended to address recovery from an abused stall, meaning a stall in which controls are held in the pro-spin position and recovery inputs are delayed, not recovery from a developed state with higher angular (rotary) momentums needing greater aerodynamic moments to counteract. Consequently, meeting the requirement does not clear an aircraft for *intentional* spins.

According to the “The Flight Test Guide for Certification of Part 23 Airplanes,” for aircraft certified for spins under FAR Part 23.221, “Recoveries should consist of throttle reduced to idle, ailerons neutralized, full opposite rudder, followed by forward elevator control as required to get the wing out of stall and recover to level flight, unless the manufacturer determines the need for another procedure.”

What the Part 23 flight test guidance has in mind are aircraft with approximately neutral wing/fuselage mass distributions, and enough rudder and elevator authority to do the job. The useful PARE acronym for recovery inputs, promoted by flight instructor Rich Stowell (Power off, Ailerons neutral, Rudder opposite, Elevator forward) follows this preferred recovery format. But the acronym is also adaptable to fuselage-loaded aircraft, because the ailerons are

^{4, 5} Available on the Internet, search the title.

Spins

still taken care of in the proper sequence—although deflected in the spin direction (for upright spins) rather than set neutral.

For certification purposes, the recovery controls described above are applied after one turn (or a three-second spin, whichever takes longer) for normal category aircraft, and after six turns for spin-approved utility or aerobatic category. At that stage, PARE-input usually produces the quickest recovery.

Although PARE input is never inappropriate in certified aircraft (unless the manufacturer says otherwise), it's by no means uniformly essential in all aircraft at the very beginning of a spin departure, when autorotation first takes effect and a wing begins to drop. At that early stage, forward pressure to break the stall on the dropping wing is usually sufficient to end autorotation, even if spin-provoking rudder and aileron are still being held. In reality, by the time a pilot not current in spins remembers the PARE acronym, a PARE-input recovery is probably necessary. Beyond the initial wing drop, once a real yaw rate begins to develop, pushing the stick forward out of the PARE sequence *can accelerate the spin*, for reasons we'll describe.

Autorotation

Spins feed on autorotation, which can follow a stall if for some reason (sideslip, yaw rate, wind gust, inherent asymmetry in response, pilot input) the wings begin to operate at different angles of attack. Figure 2 shows what happens. During our practice spins, for example, if we keep the ball centered as we slow down and simultaneously increase α , both wings should arrive at their maximum coefficient of lift, $C_{L_{max}}$, more or less together.

If we then press hard left rudder, the right wing will begin to move faster than the left. The airplane will roll to the left in response (roll due to yaw rate, plus dihedral effect). Because the wing's rolling motion adds a vector to the relative wind (Figure 3), the left wing will see an increase in α as it descends, but a *decrease* in lift, since the wing is past $C_{L_{max}}$. Because of the increase in α there will also be an increase in drag (as you'll note in Figure 5).

Figure 2
Autorotation

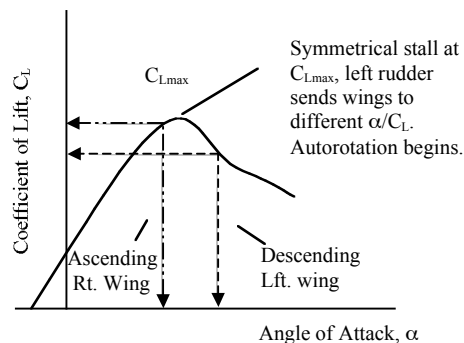
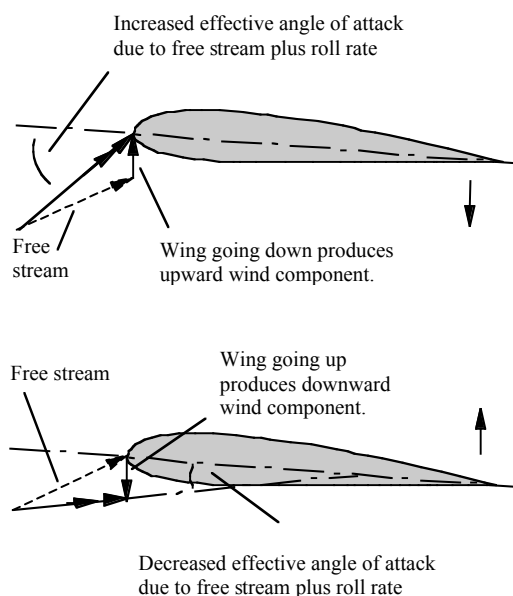


Figure 3
Roll-induced Angle of Attack



The right wing will see a decrease in α as it rises, but still more lift than the left wing. Because of the decrease in α there will also be a decrease in the right wing's drag.

As a result, the coefficients of lift and drag will vary inversely in relation to one another along the span. The outcome is a self-sustaining autorotation.

Spins

Although yaw typically leads to roll and thus to autorotation, sometimes departure happens in roll initially, even if the aircraft is in coordinated flight with zero yaw rate or sideslip. One wing might be rigged differently than the other, and stall first. Because of their sensitivity to any asymmetry along the span, wings that produce sudden leading edge stalls—or that generate sudden trailing-to-leading-edge stalls—tend to roll off. The down-going wing receives an increase in α , which leads to an increase in drag. The up-going wing gets the opposite. The asymmetry in drag sets the airplane off in yaw, which in turn reinforces roll.

Autorotation is roll damping reversed (Figure 4). Consider a wing operating normally on the left side of the C_L/α curve, before the stall region. If the wing goes down, perhaps because of a gust or an aileron deflection that the pilot then removes, it doesn't continue to roll, but stops. The downward rolling motion adds a vector to the relative wind, which produces a geometrical increase in α . The resulting increase in C_L opposes the roll. This damping, *rolling moment due to roll rate*, C_{lp} , subsides as the roll rate returns to zero.

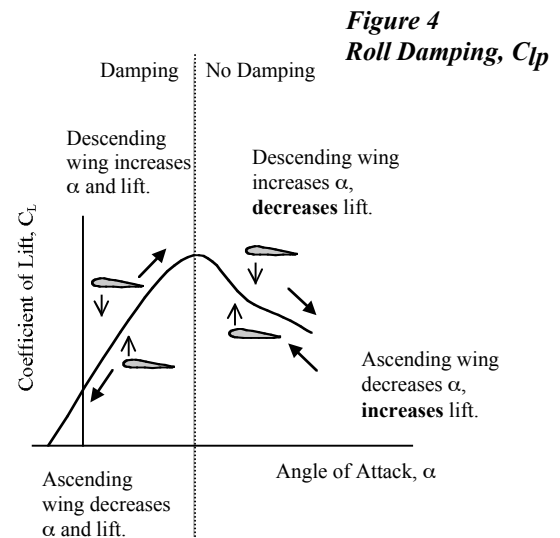
If a wing operates on the right side of the C_L/α curve, past stall, a downward roll still produces an increase in α , but now accompanied by a decrease in C_L , as we've seen. There's no damping effect. Just the reverse—the wing continues to fall. Roll damping turns unstable when the slope of the C_L/α curve turns negative past C_{Lmax} . A *rolling motion* kicks off a self-sustaining *rolling moment*.

Again consider a wing operating on the left side of the C_L/α curve, below the stall region, but now rolling upward. An upward rolling motion will induce a decrease in α (Figure 4) and a loss of lift—therefore generating roll damping. If that wing were operating on the post-stall, right side of the C_L/α curve, an upward roll would still induce a decrease in α , but an increase in C_L . The wing would continue to rise—again no damping.

For autorotation to occur, at least one wing has to operate on the right side of the curve, past the maximum coefficient of lift. Watching wing tufts in a departure, you'll typically see complete airflow separation on the inside wing (indicating low lift and high drag), while the outboard tufts

on the outside wing remain attached (more lift, less drag). Once autorotation gets going, inertial dynamics can take both wings to post-stall angles of attack, as they drive the nose up and the spin attitude flattens. Spin recovery involves getting both wings back into the roll-damping region on the left side of the C_L/α curve.

(If you remain a glutton for complication, note that the derivative *yaw-due-to-roll*, C_{np} , reverses sign at autorotation.)



Spins

Figures 5 and 6 show how the yaw component of autorotation is generated by the rise in the coefficient of drag, C_D , as α increases. As wings get shorter (smaller aspect ratio), or wing sweep increases, the slope of the lift curve decreases. This reduces the divergence in lift coefficient when the left and right wings operate at different α . In such cases, C_L might not vary much over wide values of α , but C_D will. Asymmetric drag then dominates autorotation. That means more yaw. One consequence is that spin attitude has a tendency to go flat (nose up), especially in a fuselage-loaded aircraft with flat-spin inertial characteristics.

Figure 5
Straight-Wing
Lift & Drag

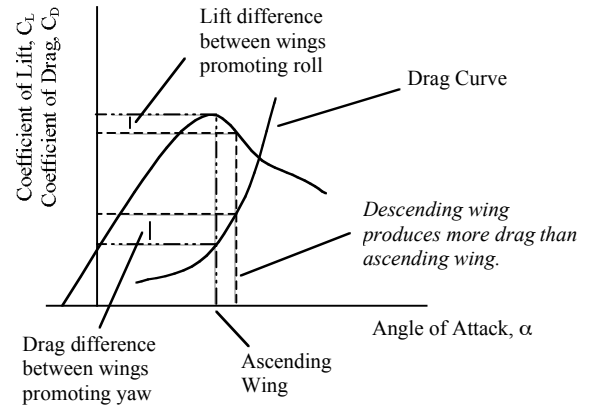
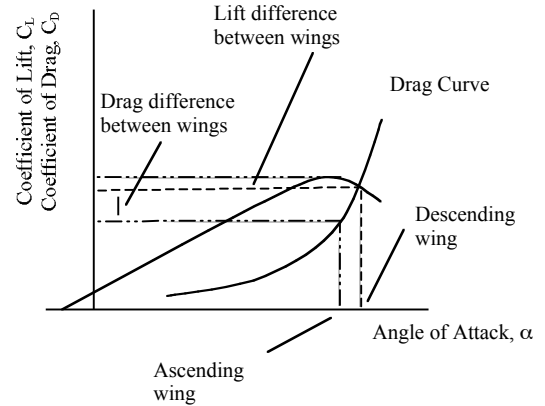


Figure 6
Swept-Wing
Lift & Drag



Spins

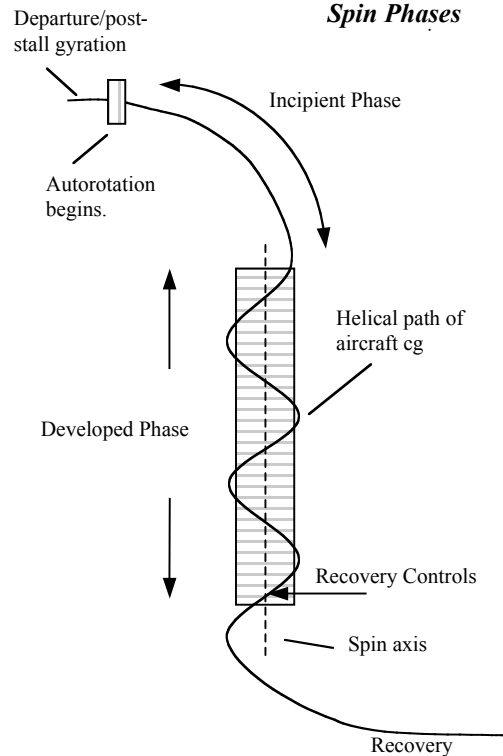
Spin Phases

Spins are typically described as passing through phases: *departure*, *post-stall gyration*, *incipient spin*, *developed spin*, and *recovery*. The developed spin may achieve steady rates of rotation and a consistent nose angle against the horizon, or the rates may oscillate—often with the nose bobbing up and down accompanied by fluctuations in roll and yaw. The notion that spins pass through identifiable phases is more a studied analytical observation than a fact immediately gladdening to pilots. If you're new to spins, or new to the quirks of a particular aircraft, one moment can blur awfully quickly into another as a spin revs up; the chief sensation being that things are simply getting worse. Until the developed state, spin phases themselves are transitional in nature, with uncommanded changes in roll, pitch, yaw, and sideslip—often going on all at once and difficult to sort into separate components. This is especially so during the incipient phase, which ends quite differently than it begins. Some aircraft will pass through the phases quickly, particularly during intentional spins if control deflections generate strong aerodynamic pro-spin forces and there's not much inertia to overcome (strong aerodynamics and weak inertias are also the formula for good recovery characteristics). Others take longer to get going and finally stabilize, if indeed they do stabilize.

Departure

The military uses the term “departure” in the sense of a boundary between controlled and uncontrolled states, a boundary between linear and nonlinear aerodynamics. Within this definition, an aircraft might depart and enter a post-stall gyration or a deep stall, but not necessarily a spin. In initial spin training, we use pro-spin control inputs to bring the aircraft quickly through departure and “shape” the post-stall gyration so that the aircraft immediately enters the incipient phase. In a training situation, the pilot knows (or quickly learns) what the aircraft is doing. However, accidental departures can come as a surprise, and the pilot might have difficulty tracking aircraft motion. The military trains its student pilots to return the controls quickly to neutral (and reduce power as appropriate) to try to prevent the aircraft from passing beyond departure and into a developing

Figure 7
Spin Phases



autorotation. If the aircraft has sufficient anti-spin stability characteristics it may then end up in an unusual attitude, but not in a spin. If a spin does develop, the military pilot uses instrument references (altimeter, AOA indicator, airspeed, turn needle) to determine the spin type and the correct recovery input. The military teaches “heads-in” recovery, it’s suspicious of outside visual references.⁶

Early in our Wide-Envelope training flights, you’ll observe directional stability and lateral stability (dihedral effect). You’ll evaluate the deterioration of control effectiveness as α increases, and you’ll find yourself introducing corrective rudder inputs as the aircraft’s directional stability diminishes. You’ll see the transformation of airflow over the tufted wing and the disappearance of roll damping as autorotation begins. These are lessons in the components of departure.

Static directional stability usually decreases as aircraft angle of attack increases and the airflow over the tail slows down and becomes disrupted by the fuselage wake. As a result, anything that causes a disturbance around the aircraft’s z-axis

⁶ Naval Air Training Command, “Out-of-Control Flight, T-34C,” 2006.

Spins

can start a yaw that may be slow to correct, thus allowing the aircraft to go to a higher sideslip angle, β , and remain there longer. If dihedral effect is present, the aircraft will tend to roll away from the sideslip. The rolling motion imposed on wings at high α can send them into the angle of attack disparity necessary for autorotation.

With American-turning engines, propeller effects yaw an aircraft to the left as α rises and speed decreases. Even if the pilot dutifully arrests the yaw rate with right rudder and keeps the ball centered, the spiraling slipstream will nevertheless tend to increase the angle of attack on the left wing and decrease it on the right. As aircraft angle of attack goes up, the left wing therefore stalls first and the aircraft departs accordingly.

Some aircraft will depart due to aileron adverse yaw. (We mentioned swept-wing fighters earlier.) The phenomenon is referred to as *lateral control divergence*, or simply “aileron reversal.” It can happen when adverse yaw introduces a sideslip that in turn produces a rolling moment opposite to and greater than the moment generated by aileron deflection. The airplane then yaws and rolls toward the down aileron, not away.

All the factors that lead to lateral control divergence increase with α . The disturbed, lower-energy air generated by the fuselage and/or wing wake causes directional stability to go down, which allows a larger sideslip angle. And adverse yaw goes up, which promotes that sideslip angle. Dihedral effect also goes up, at least to stall, although more for swept than for straight wings. The only thing that goes down is the ability of the ailerons to generate an opposing roll rate.

Pilot lore often attributes a departure caused by aileron reversal to an increase in local angle of attack as the aileron goes down. The idea is that if you lower an aileron the angle between the wing chord line (as drawn from leading to trailing edge) and the relative wind increases.

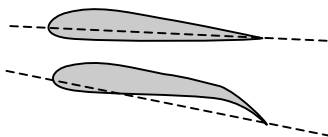
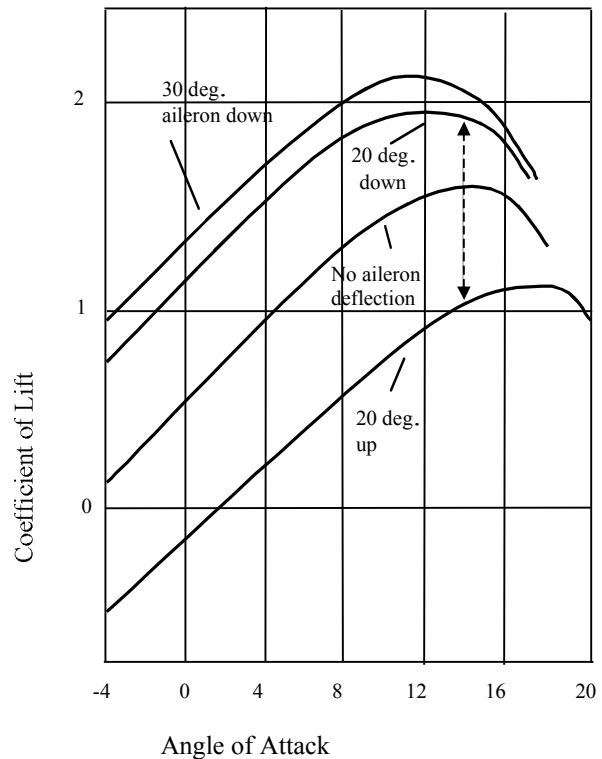


Figure 8. Aileron deflection shifts lift curve. (LS(1)-0417 wing)



This sudden increase in angle of attack is supposed to produce a local, sudden stall—the decrease in lift causing the wing to go down. In ground school, you’ll see a wind tunnel film that shows what can happen when a control surface is deflected down on a wing already operating at a high angle of attack. There can indeed be a sudden separation if airflow is unable to follow the abrupt change in camber. The effect depends in part on the shape of the hinge line. Airflow tends to stay attached if the hinge design allows a smooth curve. If the change is abrupt (piano hinge joining the top of the aileron to the top of the wing, for example), flow may separate sooner. That separation is accompanied by a large increase in profile drag, as our film reveals.

Figure 8 uses a constant chord-line reference for angle of attack and shows how deflecting an aileron down shifts the lift curve to the left—and can indeed bring a wing past stall angle of attack. But the lift curve also rises, and the lift of the stalled section actually increases (as does drag, even more). Notice the effect of a 20 deg. aileron deflection at 14 deg. α : An aileron deflected down places the corresponding wing area outside

Spins

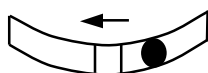
the region of roll damping. The lift of the area increases, but its contribution to damping—its resistance to autorotation—drops out!

It's usually difficult to persuade most airplanes to play along and depart into a down aileron by suddenly deflecting that aileron just before a stall. Typically, the aircraft has to start yawing due to aileron-provoked adverse yaw (drag) first; a coupled roll leading to autorotation in the direction of the down aileron then follows. If you use active rudder inputs to counter the asymmetric drag and to prevent a yaw rate from developing, an aircraft with a well-mannered trailing-to-leading-edge, root-to-tip stall typically won't depart, no matter where the ailerons are.

Planforms (wing shape as viewed from above) that tend to stall initially outboard over the ailerons, and that lack a compensating washout, might more easily misbehave following aileron deflection (bad design). The trailing wing in a sideslip is also, in effect, swept with regard to the freestream. This could cause a thickening of the boundary layer outboard, which in turn encourages separation. By generating lower pressures outboard, and creating a suction, a down aileron can definitely increase *the rate of stall propagation* from root to tip on the inside wing during a cross-controlled skidding-turn-to-final. (We'll show you this with a tufted wing in flight; so don't worry if you can't quite picture things now.)

When we practice intentional spins, we force the departure issue by pressing the rudder in the intended spin direction. We deliberately produce a yaw rate that leads to a rolling moment in response to the outside wing moving faster than the inside wing, and in response to dihedral effect. This rolling moment sets up the conditions for autorotation.

You'll notice that in all our upright spins, however we provoke them, the aircraft will always depart in the direction opposite the ball in the turn indicator or coordinator. The airplane falls "into the hole," as the arrow below indicates. So "step on the ball to prevent the fall."



The ball tells us the general direction of the relative wind or velocity vector (from/to the right, as illustrated above), and therefore of the

presence of a sideslip angle (see Figure 4 in the ground school text "Rolling Dynamics"). An aircraft that's rigged fairly symmetrically (none is perfect except by accident), that doesn't suffer from extreme prop effects, and that tends to stall straight ahead without dropping a wing won't depart into a spin if the ball is centered (zero β) and the velocity vector is thus on the plane of symmetry. The adventure starts when high α and high β combine. (Actually, an aircraft can be in a sideslip even when the ball *is centered*. A twin on one engine is in a sideslip when the pilot uses corrective rudder but keeps the wings level. This poor technique creates more drag than when the pilot reduces the sideslip by banking a few degrees into the good engine. A power-on stall in a single-engine aircraft may involve a slight sideslip. Propeller slipstream and p-factor usually require right rudder to prevent yaw. Zeroing the yaw rate puts the aircraft in a sideslip to the left. The ball will be centered if the wings are level.)

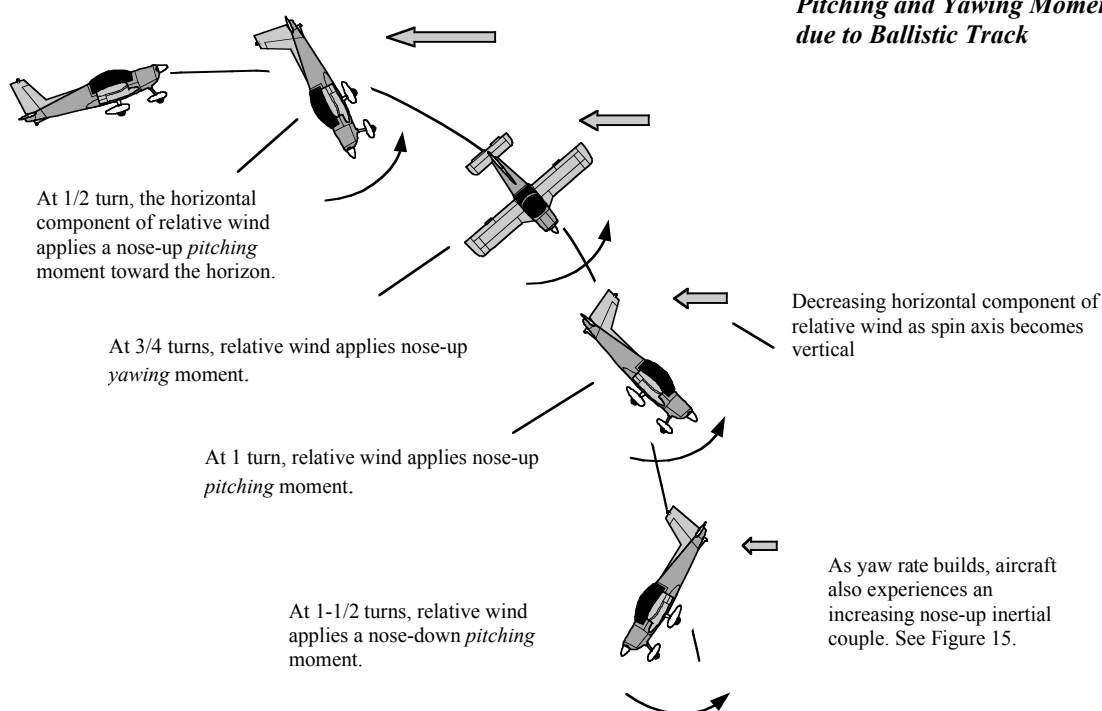
The displaced ball is predictive. It tells you which direction a departure will go. During a spin it's an unreliable indicator of spin direction—unlike a turn needle, which is reliable upright or inverted. The aircraft symbol in a turn coordinator is reliable only in upright spins.

Since geometric dihedral causes an angle of attack change in a sideslip—the angle of attack going up on the wing toward the slip—why doesn't dihedral cause that wing to stall and drop first during a sideslip (into the ball rather than into the hole)? It's because the aircraft rolls away from the slip as dihedral takes effect, the roll causing a decrease in α on the upwind, up-going wing. Because it rolls to lower α , it doesn't stall. The down-going wing rolls past stalling α , however.

In our Zlin aircraft, if you're carrying power and simply hold the rudder neutral and continue to hold the stick full back after the stall, P-factor and spiraling slipstream will set up the necessary yaw for a departure to the left. If you're at idle power (and depending on rudder trim, c.g., or turbulence), usually the airplane will oscillate around its axes (in a post-stall gyration, see below) until it eventually trips into a divergent roll and autorotation takes over. Very polite, elevator-limited, directionally and laterally stable aircraft often won't spin if you do nothing more than hold the stick back with the rudder neutral

Spins

Figure 9
Incipient Phase
Pitching and Yawing Moments
due to Ballistic Track



or free, because they can't generate the necessary combinations of angle of attack and yaw without pilot intervention.

Post-Stall Gyration

A post-stall gyration is defined as an uncontrolled motion about one or more axes following departure. The motions can be completely random, and the angle of attack can wander significantly, as well. The military includes snap rolls and tumbles as uncontrolled post-stall gyrations. The term post-stall gyration has particular application to the behavior of aircraft with the characteristics of fuselage-loaded, swept-wing fighters, as described at the start. In a ready-and-willing straight-wing trainer, if you do a standard entry, with stick back and full rudder at or just before stall in the intended spin direction, autorotation begins immediately and no post-stall gyrations may be evident. The aircraft goes directly to the incipient state.

Incipient Spin

The rate at which an aircraft decelerates into a stall is important. Certification flight-testing to determine stall speed (and thus a collection of numbers derived from stall speed) is done at a one-knot-per-second rate of deceleration. If you increase the rate of deceleration just a bit by bringing the stick back faster, you can often drive the stall speed down by virtue of the lag in the change of pressure distribution over the wings. If you overdo it however, and start to pull g, the load factor goes up and stall speed increases. You can also decrease stall speed by entering the stall nose-high, power on.

Stall speed affects the ballistic track of the incipient phase. Higher speeds mean that the aircraft travels a longer path over the ground before the spin axis becomes vertical, and is subject to higher aerodynamic forces at the beginning of the phase. The forces create oscillations in roll, pitch, and yaw as the aircraft changes orientation to the flight path, as shown in Figure 9.

Spins

For example, after an aircraft departs and nears inverted at 1/2 turn, the nose tends to stop falling, even if the stick is held back, because the relative wind hits the bottom of the horizontal stabilizer. As the aircraft approaches the 3/4-turn point, the nose may yaw upward, the relative wind having shifted to the vertical tail. At the one-turn point, the horizontal stabilizer again takes over, tending to hold the nose up. As the aircraft continues to the 1-1/2-turn point, the nose pitches down as the relative wind hits the stabilizer from beneath. These gyrations typically decrease in intensity as entry stall speed goes down and the horizontal wind component becomes less.

This, essentially weathervane, behavior is only part of the story. During the incipient phase the airflow can detach and reattach to the fuselage, wings, and tail surfaces, creating varying moments around the aircraft's axes. This is particularly evident on the outside wing on our trainers, as the wing tufts will show.

Judging from the training materials, the P-51 grabbed a pilot's attention during the incipient stage: "Upon entry in a power-off spin, the plane snaps 1/2 turn in the direction of the spin. Nose drops nearly vertical. After one turn, the nose rises to or above the horizon and spin almost stops. Snaps 1/2 turn again and nose drops 50 to 60 degrees below horizon. Upon application of controls for recovery, nose drops to near vertical and spin speeds up, then stops in one to 1-1/4 turns. Approximately 1000 feet altitude lost per turn."

Note that in half a turn the nose went from down "nearly vertical" up to "above the horizon." That's pretty frisky, but not unique. Note also that initially the "spin speeds up" after the application of recovery controls. That's very typical, for reasons we'll see.

An aircraft's mass distribution and its resulting inertial characteristics play an important roll in incipient spin behavior. In the case of the P-51, the interactions going on between propeller effects, inertias, and nonlinear aerodynamics would challenge simulation even today. In general, an aircraft with low moments of inertia around its axes will be more susceptible to the changing aerodynamic forces and easier to influence in the manner described above.

An aircraft with higher inertias might initially be harder to boss around aerodynamically. Once it starts rotating, however, inertial characteristics become increasingly influential as the spin axis settles down to vertical. *Inertia moments* (which are not the same as moments of inertia!) can then start to define spin behavior. We'll see this later.

Spins

Figure 10
Spin Helix

Developed Spin

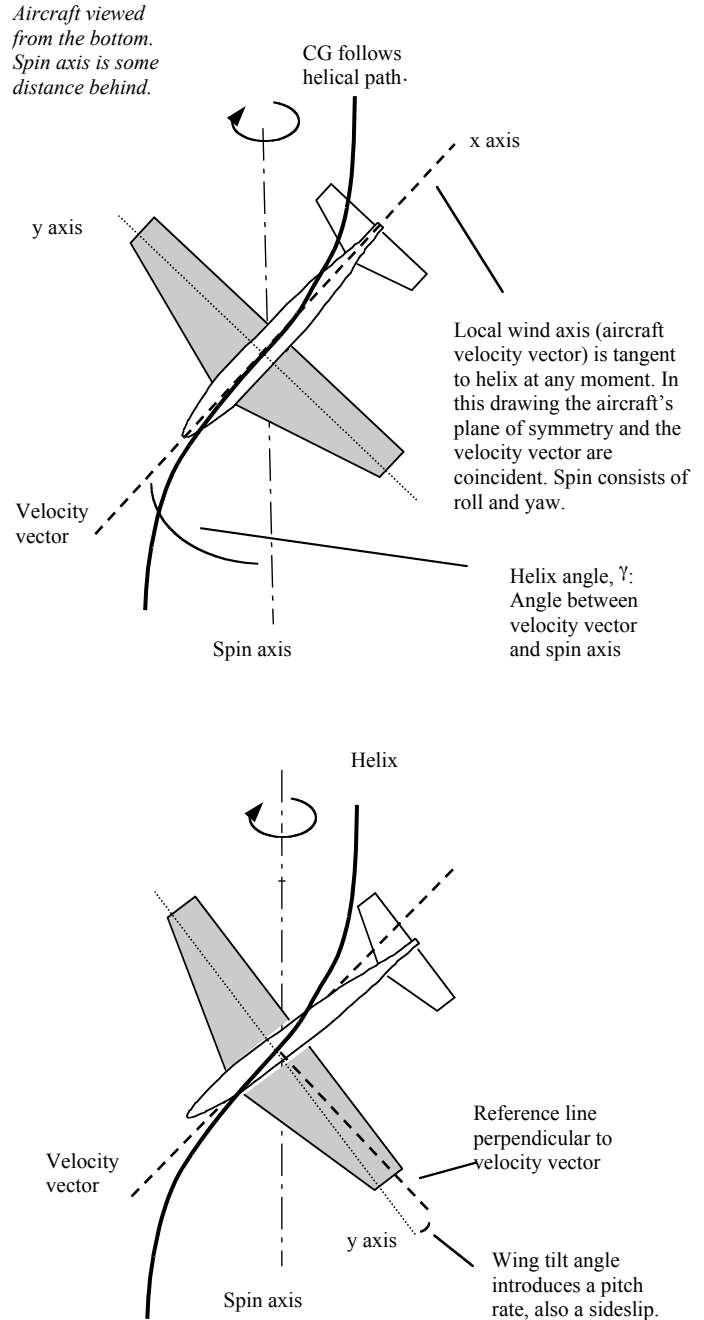
In a steady, developed spin, aerodynamic and inertia forces come into balance. Yaw, roll and pitch rates settle down to constant values. Angle of attack, descent rate, and pitch attitude do the same. In the case of oscillatory developed spins, which never settle down, the rates may fluctuate around average values, with aerodynamic moments in ascendance at one instant, inertia moments at another. Dynamic equilibrium in a developed spin can take longer to reach than many realize. The aerobatic certification requirement of six turns before recovery inputs are applied doesn't guarantee the aircraft has reached equilibrium.

Spin Attitudes

Spins consist primarily of roll and yaw, with the airplane center of gravity following a helical path around, and displaced from, the spin axis, as shown in Figures 7, 10, and 11. If the wings are tilted, relative to the helical path (Figure 10, bottom) the *wing tilt angle* introduces a component of pitch.

Flat spins are mostly yaw, while steep spins are mostly roll. Spins at 45-degrees nose down are equal parts roll and yaw. You can see why this is so by holding a model aircraft wings-level at a 45-degree nose down angle and yawing it around its z-body axis. The nose is 45-degrees above the horizon after half a turn. You need to roll as you yaw in order to keep the nose down. If you play with other angles, you'll see how roll and yaw interact. If you can figure out how to move the model on a helical path and tilt the wing as illustrated, you'll discover the need for a pitch rate, as well.

From the cockpit, spins often appear as mostly yaw, even past the 45-degree nose-down angle, when roll rate is actually taking over. As the pitch attitude becomes steeper, roll rate increases and roll perception starts to dominate. With the nose down it can be difficult for the pilot to recognize that he's actually entered a spin and not a vertical roll, or that he's still in a spin with a yaw rate that has yet to be stopped.



Spins

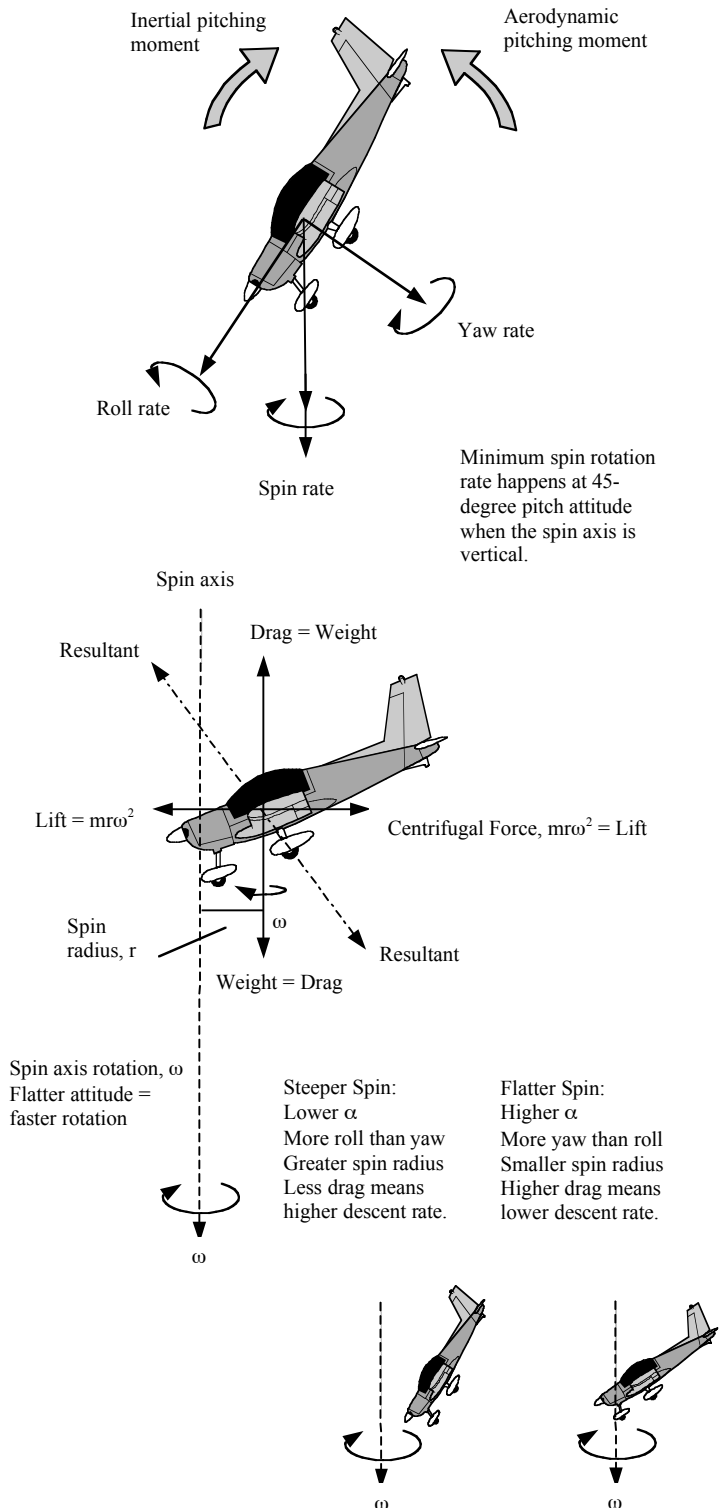
Figure 11 shows some of the characteristics of flat versus steep spins. In the example shown, for simplification the spin consists of roll and yaw only—no pitch rate. In an equilibrium state, the aerodynamic pitching moments, which are nose down, are opposite to and equal the nose up inertia moments (more about this later).

As the angle of attack, α , increases and the spin becomes flatter, the coefficient of drag, C_D , increases. Because of the drag rise, the descent rate decreases. Lift goes down. The distance, r , from the aircraft center of gravity—riding the helix—to the spin axis also decreases.

The figure shows the balances of forces in a steady spin. The resultant aerodynamic force (vector sum of lift and drag) balances the resultant of weight (the acceleration of a mass by gravity) and centrifugal force. As aircraft angle of attack increases, and lift consequently decreases, the aerodynamic resultant tilts more toward the vertical, or clockwise in the illustration. The resultant of weight and centrifugal force tilts clockwise as well. Since weight stays the same, this means centrifugal force decreases. As it does, the radius of the helix, r , around the spin axis decreases. As the aircraft c.g. moves closer to the spin axis, spin rate, ω , increases. In an aircraft with the c.g. behind the cockpit, the axis can pass behind the pilot; the spin accelerating and becoming “eyeballs out.” Not fun, says those who have been there.

Whether the spin is steep or flat will depend on the attitude necessary to balance the moments—aerodynamic versus inertial—around the aircraft’s axes. As we’ll see, an aircraft with its mass predominately in its fuselage will tend to spin more nose-up. An aircraft with its mass predominately in its wings will spin more nose-down.

Figure 11
Spin Attitudes,
Steady Spin Balance of
Forces



Spins

Spin Practice

Spin practice should build anti-spin and spin-recovery responses that will stick with you throughout your flying career. A good flight instructor lays the groundwork by unraveling spins in *stages* you can absorb, not with a sudden, multiple-turn baptism. (Teaching spins is not for instructors with lingering personality issues.) Since you will likely be in survival mode, concentrating on the plan for recovery, there's a limit to how much real motion information you'll be able to take in the first few times. The initial blur factor is high, and spins become increasingly difficult to follow as the rotations accelerate and your tracking reflexes break down.

When practicing spins with an instructor the first time, READ THE AIRCRAFT Pilot's Operating Handbook or AFM. Don't go flying until *you* have. If you're experienced with spins, but spinning an unfamiliar aircraft for the first time, READ THE POH/AFM. Don't make assumptions based on other aircraft. *Assumptions fail*. When it comes to spins, the voice of caution should be the one in charge of the plans. Or you can listen to the voice of Murphy, The Lawgiver, who actually was a flight-test engineer, "If it can go wrong, it will."

Always run a weight-and-balance on an unfamiliar aircraft or a suspicious loading. A c.g. shifted aft of the approved envelope can cause a spin to flatten out due to diminished nose-down elevator authority. A c.g. shift measured in inches may not seem like much as a percentage of the distance (or arm) between the c.g. and the aerodynamic center of the elevator, but that's not the distance that matters. It's the distance between the c.g. and the aircraft's neutral point that makes the difference. (See "Longitudinal Static Stability.")

As you do before any aerobatic flight, clear the cockpit of all foreign objects. (Things hide—the writer, now more vigilant, once brained his aerobatic instructor with a quart-size can of fuel additive.) Search the manual for and ask knowledgeable pilots about any characteristics different from those you've experienced. And check for stretch in the elevator cables: Have someone hold the stick full forward while you look for play by pulling up on the trailing edge of the elevator. Do you have full down elevator for recovery?

Some aircraft require power to enter a spin. If you're accustomed to entering practice spins power-off, you'll have to remember to pull the power once autorotation begins, both in consideration of propeller gyroscopic effects and for speed control during recovery. Simple details like the settings for trim and mixture control are easy to forget, but can be important. Remember that an aircraft reluctant to enter a spin can also have limited aerodynamic authority for recovery. The aircraft may be asking you not to force the issue. "Spin-proof" aircraft can enter spins if improperly rigged and their control surfaces exceed design deflection, but might not be recoverable.

Practice Spin Entry

Unless an aircraft is reluctant to spin, and requires the encouragement of a special departure technique endorsed by the manufacturer, the following is typical for a practice spin.

Altitude. (Adequate if planned recovery is delayed? The FAA says recovery from an intentional spin must be able to occur no lower than 1,500 AGL.)

Cockpit check. (Seatbelts, loose objects? Trim, engine controls, fuel valves set as specified in the POH/AFM?)

Clear Airspace.

Power to idle. (But some, like the Cessna 150 and 172 series, may need aid from the slipstream to enter a spin.)

Stick back for standard 1-knot-per-second deceleration. (This is the deceleration rate used in certification to determine the "book" stall speed. Just bring up the nose as necessary to hold altitude or climb slightly as airspeed bleeds.)

Ailerons Neutral. (Although some aircraft may require that the stick be held opposite the intended spin direction. In that case the aileron deflected down contributes an additional yawing moment—from adverse yaw—in the same direction as the rudder.)

Spins

Rudder deflected fully toward intended spin direction just before the stall. (The aircraft might not enter a spin, or entry might be delayed if a stall break occurs and the aircraft dumps the necessary angle of attack before the rudder is applied. Smoothest entries come from applying the rudder first.)

Hold full rudder deflection.

Stick full back as aircraft departs.

Spin or Spiral?

Spin-reluctant aircraft will often reward you with a spiral departure, until you figure out the trick of getting them to spin (rudder timing, blast of power, rapid deceleration leading to a higher angle of attack). You'll immediately recognize a spiral departure, because the roll-off happens slowly. A spin departure will roll you faster. Opposite aileron will recover a spiral, but the resulting adverse yaw may aggravate a spin departure. Airspeed and z-axis load factor will increase in a spiral, and the ball will respond to your feet in the normal ways, remaining centered if your feet are off the rudders.

Recovery Controls

Neutral rudder and aileron, and neutral elevator (or perhaps stick forward of neutral) are all that's required for recovery from the immediate departure stage in a typical trainer. Responding quickly to a wing drop in this manner is usually enough to break autorotation. PARE-sequence recovery controls become more critical as angular momentum starts to grow and the spin heads toward a developed state. To recover from an upright spin:

Power to idle. (Reduces propeller gyroscopic effects and slipstream-induced yaw.)

Ailerons neutral. (Removes any inadvertent deflection that may delay recovery. *In a fuselage-loaded aircraft the ailerons go toward the yaw direction—toward the turn needle whether upright or inverted—to produce anti-spin inertia moment in yaw.*)

Rudder opposite yaw direction. (Provides anti-spin aerodynamic yaw moment.)

Elevator forward to neutral or past neutral. (Unstalls the wings; for wing-loaded aircraft generates anti-spin inertia moment in yaw.)

When the spin stops, pull out with the rudder neutral. (If the recovery rudder is still deflected and you pull too hard, aircraft can snap roll into a spin in the opposite direction.)

In the following, we refer to inertia moments and gyroscopic effects that depend on how the mass of the aircraft is distributed around its three axes. For simplicity in presentation we'll just make reference to them now; try to explain them later.

Power

Power goes back to idle to reduce gyroscopic and slipstream effects. In an aircraft with a clockwise turning propeller as seen from the cockpit, power in an upright spin to the left tends to raise the nose due to the gyroscopic forces illustrated in Figure 14. Spiraling slipstream tends to increase in-spin yaw moment. In a spin to the right, gyroscopics can bring the nose down and the slipstream can supply anti-spin yaw moment. Properly timed, power application in a right-hand spin can help damp the oscillations of the incipient phase shown in Figure 9. But that's an advanced spin technique; just bring the power to idle in an emergency recovery.

In jets, power to idle is typically recommended. Although modern fighters designed to operate at high angles of attack have capable fuel controllers, earlier jets or less robust designs have trouble handling the unsteady inlet flows accompanying spin departures. Compressor stalls and flameouts are common. In spin tests of the T-38 supersonic trainer, there were three flameouts of both engines and eighteen single flameouts in twenty-one upright spins. Someone got good at restarts!

Note that power often isn't mentioned in the aircraft handbook recoveries reproduced farther on.

Spins

Ailerons

Aileron deflection works in the normal rolling sense during a spin, even if both wings are stalled. At spin attitudes, aileron deflection causes a span-wise difference in drag. This produces a component of roll as well as yaw. A glance back at Figure 11 shows how the drag vector tilts toward the aircraft's z-axis and thus toward roll effectiveness in a spin. Out-spin stick deflection lowers the inside aileron. In a typical spin trainer, this tends to drag the inside wing up, and bring up the nose, causing the spin to flatten.

Ailerons go to neutral for a recovery in an aircraft with broadly neutral mass distribution. Sometimes ailerons are hard to hold in neutral, because they have a tendency to float with the spin. Aircraft that recover more slowly if the ailerons are deflected often have a line painted on the instrument panel. The pilot uses this as an aim point to be sure that the ailerons are centered when the stick goes forward.

As we'll explain later, a roll moment can produce a yaw moment, depending on the aircraft mass distribution. ***In a fuselage-loaded aircraft, aileron deflection into the spin typically produces an anti-spin yaw inertia moment*** that helps recovery.

This anti-spin yaw moment generated by in-spin aileron in a fuselage-loaded aircraft tends to raise the outer wing and increase wing tilt. Greater wing tilt increases the nose-up pitch rate. This in turn causes an increase in both anti-spin rolling and anti-spin yawing inertia moments. (Relax. You're not supposed to understand this yet.)

The standard recommendation for aircraft that require aileron into the spin is aileron first, then rudder and elevator.

Aileron deflection could make it difficult to figure out when the spin has stopped, however. If held, aileron will cause the aircraft to continue to roll after it ceases autorotation. Look at the F-4 recovery procedure given later. You'll see that the pilot is instructed to "Neutralize controls when rotation stops." You have to wonder if it would stop. Since the purpose of aileron deflection is the creation of anti-spin yaw moment, and since the nose would go down as yaw rate decreases, pitch attitude would likely be an important cue in an aileron-assisted recovery.

In a *wing-loaded* aircraft ($I_{xx} > I_{yy}$) aileron *into* the spin can increase spin yaw rate and bring up the nose. Aileron *against* the spin will produce anti-spin yaw moment, but a *pro-spin, accelerating moment in roll*, the dramatic opposite of what the pilot's instincts are suggesting. Since wing-loaded aircraft generally spin nose down, with a high apparent roll rate seen from the cockpit, the temptation to use aileron against the spin can be strong. ***Neutral ailerons are usually recommended for spin recovery in wing-loaded aircraft.***

Rudder

Stopping a spin requires slowing down the rotation in yaw to the point where angle of attack can be decreased, the wings returned to the pre-stall side of the lift curve, and roll damping reestablished. ***The primary anti-spin recovery control in most aircraft is opposite rudder. Full rudder opposite the spin direction is always appropriate.***

Opposite rudder decreases the yaw rate, which in turn decreases the inertial couple driving the nose-up pitching moment. (Figure 15 will explain this nose-up couple.) The rudder's effectiveness will depend on the surface area exposed to the relative wind at spin attitudes (perhaps the airflow to the rudder is partly blocked by the horizontal stabilizer and elevator), by the additional available yaw damping effect of the fuselage, and by the position of the center of gravity. Aft c.g. reduces the arm and thus the available anti-spin aerodynamic moment.

Take a look at the wing tilt angle illustrated at the bottom of Figure 10. During spin recovery, with recovery rudder deflected, the outside wing tends to rise. This increases the wing tilt angle, which reduces any outward, pro-spin sideslip, and introduces a positive, nose-up pitch rate. In fuselage-loaded aircraft, the pitch rate precesses to an anti-spin yaw inertia moment, assisting recovery.

Elevator

After applying opposite rudder, apply forward stick. (In the case of an inverted spin, the stick comes back.) The sequence of rudder-then-elevator is important, since, once the yaw rate

Spins

begins to develop, leading with the elevator can accelerate the spin rate gyroscopically, making the rudder's task more difficult. As just mentioned, elevator deflected down may also decrease the rudder surface exposed to the relative wind, limiting its effectiveness. In many instances, even aircraft designed for spins may not recover if anti-spin rudder is applied while the stick remains too far forward (for example, after an instructor demonstrates an accelerated spin but then fails to bring the stick all the way back in a Pitts). ***Recovery from a developed spin should start with full back elevator.***

Once the yaw rate begins to build and gyroscopics come into play, ***a nose-down pitch produces a pro-spin inertia moment in roll.*** You'll feel the roll rate increase as the nose comes down. This is always the case, once the aircraft begins to develop angular momentum about the yaw axis, regardless of wing/fuselage mass distribution or spin direction. With the controls applied in the proper opposite-rudder, elevator-forward sequence, the roll acceleration means that recovery is on the way, but it's a disconcerting sensation. It appears that the spin is getting ready to become nasty, when it's actually getting ready to stop. The gyroscopic mechanism at work is a pitching moment that precesses 90 degrees around the yaw axis, producing a rolling moment. The initial anti-spin rudder will slow down the yaw rate (z-axis angular momentum) so that when the stick then comes forward less spin-direction roll acceleration will occur.

Down-elevator can be the most effective recovery control with an aircraft with a wing-loaded mass distribution, because it produces an anti-spin inertia moment in yaw. That could be crucial if the rudder is too weak to produce enough aerodynamic anti-spin yawing moment on its own. The amount of forward stick necessary may increase at aft c.g. loadings.

Our trainers actually behave as if they were wing-loaded as the spin just gets started. Their roll acceleration is initially high; their yaw rate picks up more slowly. As a result, angular momentum is greater initially in roll than in yaw. Pushing the stick forward causes gyroscopic precession around the roll axis that leads to an anti-spin moment in yaw. Plus, pushing gets the angle of attack back down, out of autorotation. But once the aircraft's yaw rate and angular momentum about the yaw axis has begun to

build, forward stick will cause the momentary acceleration described above, even when it follows the rudder in proper sequence.

If you hold pro-spin rudder while holding the control forward, the aircraft typically will stay in an accelerated spin. Decelerate the spin by bringing the control all the way back, and then recover in the normal way: use full anti-spin rudder followed by forward stick.

Flaps

Flap recommendations are inconsistent, as you can see in the pilot-handbook recoveries listed farther on. With the exception of flaps used during practice slow-flight, flap deployment implies an aircraft flying close to the ground. In that case, unless the manufacturer directs, emphasis should be on the primary anti-spin controls. During flight testing under Part 23.221(a) iv, an aircraft is required to demonstrate spin recovery in the flaps-extended condition: "...the flaps may be retracted during the recovery but not before rotation has ceased." Thus, by design, flaps at very least cannot delay recovery beyond the maximum turns allowed by certification. Retraction after rotation stops will reduce the chance of overstressing the wings while returning to level flight. Limit load usually drops to 2g when the flaps are fully deployed.

Pull Out

Spin students sometimes remind instructors that the game isn't over once the spin stops. Ground rush, the sensation that the closure rate with the planet is accelerating, can lead inexperienced pilots to start yanking. The aircraft then goes into a heavy buffet, and the pilot loses the nose-up pitch authority he's desperate for. Pilots can also find themselves holding recovery rudder. If the pilot pulls too aggressively while holding rudder deflection, the aircraft can depart into a rapid rotation in the direction opposite the original spin. This is one of those scenarios in which an aircraft answers a pilot's fearful response by giving him even more to worry about. The solution is to neutralize the rudder and momentarily decrease the aft pressure on the stick.

Spins

Inverted Spins

Inverted spins present unusual motion clues. Pilots are accustomed to seeing aircraft yaw and roll in the same direction, a visual paring reinforced whenever entering an ordinary turn. But in an inverted spin the aircraft appears to roll one way while yawing the opposite. (If you were sitting upright on the belly of the inverted aircraft, however, the yaw/roll relationship would appear normal.) The aircraft's motion path relative to the landmarks below also takes getting used to. Until you've had some practice, it's hard to count the turns in an inverted spin.

In upright and inverted spins, one thing remains the same: In a standard intentional entry, *rudder causes the corresponding wingtip to fall*. Imagine an aircraft beginning an intentional upright spin to the left. The left wing falls toward the earth when you press the left rudder with your left foot. The same thing happens flying inverted when you press your left foot during an intentional inverted spin entry: the left wing falls toward the earth. Anti-spin rudder application is identical in both the intentional upright and inverted cases. *Use the foot opposite the falling wing*. If you press the left rudder to enter an inverted spin, the spin will be to the right as seen from outside. But the outside direction only matters in aerobatic competitions. Think of your introductory inverted spins in simple cockpit terms, as left- or right-footed.

Recovery from an inverted spin follows the same PARE sequence as recovery from upright, except for the direction of elevator deflection. ***The stick comes back in an inverted spin recovery.***

An intentional inverted spin entry may look weird from the cockpit at first, yet with practice it's easy to initiate or react to correctly, if you remember your feet. But an intensifying inverted spin entered by surprise is a different matter. If your thoughts were elsewhere, or if the spin is highly coupled and oscillatory or unexpectedly transitions from upright to inverted, determining yaw direction can take a while. Since spin recovery technique depends on yaw direction, recognition is critical. Again, a turn needle will show you the correct yaw direction, whether upright or inverted. A turn coordinator, however, only works upright. In the absence of a turn needle, look directly over the cowling to pick up the yaw direction. Peripheral cues tend to be distracting since they correspond more strongly

to roll. Looking back, behind the spin axis, gives you a false yaw direction.

Inverted spins usually respond quickly to anti-spin rudder. With conventional tails (as opposed to T-tails), more unshielded rudder area is exposed to the relative wind in an inverted spin than when the aircraft is upright. The aircraft handbook tells you how far back to bring the stick after applying opposite rudder.

The possible difficulty of recognizing spin type and direction is reflected in military recovery procedures. Check the procedures for the T-34C and F-4, farther on. When there's confusion, the turn needle and angle of attack indicator dictate pilot response, not the view outside. (Although anti-spin control inputs can be easier to determine from instrument reference, identifying the recovery and regaining orientation is much easier using external cues.)

During spin recovery, less experienced aerobatic pilots sometimes unintentionally tuck-under from an upright into an inverted spin by pushing too aggressively while holding recovery rudder. As viewed from outside, the spin direction remains constant as the aircraft switches to inverted. The transition is hard for the pilot to see. Another way to tuck into an inverted spin is by applying too much forward stick during the yawing transition to the descending line of a hammerhead. Aerobatic spin training doesn't have to exhaust the complete spin matrix, but dual instruction that cautiously points to such dangers is invaluable.

Spins

Müller-Beggs Recovery

With the above in mind, aerobatic pilots should learn the Müller-Beggs method, used for recovery from unintended spin departures when the direction and mode is unclear.

The steps are:

- Power to idle.
- Let go of the stick.
- Establish the yaw direction by looking directly over the nose (or at the turn needle).
- Apply opposite rudder, and recover from the dive when the rotation stops.

Look at the rudder pedals if you can't figure out spin direction. In an aircraft with reversible controls, the rudder will float trailing-edge-toward the spin. This will set the rudder pedals so that the recovery rudder will be the one closer to you when the cables are taut. In a dim cockpit the pedals might be hard to see. The recovery pedal is the one that offers the most resistance when you press.

This release-the-stick technique works well with certain aerobatic aircraft, but not always with others, a point that usually unleashes claims, counter-claims, and a certain amount of posturing when aerobatic pilots start making comparisons. Spins are very sensitive to mass distribution, to e.g. location, and to the time histories of complex, nonlinear airflows. Different examples of even the same aircraft model can behave in different ways, depending on the inevitable differences in rigging. Pilots do things differently without knowing it. The reaction of an aircraft to control inputs can depend on how far a spin has developed and on its current oscillatory phase. So take the suggestions of experienced pilots concerning Müller-Beggs seriously, but beware those who make messianic pronouncements unsupported by evidence. You might be listening to the aforementioned Joe-Bag-of-Donuts. Neither the Decathlon nor the Zlin 242L nor the De Havilland Chipmunk should be considered Müller-Beggs recoverable.

The procedure of letting the stick go assumes the pilot is too confused to perform the aircraft manufacturer's recommended recovery, and can't identify the spin mode as upright or inverted. It releases any impulsive out-spin stick deflection that might tend to flatten the spin, but

it usually also accelerates the roll rate through inertial effects generated when the nose pitches down. The roll acceleration could delay recovery compared to the recommended procedure.

Training in the Müller-Beggs technique is essential if you plan to fly or instruct aerobatics in aircraft that depart quickly and can quickly shift between upright and inverted modes if mishandled—characteristics that can make visual tracking difficult. Fly with a qualified instructor in an aircraft with a known, positive Müller-Beggs response. Start with upright spin entries at altitudes allowing delayed recovery. When you release the stick, watch where it goes in response to the float angles of elevator and ailerons. Note the force required to move it. The stick can feel alarmingly stiff. (In a tandem trainer, you might think the other pilot has frozen the control.)

Practice and familiarization are important so that differences in aircraft motion and recovery time between the recommended and Müller-Beggs procedures don't come as a surprise during an emergency. If they do, you may be tempted to change control inputs before they have time to work, delaying recovery even more. During training, be prepared if necessary to return the controls to the initial *full stick-back, in-spin-rudder, spin entry position* before beginning the manufacturer's recommended recovery. This should return the aircraft to a known recoverable state.

Spins

Handbook Recoveries

The following are directly from the respective aircraft handbooks, unless indicated. For foreign aircraft, the translation is from the manufacturer, including the original spelling and syntactical charm. Format follows the original as much as possible.

All specify full rudder against the spin, as expected. Elevator recommendation varies from neutral to forward of neutral. Except for the Falcon and the F-4, ailerons remain neutral. Most remind the pilot to pull out of the dive, just in case:

Falcon 20 Business Jet

Intentional spins are prohibited. This aircraft has not been spin tested in flight. However, results of wind tunnel tests have shown that the following procedure should be applied:

Configuration	Clean
Roll	Same direction of rotation
Yaw	Opposite direction to spin rotation
Elevator	Neutral

AT-6C (Army) and SNJ-4 Navy Trainers

Spins should not be made intentionally with flaps and landing gear down. Should an inadvertent spin occur, recovery can be effected after 1-1/2 or 2 turns by first applying full opposite rudder and then pushing the control stick forward to neutral. The ailerons are held in the neutral position. Centralize the rudder as soon as the airplane is in a straight dive to prevent a spin in the opposite direction. Bring the airplane out of the dive and return the control stick to neutral.

Zlin 242L Single-engine Trainer

Mixture	Max rich
Throttle	Idling
Rudder	Full deflection opposite to direction of rotation.
Elevator	Immediately after full counteraction of rudder push smoothly control stick minimally to half of the travel between neutral and full forward within 1-2 sec. Ailerons in neutral position.
After rotation is stopped:	
Rudder	Neutral position
Elevator	Pull steadily control stick to recover aircraft from diving.

Spins

National Advisory Committee for Aeronautics
Technical Note No. 555, "Piloting Technique for Recovery From Spins," W. H. McAvoy, 1936.

The recommended operation of the controls for recovery from a spin, which presupposes that the ailerons are held in neutral throughout the recovery, is as follows:

1. Briskly move the rudder to a position full against the spin.
2. After the lapse of appreciable time, say after at least one-half additional turn has been made, briskly move the elevator to approximately the full down position.
3. Hold these positions of the controls until recovery is effected.

(The recommended delay in applying elevator addressed fact that in many aircraft the elevators, when deflected down, reduced the efficiency of the rudder by blocking its airflow.)

PZL M-26 Iskierka (Air Wolf)

Be sure of the direction of the aircraft's rotation.

Rudder	Set vigorously opposite the self-rotation.
Elevator	Slightly forward, beyond neutral position.
Ailerons	Neutral Position
After stopping rotation:	
Rudder	Neutral
Flaps	Up
Control stick	Smoothly backward (recover the aircraft from dive without exceeding the airspeed and load limits).
Engine power	Increase smoothly

Cessna Model 172P

1. Retard throttle to idle position.
2. Place ailerons in neutral position.
3. Apply and **hold** full rudder opposite to the direction of rotation.
4. After the rudder reaches the stop, move the control wheel **briskly** forward far enough to break the stall. Full down elevator may be required at aft center of gravity loadings to assure optimum recoveries.
5. Hold these control inputs until rotation stops. Premature relaxation of the control inputs may extend the recovery.
6. As rotation stops, neutralize the rudder, and make a smooth recovery from the resulting dive.

F-4 Phantom

TA-4F/J NATOPS Flight Manual

- Neutralize flight controls and physically hold the stick centered (visually check position of the stick).
- Retard throttle to idle.
- Determine type and direction of spin.
- Apply and maintain recovery controls.
 - Aileron: Full with turn needle if spin is erect. Full opposite turn needle if spin is inverted.
 - Rudder: Full opposite turn needle deflection.
 - Stick: Neutral to slightly aft.
- Neutralize controls when rotation stops and recover from the ensuing dive at a maximum of 18 to 20 units angle of attack.
- PSG recovery procedures: Neutralize all controls.

Spins

T-34C Turboprop Trainer

Naval Air Training Command, "Flight Training Instruction, T-34C Out-of-Control Flight," Q-2A-0017, 1993.

1. Landing gear and flaps – Check "up"
2. Verify spin indications by checking AOA, airspeed and turn needle.

Warning – Application of spin recovery controls when not in a steady state spin (as verified by AOA, airspeed and turn needle) MAY further aggravate the out-of-control flight condition.

3. Apply full rudder OPPOSITE the turn needle.
4. Position stick forward of neutral (ailerons neutral).

Warning – "Popping" down elevator CAN result in the spin going inverted in some airplanes. A "smooth" forward movement of the stick is best for most light aircraft during spin recovery.

5. Neutralize controls as rotation stops.
6. Recover from the ensuing unusual attitude.

(Note that the recovery procedures are instrument-based in the two military examples above. Angle of attack indicator and airspeed verify the spin. The turn needle determines recovery rudder and aileron deflection if called for. The recovery procedure for the T-37B trainer—a side-by-side jet twin built by Cessna—reproduced in part below, takes an unusual approach. The pilot first attempts recovery from an inverted spin. If that doesn't work, he tries to recover from an upright spin.)

T-37B Trainer

One procedure which will recover the aircraft from any spin under all conditions:

1. THROTTLES – IDLE.
2. RUDDERS AND AILERONS – NEUTRAL.
3. STICK – ABRUPTLY FULL AFT AND HOLD.
 - a. If the spin is inverted, a rapid and positive recovery will be affected [sic] within one turn.
 - b. If the spinning stops, neutralize controls and recover from the ensuing dive.

- c. If spinning continues, the aircraft must be in an erect normal spin (it cannot spin inverted or accelerated if the controls are moved abruptly to this position). Determine the direction of rotation using the turn needle and outside references before proceeding to the following steps.

4. RUDDER – ABRUPTLY APPLY FULL RUDDER OPPOSITE SPIN DIRECTION (OPPOSITE TURN NEEDLE) AND HOLD.
5. STICK - ABRUPTLY FULL FORWARD ONE TURN AFTER APPLYING RUDDER.
6. CONTROLS – NEUTRAL AFTER SPINNING STOPS AND RECOVER FROM DIVE.

L-39 Albatross Jet Trainer

Note

Spin character is stable during the first turn, with increasing instabilities typical for jet aircraft in continuous turning. Unregular [sic] longitudinal oscillations develop with increasing amplitude and shudder. Rudder bounces and increasing varying pedal forces must be overcome [sic]. Unadequate [sic] control inputs can lead to inverted spin development (especially with extreme forward stick position), or to the change in turning sense (ailerons against spin turning).

Upright Spin Recovery

Recovery is initiated with rudder and elevator centering. The aircraft stops turning and passes to steep dive with maximal one turn overturning. Ailerons remain held in neutral position. More aggressive turning stop can be initiated with rudder deflected against turning first, with subsequent all controls centering.

Spins

Aircraft Gyroscopic Inertial Characteristics

We've referred to pro-spin and anti-spin inertia moments without defining what we mean or describing how they work. The following may not be entirely easy going, but give it some effort—especially if you're headed for your CFI. You won't go into (or remember) this much detail with your primary students, but you do need to get a sufficient handle on things to answer some tough questions without leading your students too far astray. You should take your eventual CFI students to as high a level of understanding as you both can manage. Don't shirk your responsibility! And get a toy gyroscope to play with. It will help you figure things out.

Some definitions:

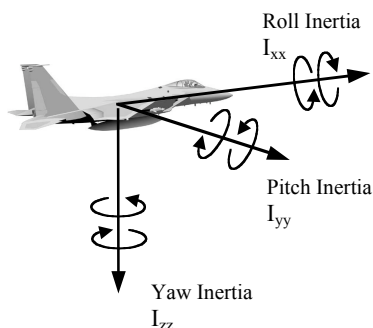
A moment causes rotation about an axis.

The moment of inertia, I , of a rigid body about a given axis is a measure of its rotational inertia, or resistance to change in rate of rotation. It equals the sum, Σ , of the body's various masses, m , multiplied by the squares of their respective distances, r , from that axis:

$$\text{Moment of inertia, } I = \Sigma (mr^2)$$

The greater its moment of inertia about an axis, the greater the applied moment or torque (force applied \times lever arm) needed to change the rotational motion of the body around that axis.

Aircraft have moments of inertia around each inertial, or *principal axis*, which are normally close to the body axes.



I_{xx} Roll Moment of Inertia A	Predominantly the mass of the wings.
I_{yy} Pitch Moment of Inertia B	Predominantly the mass of the fuselage.
I_{zz} Yaw Moment of Inertia C	Mass of wings and fuselage. I_{zz} is always greatest.

If $I_{xx} > I_{yy}$, then wing mass $>$ fuselage mass.

If $I_{xx} < I_{yy}$, then wing mass $<$ fuselage mass.

(A, B, C are symbols used in Great Britain.)

Since it comprises all the aircraft's mass, *yaw moment of inertia, I_{zz} , is always greatest.* Pitch or roll inertia are greater, respectively, depending on the aircraft's distribution of mass between fuselage and wing. An aircraft with puny wings and a heavy fuselage, so that $I_{xx} < I_{yy}$, has roll inertia $<$ pitch inertia, for example.

The pitch/roll, I_{yy}/I_{xx} inertial ratio is important to the character of an aircraft's spin and recovery. $I_{yy}/I_{xx} = 1.3$ is approximately the neutral value. Above that number, when $I_{yy}/I_{xx} > 1.3$, aircraft are considered fuselage-loaded in their behavior. Below that number, when $I_{yy}/I_{xx} < 1.3$, aircraft are wing-loaded in behavior.

An aircraft's external shape determines its aerodynamics. Pilots are accustomed to looking at the external shape and anticipating aircraft behavior (often unsuccessfully). But aircraft also have an "internal shape," as determined by the distribution of mass. Aircraft stability and control is a contest between the two. That's always so, and especially so in spins, when the internal shape starts to take on angular momentum.

Spins

	(In pounds)	Moments of Inertia (in slug-ft ²) Source: www.jsbsim.sourceforge.net/MassProps.html		
Aircraft	Weight	Ixx Roll	Iyy Pitch	Izz Yaw
F-16C (BLK30)	18,588	6,702	59,143	63,137
F-4 Phantom w/2 AIM- 7, 20% fuel	33,196	23,668	117,500	133,726
C-5 w/220,000 lb. Cargo, 20% fuel	580,723	19,100,000	31,300,000	47,000,000
X-15 w/zero fuel	15,560	3,650	80,000	82,000
Cherokee PA-28	2,100	1,070	1,249	2,312
C172 Skyhawk	1,700	948	1,346	1,967
Learjet Empty weight	7,252	3,000	19,000	50,000
B-727 Empty weight	38,000	920,000	3,000,000	3,800,000
B-747	636,600	18,200,000	33,100,000	49,700,000
T-38 Empty weight	7,370	14,800	28,000	29,000
F-15	26,000	22,000	182,000	200,000
Schweizer Sail plane	874	1,014	641	1,633
Twin Otter	9,150	15,680	22,106	33,149

Angular Momentum

Momentum is inertia in motion. A rotating body's angular momentum, $I\omega$, is its moment of inertia, $\sum (mr^2)$, about a given axis times its angular velocity, ω , around that axis.

$$\text{Angular momentum} = \sum (mr^2) \omega$$

or

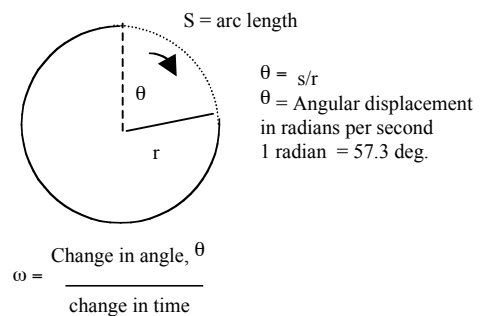
$$\text{Angular momentum} = I\omega$$

Angular momentum is also referred to as rotary momentum.

Angular velocity

Angular velocity, ω , just referred to, is the rate of change of angular displacement. Consider a flat, rotating disk with a line drawn from center to circumference, as below. The axis of rotation is perpendicular to the page. As the disk rotates through an interval of time, the displaced reference line forms an angle with its original position. Angular velocity is typically stated in radians-per-second (and in aerodynamics denoted by the symbols p, q, and r, for roll, pitch, and yaw).

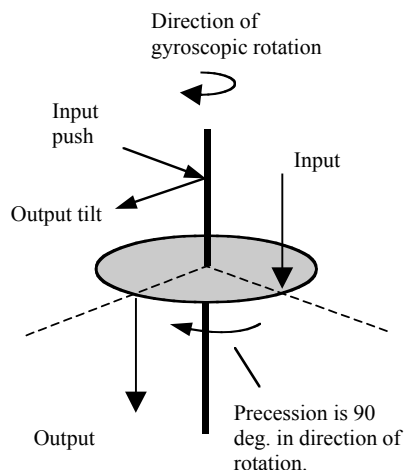
ω = angular velocity



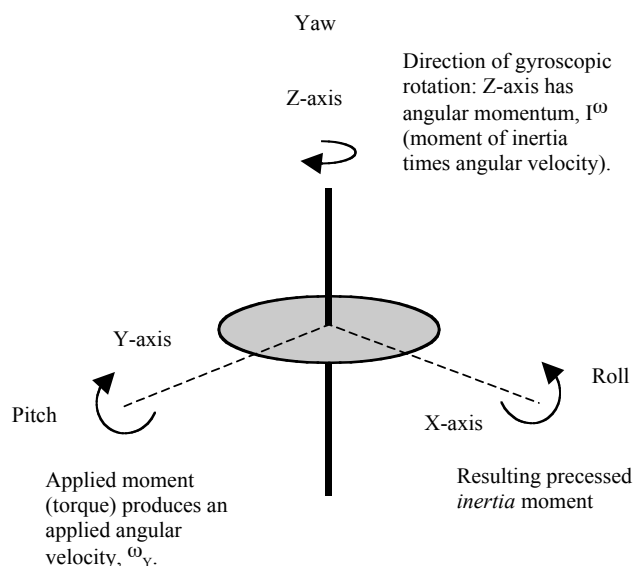
Every point on the line has the same *angular* velocity. Its *tangential* velocity is proportional to its distance from the axis.

Spins

Figure 12
Gyroscopic
Precession



Gyroscopic precession is the result of the conservation of angular momentum.



Inertia moment = Angular Momentum x Applied Angular Velocity

(Moments of inertia and inertia moments are two different things. The former resist changes in angular velocity, the latter produce changes in angular velocity as the result of gyroscopic effects.)

Gyroscopes

A spinning aircraft is a system of gyroscopes. The rotating mass of a gyroscope has two important features. The first is rigidity in space—as the spin rate of the rotor increases around its axis, it takes increasing force to tilt the axis in a new direction.

The second feature is *precession*: An applied “input” will precess (go forward) and generate an “output,” 90 degrees ahead in the direction of rotation. This is shown in the simplest and probably easiest-to-visualize way in the drawing on the left, in Figure 12.

The same input is occurring in Figure 12, right, but presented in terms of moments. The gyroscopic rotation is around the z-axis. If you apply a moment (or torque) around the y-axis, as shown, it will precess, causing a resulting **inertia moment** around the x-axis. The inertia moment is our output.

Think of the drawing in Figure 12, right, in terms of the axis system of an airplane. If the aircraft is yawing around the z-axis (in a spin, perhaps) and you apply a pitching (y-axis) moment with elevator, you’ll end up getting a rolling inertia moment (x-axis), as well.

Because inertia moment = angular momentum x applied angular velocity, the higher the applied pitching angular velocity (i.e., greater the applied pitching moment), the greater the resulting rolling inertia moment.

Aircraft Gyroscopics

The basic gyroscopic relationships in a spinning aircraft are easy to imagine once you get the trick. If an aircraft is already rotating around an axis, and thus acting like the rotor of a gyroscope around that axis, a moment applied around a second axis results in a moment produced around the remaining third. Therefore:

Pitching into a yaw rotation gives a roll.

Pitching into a roll rotation gives a yaw.

Yawing into a pitch rotation gives a roll.

Yawing into a roll rotation gives a pitch.

Rolling into a pitch rotation gives a yaw.

Spins

Rolling into yaw rotation gives a pitch.

Somewhere before the end of the list, you probably got the point. It's not so simple in practice, however, because in an actual spinning aircraft a moment around one axis precesses around two "gyroscopes" simultaneously. For instance, the applied angular velocity following a pilot's pitch input works both the yaw-axis and roll-axis gyroscopes. The resulting inertia moments generated depend on the relative angular momentums (angular momentum = moment of inertia \times angular velocity) around those axes. Thus for a given applied angular velocity around the first axis, the second axis with the highest angular momentum will "precess" the highest inertia moment into the third.

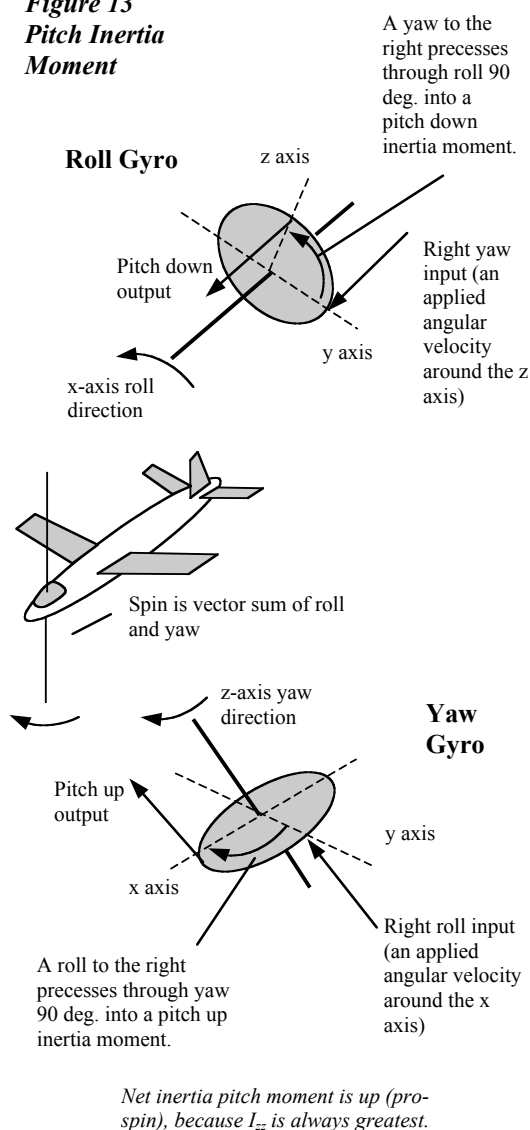
Take, for example, *pitch inertia moment*. Imagine an aircraft rolling and yawing in a spin to the right, as in Figure 13, top. It has an angular momentum in roll (equal to I_{xx} times angular velocity in roll, p). Since it's also yawing to the right, it has an applied angular velocity around the yaw axis. The yaw precesses 90 degrees in the direction of roll, and produces a nose down pitching moment. This is an anti-spin moment.

At the same time, the aircraft also has angular momentum in yaw (equal to I_{zz} times the angular velocity in yaw, r), as in the bottom drawing. In this case the applied angular velocity is provided by the roll rate. The applied roll precesses 90 degrees in the direction of yaw, and produces a nose-up pitching moment. This is a pro-spin moment.

This nose-up moment will be larger than the nose-down moment already described, because the moment of inertia around the z-axis, I_{zz} , is always greater than the moment of inertia around the roll axis, I_{xx} . *The net effect of the gyroscopic interplay between roll and yaw is always a nose-up, thus pro-spin, pitch inertia moment.*

What if the pilot steps in and imposes a pitch rate aerodynamically, by moving the elevator? Because yaw moment of inertia, I_{zz} , is always higher than roll moment of inertia, I_{xx} , roll is more likely to be affected than yaw. The rolling inertia moment generated will be higher, and the mass it has to accelerate will be less. *In a spin, a pitch down always produces a pro-spin roll inertia moment. A pitch up always produces an anti-spin roll inertia moment.* If a spin oscillates

Figure 13
Pitch Inertia Moment



in pitch, its roll rate will vary as it pitches up and down.

OK, you deserve a break.

Propeller Gyroscopics

There's a fourth gyroscope to consider, and it's the one you actually learned about first in primary ground school—the propeller.

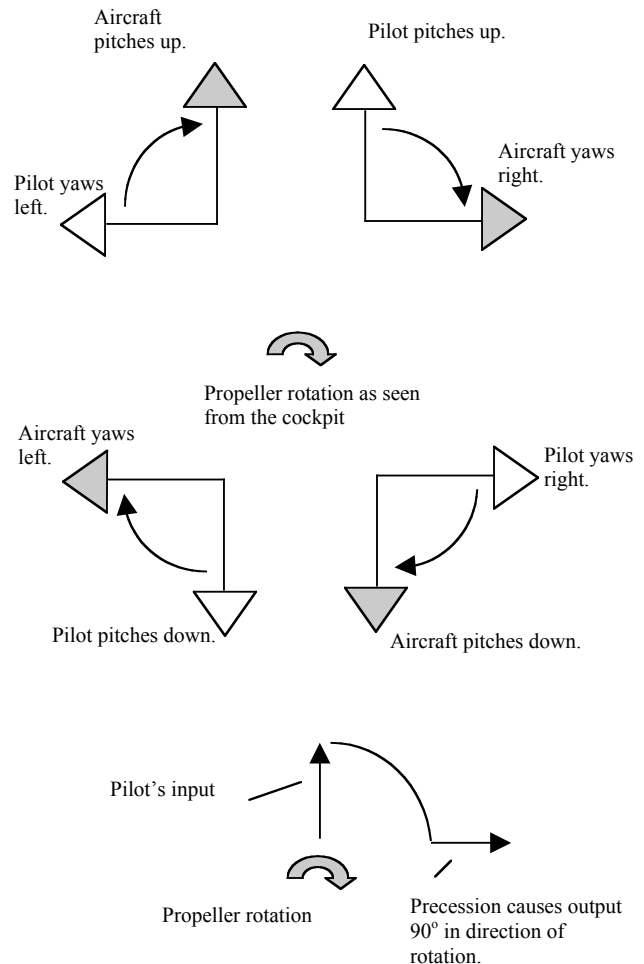
The effects of propeller gyroscopics are most evident in aircraft with heavy props and rather low directional and longitudinal stabilities, whenever the aircraft yaws or pitches rapidly at high prop rpm and low airspeed. It also helps if the prop is a substantial distance from the aircraft center of gravity and can exert some leverage. High rpm gets the gyroscope's angular momentum going, and low airspeed reduces the aircraft's stabilizing aerodynamic moments to the point where prop gyroscopic effects can become apparent. Gyroscopic precession (not just prop but also aircraft mass) is the essential driving force behind the aerobatic tumbling maneuvers derived from the Mother of Tumbles, the *lomcovak*.

Gyroscopic effects acting through the propeller cause yaw to produce a secondary pitch response, and pitch to produce a secondary yaw response, as Figure 14 describes. With a clockwise prop, yawing to the left causes the nose to precess up. A spin to the left can go flat with power, and possibly refuse to budge until power is reduced and the prop's angular momentum decreased.

In a spin to the right, power increases the gyroscopic tendency to bring the nose down and also generates an anti-spin slipstream effect over the tail. That may assist recovery (the gyroscopic part may also increase the tendency for a spin to go inverted if the pilot applies forward stick too aggressively). Many flight manuals—as well as the usual generic recovery procedures—specify power off at the start of spin recovery regardless of direction. The idea is to prevent the prop from contributing anything harmful during the ensuing confusion, and to prevent excessive airspeed during the recovery pull out.

Unlike other propeller-induced effects, gyroscopic precession occurs only in the presence of pitch or yaw *rates*, and depends on their magnitude. Precession tends to hold an aircraft's nose up in a turn to the left and to force it down in a turn to the right. Precession occurs throughout looping maneuvers and actually decreases the amount of rudder input that compensating for p-factor and spiraling

Figure 14
Prop-induced Gyroscopic Response



slipstream would otherwise require (right rudder in positive maneuvers).

In jets, the rotating masses of compressors and turbines supply the fourth gyroscope. A clockwise rotating engine, as seen from behind, produces a faster spin to the right. Remember the movie *The Right Stuff*, when Chuck Yeager took the rocket boosted F-104 above 100,000 feet and lost control? Aerodynamic damping was insignificant at that altitude. The air-breathing jet engine had been throttled back, but its rotation still produced a significant yaw couple. According to a well-placed authority, this took Yeager by surprise, *because he hadn't flown the flight profile in the simulator like everybody was supposed to* and was therefore late getting on the yaw thrusters.

Spins

Dumbbells

Figure 15 shows the fuselage and wing of an aircraft represented as dumbbells possessing the equivalent inertial characteristics. Rotation produces centrifugal forces that tend to drive the masses apart. In this situation, equal and opposite forces, acting along different lines, produce a rotary *inertial couple*.

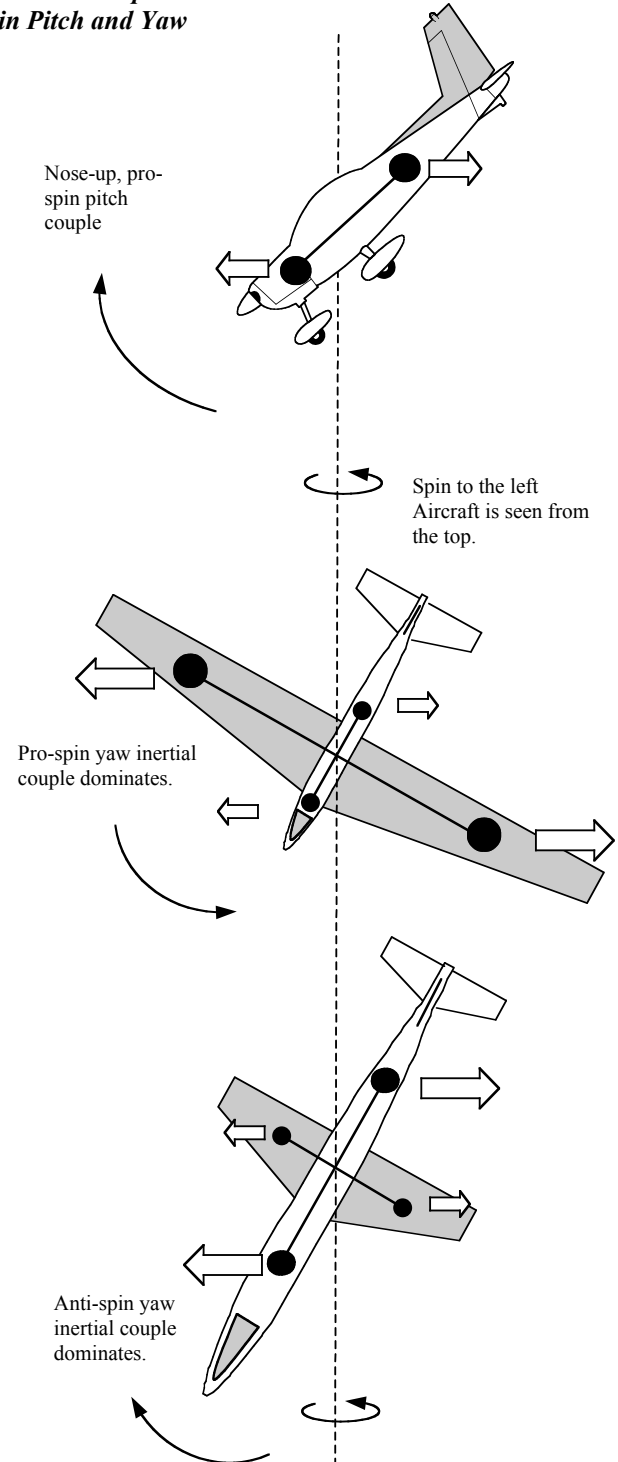
By itself the *fuselage couple tends to drive the nose up, flattening the spin attitude* (a pro-spin pitch couple).

The fuselage couple also tends to yaw the nose opposite the spin direction (anti-spin yaw couple), as in the bottom drawing. The dumbbells in the wings, however, tend to yaw the aircraft in the pro-spin direction. The ultimate inertial couple in yaw depends on the aircraft's mass distribution. *Yaw couple is pro-spin when the wings are the dominant mass ($I_{xx} > I_{yy}$). Yaw couple is anti-spin when the fuselage is the dominant mass ($I_{xx} < I_{yy}$).*

Fuel load affects spin behavior by shifting the balance. Filling the outboard or tip tanks is usually prohibited before intentional spins in aerobatic aircraft that have them, partly for weight concerns and partly because the buildup of greater angular momentum in roll and the greater pro-spin yaw couple have to be overcome during recovery.

Note that the rotary inertial couples have the same effect (the same positive or negative sign) as the gyroscopic inertia moments we've been discussing.

Figure 15
Inertial Couples
in Pitch and Yaw



Spins

Positives and Negatives

In the three simplified moment equations on the following page, the relative magnitudes of I_{xx} , I_{yy} , and I_{zz} determine whether an inertia moment generated by precession will be pro-spin or anti-spin. This is key to understanding how the distribution of mass in an aircraft affects spin rate and attitude, and how control inputs affect recovery.

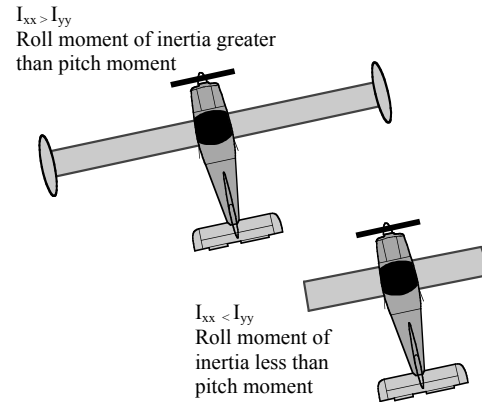
Remember that in the aerodynamics sign system positive values are up and/or to the right, negative values are down and/or to the left. (Remember from algebra that a negative times a negative equals a positive; a negative times a positive equals a negative; and a positive times a positive equals a positive.)

In the case of the *inertia moment in pitch*, M_i , imagine an airplane is spinning to the positive right. Roll, p , and yaw, r , are both positive in this case. Since I_{zz} is always the greatest moment of inertia, $(I_{zz} - I_{xx})$ is also positive. Since a positive times a positive times a positive equals a positive, the inertia moment in pitch, M_i , is positive. That means nose up, pro-spin. The same goes for spinning to the negative left, since a negative times a negative ($-p$ times $-r$) again equals a positive.

Look at *inertia moment in roll*, L_i : $(I_{yy} - I_{zz})$ is always negative, because I_{zz} is always greatest. In a spin to the left, a negative $(I_{yy} - I_{zz})$ times a negative yaw, r , times a positive or zero⁷ pitch, q , equals a positive. When spinning to the negative left, a positive (rightward) inertia moment in roll is anti-spin. In a spin to the positive right, the inertia moment in roll would be negative, again anti-spin.

In the last equation, the direction of the *inertia moment in yaw*, N_i , may be anti- or pro-spin depending on which is greatest, I_{xx} or I_{yy} . In other words, on whether the aircraft carries more of its mass in the wings ($I_{xx} > I_{yy}$), or in the fuselage ($I_{xx} < I_{yy}$).

Figure 16
 I_{yy} / I_{xx} Ratio



Axis	Inertia Moment	Angular Velocity	Moment of Inertia	Aircraft Component
x Roll	L_i (positive right, negative left)	Roll rate, p (positive right, negative left)	I_{xx} Roll Inertia	Predominantly the mass of the wings.
y Pitch	M_i (positive up, negative down)	Pitch rate, q (positive up, negative down)	I_{yy} Pitch Inertia	Predominantly the mass of the fuselage.
z Yaw	N_i (positive right, negative left)	Yaw rate, r (positive right, negative left)	I_{zz} Yaw Inertia (always greatest)	Mass of wings and fuselage.

⁷ Zero is neither negative nor positive.

Spins

Inertia moment in pitch = (yaw axis moment of inertia – roll axis moment of inertia) times roll rate times yaw rate

$$M_i = (I_{zz} - I_{xx})pr$$

Inertia moment in pitch, M_i , is nose-up, pro-spin. (I_{zz} always $> I_{xx}$; sign in brackets always positive)

Inertia moment in roll = (pitch axis moment of inertia – yaw axis moment of inertia) times pitch rate times yaw rate

$$L_i = (I_{yy} - I_{zz})qr$$

Inertia moment in roll, L_i , is anti-spin. (I_{yy} always $< I_{zz}$; sign in brackets always negative)

Inertia moment in yaw = (roll axis moment of inertia – pitch axis moment of inertia) times roll rate times pitch rate

$$N_i = (I_{xx} - I_{yy})pq$$

Inertia moment in yaw, N_i , may be pro-spin if roll inertia, I_{xx} , is greater than pitch inertia, I_{yy} ($I_{xx} > I_{yy}$; sign in brackets positive), or anti-spin if roll inertia is less than pitch inertia, ($I_{xx} < I_{yy}$; sign in brackets negative).

If the aircraft is wing loaded, and thus I_{xx} is greater than I_{yy} , the value in the brackets will be positive. In a spin to the positive right, p is positive, q is positive or zero, and so the applied inertia moment in yaw will be positive and pro-spin. In a spin to the negative left, p is negative, q is positive or zero. A negative times a positive is a negative, thus again causing pro-spin yaw. (Note how this also corresponds to the dumbbell illustration.)

Wing-loaded, $I_{xx} > I_{yy}$, aircraft generate pro-spin yaw inertia moments.

If the aircraft is fuselage loaded, and thus I_{xx} is less than I_{yy} , the value in the brackets will be negative. In a spin to the negative left, p is negative, q is positive or zero. The result of all three is positive, thus anti-spin in a spin to the negative left. It's also anti-spin in a spin to the positive right.

Fuselage-loaded, $I_{xx} < I_{yy}$, aircraft generate anti-spin inertia yaw moments.

Aircraft become spin resistant, *in terms of their inertia moments*, roughly when the ratio $I_{yy}/I_{xx} = 1.3$ or greater; in other words, when they lean toward the fuselage-loaded, with more pitch moment of inertia than roll moment of inertia.

Once they get going, however, spins in fuselage-loaded aircraft may be more oscillatory or have a tendency to go flat, due in part to their powerful inertia moment in pitch, M_i . Anti-spin aerodynamic moments generated by the rudder may not be sufficient for recovery against the angular momentum built up in yaw. So additional anti-spin yaw inertia moments, N_i , may be necessary for rescue. In this case, to generate those moments, recovery may require aileron into the spin direction in addition to out-spin rudder. This accelerates the roll rate, p , which precesses into a resulting anti-spin yaw inertia moment (when $I_{xx} < I_{yy}$). The adverse yaw provoked by the aileron going down on the outside wing might also provide some helpful anti-spin aerodynamic yaw moment (one certainly easier to visualize and understand than convoluted gyroscopic moments—and a perfectly good way to remember the recovery action), but generating that anti-spin yaw inertia moment is the main idea.

Note from the third formula that when mass shifts to the wings and roll moment of inertia becomes higher than pitch moment of inertia, the sign in the brackets becomes positive. Aileron into the spin now produces a pro-spin moment in yaw.

After this, is your head spinning? It's not easy.

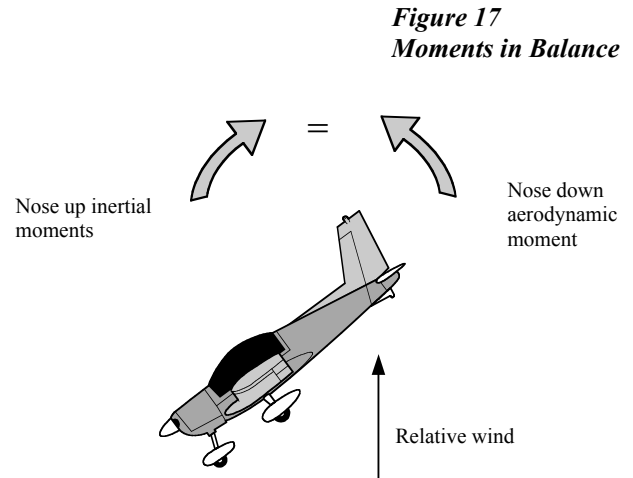
Spins

Moments in Balance

As already noted, in a steady spin, rotary and gyroscopic inertia moments about the aircraft's axes and aerodynamic moments about those axes balance (or sum to zero, since they have opposite signs). Take the example, in Figure 17, of the inertia moments in pitch, which are always nose-up. An aerodynamic, nose down moment, generated mostly by the horizontal stabilizer, balances this. (Even if you're holding back-stick in a practice spin, the aerodynamic moment is nose down.)

Likewise, the inertia moment in roll, which is always anti-spin, will be balanced by the pro-spin aerodynamic roll moments generated by sideslip and autorotation.

The situation around the yaw axis is more complicated, since the inertia moments in yaw are affected by the ratio I_{yy}/I_{xx} . They tend to be pro-spin in wing-loaded aircraft, as described above. In that case the balancing aerodynamic moment is the damping moment generated by the fuselage and tail. If the aircraft is fuselage-loaded, the inertia moments are anti-spin and balanced by the aerodynamic moments driving the spin (pro-spin yaw moments generated by autorotation and by rudder deflection if the spin is intentional).



Inertia Pitching Moment in Particular

Figure 18a shows a curve of inertia pitching moment plotted against angle of attack for a developed steady spin. It's always greatest at 45 degrees for a given angular velocity, and increases overall with angular velocity, ω (spin rate), as shown. Although inertia pitching moment is always positive (nose up), in this case it's plotted in the negative direction. Note that the curves each represent a different but constant angular velocity.

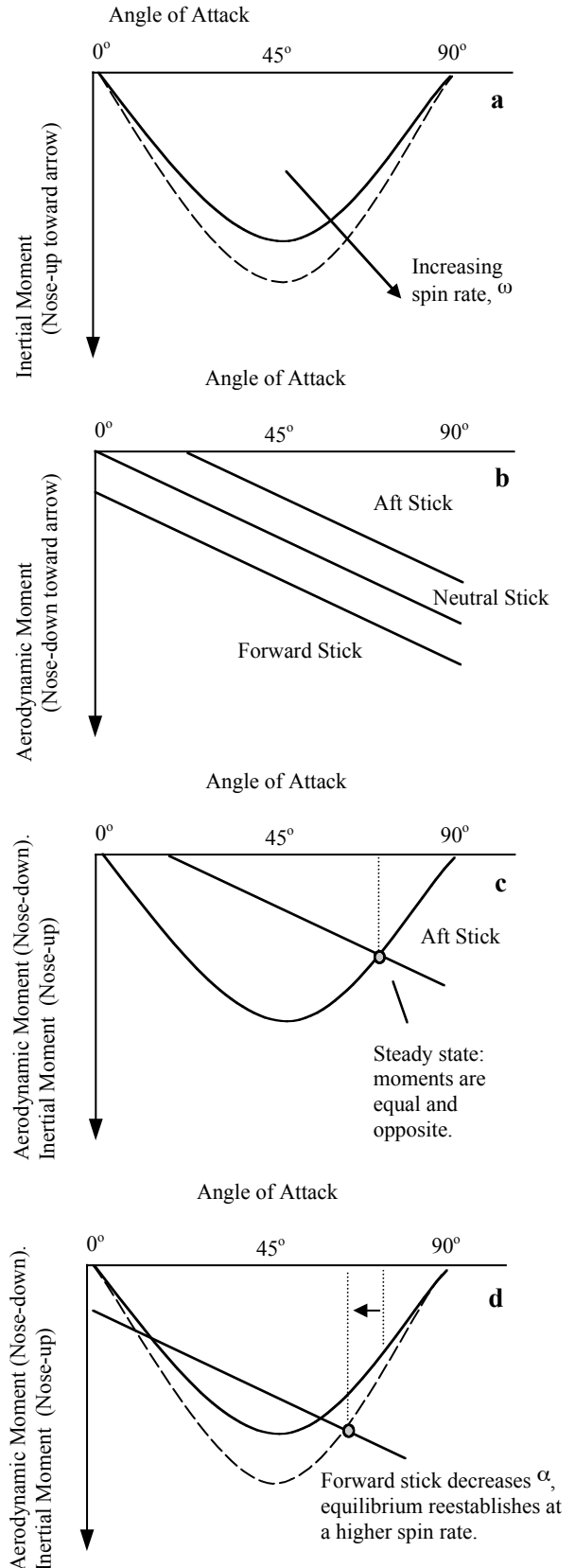
Figure 18b shows aerodynamic pitching moment, which is always nose down, plotted against angle of attack. Note the increase in aerodynamic moment as angle of attack increases and/or as the stick moves from aft to forward.

Both moments appear in Figure 18c. The point of intersection, where inertia pitching moment and aerodynamic pitching moment are equal and opposite, shows the angle of attack at which a stabilized spin can occur.

Finally, Figure 18d shows what happens when the stick is moved from aft to the forward position. Angle of attack decreases as the increased aerodynamic moment forces the nose down. At the new angle of attack, the line of increased aerodynamic moment intersects a new inertia moment curve. The aircraft stabilizes at a faster spin rate.

The figures underscore the importance of stick position and timing during spin recovery. *Applying forward stick, before opposite rudder, can accelerate a spin rate.* This increases the nose up inertia moment and actually makes the elevators less effective in reducing the angle of attack and breaking the spin—since they have more to work against. Holding the stick back decreases the aerodynamic moment and therefore the inertia moment as the system restores balance. Opposite rudder applied first allows the spin rate to decelerate to the point where forward stick can be applied and the elevator will have sufficient authority to decrease the angle of attack and break the spin. In practice, forward stick following opposite rudder typically leads to a momentary acceleration, but anti-spin aerodynamic moments quickly prevail.

Figure 18
Pitching Moments



Spins

Flightlab Ground School

11. Some Differences Between Prop Trainers and Passenger Jets

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As we work through our flight test and upset maneuvers, keep in mind the possible differences between our aircraft and the one you normally fly. Below is a quick review of some of the differences between typical aerobatic prop trainers and passenger jets.

Although they are different in quickness and in attainable rates of roll, pitch, and yaw, different in stability versus maneuverability, and different in control forces and gradients, *aerobatic trainers and passenger aircraft still follow the same set of rules*. If you exclude prop effects for our trainers and various inlet and thrust effects for jets, each “calculates” the same basic matrix, constantly working out a balance between the forces of lift, weight, thrust, and drag, and between the opposing moments generated about the aircraft’s axes. One can observe these basic forces and moments in any aircraft.

However, that doesn’t mean that they actually *have been observed* during flight test to anywhere near the same extent in all aircraft. For example, flight-test requirements for an FAA spin approved trainer take it to much higher combinations of angle of attack, α , and sideslip, β , than required for passenger jets. The demonstrated ability to recover from a six-turn spin is required of the former. Adequate stall warning and the demonstrated ability to recover from a stall without needing extraordinary pilot skill are required of the latter. Between the one obligation and the other lies plenty of unexplored territory.

Accordingly, when we do our maneuvering exercises in our trainers at high α and β , we’ll be in a regime where the behavior we observe will not be the same for all aircraft. That won’t invalidate our observations, or the principles of aerodynamics they illuminate, but it will make us think.

What happens if you simply scale up an aircraft, keeping the proportions and the wing loading constant? Aerodynamic moments increase approximately as the third power of aircraft

dimension. But moments of inertia increase as the fourth power—which slows down aircraft response.

Maneuvering

If you normally fly a people-hauler, you’ll immediately notice a livelier feeling in our aerobatic trainers:

In pitch, *short period* response will be faster than you’re accustomed to (your instructor will demonstrate short period response, and we’ll cover it in ground school). For our purposes, short period response is essentially a measure of aircraft quickness—how rapidly an airplane can respond to a control deflection in pitch. Our aircraft have high short period frequencies, and are also quick to respond in roll and yaw. The significance is that you’ll be learning maneuvers in an airplane that’s more instantaneously responsive (higher initial accelerations) around its axes than the one you normally fly, and can build up higher rates of rotation about those axes, as well. As a result, you may tend to overcontrol at first.

But once you get accustomed to the training aircraft, your response expectations may then become unrealistic in terms of what your own aircraft can do. Your own aircraft might also feel somewhat out of phase during upset maneuvers compared to the trainer. It might respond to the controls at different rates around each axis. Control forces may not be as nicely harmonized, which can make it more difficult to coordinate unusual-attitude control inputs in a smooth manner.

Stability and maneuverability mark the opposite ends of a continuum. Passenger aircraft designed with the geometry and mass distribution for high longitudinal stability (or equipped with control systems that produce high stability artificially) are reluctant to maneuver. As the center of gravity shifts aft, stability relaxes, maneuverability increases, and required elevator

Some Differences Between Prop Trainers and Passenger Jets

deflection and control forces diminish. An aft center of gravity also means that less down force has to be generated by the horizontal stabilizer to trim the aircraft, and there's less accompanying drag. Any down force at the tail in effect increases the weight of the aircraft, and so more lift is required of the main wing, which then has to operate at a higher angle of attack, again adding to the total drag necessary to trim. Transports designed with "relaxed" longitudinal stability can take advantage of lower drag, but require control systems that augment stability. If stability augmentation fails at aft loadings, the pilot needs to keep control movements in check, since response will be livelier.

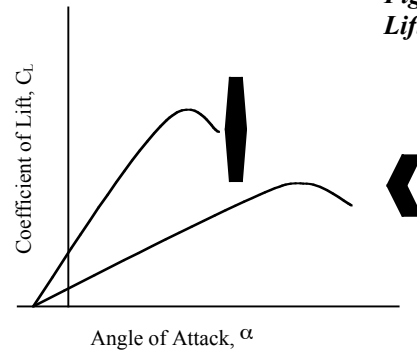
Maneuvering produces loads. While our trainers are designed for maneuvering and built for the high g-loads that maneuvering entails, passenger aircraft are designed for a narrower maneuver envelope. Because aggressive maneuvering could produce excessively high structural loads, low-g passenger aircraft require higher control forces and steeper gradients of stick-force-per-g to discourage the pilot from exceeding structural limits. Aircraft stressed for higher g need lower pitch control forces and shallower gradients to avoid exceeding a pilot's strength during highly accelerated maneuvers. A 2-g pull in our aircraft will require much less force than in yours.

Propeller Effects

Propeller effects include spiraling slipstream, p-factor, precession, and torque. These tend to make the nose wander on an aerobatic aircraft in response to changes in power (slipstream effects), changes in angle of attack and sideslip (p-factor), and changes in pitch and yaw rates (precession), and can introduce rolling moments (torque). Lacking such annoyances, jet's track straighter and require much less attention to rudder for yaw control during normal aerobatics. In fact, the most-welcome discovery in the transition from aerobatics in a propeller aircraft to aerobatics in jets is the absence of the footwork associated with a prop, and the lack of directional trim change due to speed change that propeller effects require.

On the other hand, the least-welcome discovery is the loss of on-command airflow associated with a prop. At low speeds, prop-induced slipstream over the wing and tail surfaces helps maintain longitudinal and directional control.

Figure 1
Lift Curve



The enhanced airflow over the wing can decrease power-on stall speed by a considerable amount, and by decreasing effective angle of attack over the wing roots tends to increase the overall deck angle at which stalls occur. The effects of power increase on stall speed and recovery control are more immediate and pronounced for propeller-driven aircraft than for jets, which don't see a marked induced airflow with power application but instead have to accelerate to build up the dynamic pressure necessary to reestablish lift and control authority. And propellers provide almost immediate thrust, while jets spool up and generate thrust and aircraft acceleration more slowly. These differences are especially important during the approach phase of flight, when speed control and engine rpm management become critical in jets. Excessive sink rates that require only a power increase for immediate correction in a prop aircraft take more time to correct in a jet.

Lift and Drag

Lift curve slope affects stall behavior. Wing sweep has the result shown in Figure 1. When slope is reduced, C_L varies less rapidly with angle of attack, α . For a straight wing, small differences in angle of attack produce notable changes in lift and potentially a quicker stall recovery when the nose goes down. Swept wings stall at higher angles of attack, and the stall and recovery may not be so well defined—more a mush than a break. Induced drag is also higher in the stall region with swept wings.

At idle, a propeller creates substantial drag, while a jet still manages a small amount of thrust. The ability to produce parasite drag with the prop one moment, and thrust the next makes speed control an easier matter. In a jet, with its relative lack of parasite drag to slow things down

Some Differences Between Prop Trainers and Passenger Jets

and its delay in thrust to speed things up, plus greater inertia to overcome, speed control using throttle requires more anticipation and planning

Because of the high induced drag at low speed, shallower lift curve peak, greater aircraft inertia, and longer spool-up time, stall recovery with minimum altitude loss can be touchy in jets. The method usually taught is to set the nose close to the horizon, add full power, and regain flying speed at as high a coefficient of lift as possible— C_L then being gradually reduced as airspeed builds. However, high-altitude recoveries may require putting the nose down to compensate for deficiencies in thrust. Transport pilots have been known to apply power during a recovery at altitude, *but attempt to hold the nose level*, allowing the stall to persist, even through repeated pitch breaks and buffet, until the airplane loses lateral control before hitting the ground. (Airborne Express, Douglas DC-8-63, Narrows Virginia, 12/22/96.)

The Rudder

On jets, the rudder is secondary to aileron and elevator. Without the various propeller effects to tame, rudders are used for countering asymmetrical thrust during engine failure and for directional control in crosswind landings. Pilots otherwise tend to keep their feet on the floor and let the yaw damper maintain turn coordination, especially in swept-wing aircraft that Dutch roll in response to sideslip. As a result, jet pilots often have to rediscover the rudder when learning unusual-attitude skills in aerobatic trainers (just as prop pilots have to learn to stop playing with their feet when transitioning the other way). In transferring those rudder skills back to their normal flying, jet pilots need to consider that the vertical fin and rudder structure and the rudder limiting system in their own aircraft may not be designed for the loads that poorly executed or maximum performance recoveries might generate or require. They'll also need to remember that, compared to a straight-wing trainer, in a large, high-yaw-inertia swept-wing aircraft it can be difficult to apply the rudder in phase to augment roll rate. Possibly, at first nothing happens, then too much happens and the aircraft over-rotates and begins a Dutch roll cycle. We'll need to keep this in mind throughout our flights, as we think about how (or if) specific techniques learned in the trainer should be transferred to other aircraft.

Speed and Altitude

Other differences between aerobatic trainers and jets include the latter's greater speed and altitude envelopes. Our trainers can't go fast enough and climb high enough to become involved with Mach-induced buffet and trim effects, or with the narrowing speed band between Mach buffet and low-speed stall (the "coffin corner"). Nor can they climb high enough to experience the change in stability and flying qualities caused by the reduction in aerodynamic damping due to decreased atmospheric density.

Finally, because of their lower speeds, at a given g-load our trainers will fly much tighter radii than jets during looping maneuvers or pull-up recoveries from nose-down attitudes. They can pull to higher limiting g-loads than passenger jets, as well. For a given g the radius of a turn (or of a pull-up) at any instant varies directly with the square of the true airspeed. Double the speed means four times the altitude consumed. As a result, the altitude required during maneuvers in the vertical plane will be much less in an aerobatic trainer than in a jet. The latter needs exponentially more sky.

Some Differences Between Prop Trainers and Passenger Jets

Flightlab Ground School

12. Vortex Wake Turbulence

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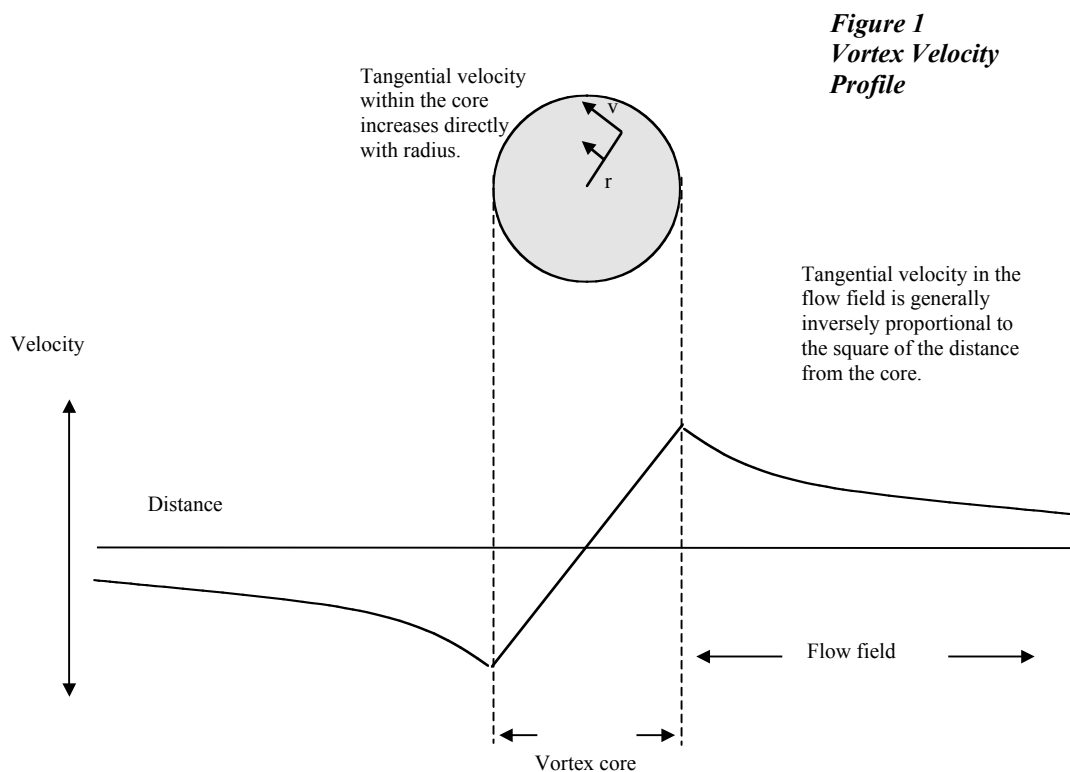
Vortex Characteristics

The wake generated behind an aircraft has two sources. The first is turbulence caused by profile drag and engine thrust—a disorganized motion that diminishes to a harmless level several wingspans behind the aircraft. The second source is the vortex pair. The vortices are highly organized and decay only slowly, persisting for miles behind the generating aircraft.

The FAA publications do a good job of describing the typical behaviors of aircraft vortex wakes, and in describing the appropriate avoidance techniques for aircraft following behind. But the graphics used (often a widening spiral) tend to give a misleading impression of

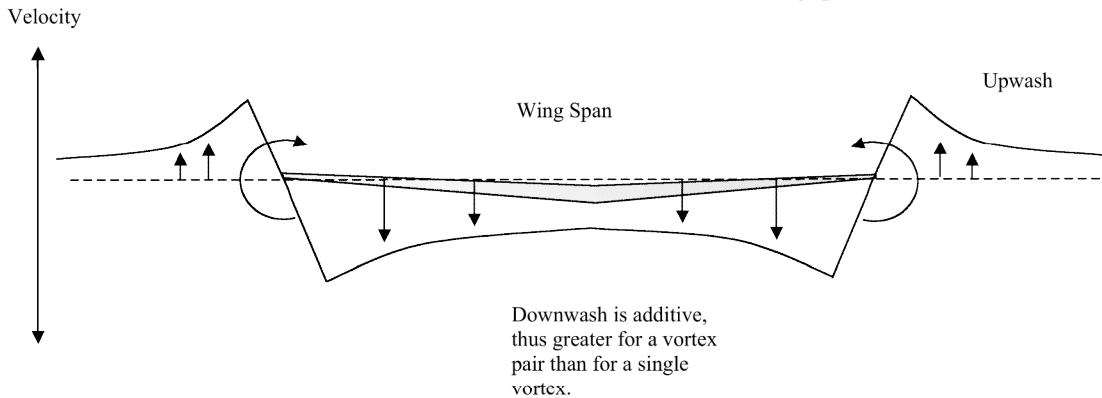
vortex structure and therefore of aircraft response. We'll address that here. In addition, in ground school you'll see wind tunnel films showing how the vortex rolls up around a wingtip, and also videos from NASA that show vortex structure and encounter dynamics downstream. The NASA videos reveal how mobile the vortex core is in turbulent conditions, and how abruptly it can change position in response to penetration by a large aircraft.

Figure 1 shows vortex structure in terms of the tangential velocity at increasing distance from the core.



Vortex Wake Turbulence

Figure 2
Combined Velocity Field,
Both Wingtips



Core size depends on vortex intensity. The cores from transport aircraft have been estimated to be anywhere from two to five feet in diameter. Core size is believed to be of minor importance in a vortex encounter, as long as the ratio of the wingspan of the follower aircraft to core diameter is large. The radius of influence of the vortex flow field surrounding the core is typically twenty-five to fifty feet, according to the FAA.

The vortex pair descends behind the generating aircraft because of the mutual induction between the two fields of circulation—each vortex pushes the other down. The rate of descent depends directly on vortex strength, and on wingspan: for a given vortex strength, the greater the wingspan the slower the descent. It also depends on temperature stratification in the atmosphere (a descending vortex pair heats up due to adiabatic compression and becomes buoyant). Crosswinds can reduce sink rates, sometimes more on one vortex than the other, causing the pair to tilt. Vortices formed close to the runway have been observed to “bounce” back to higher altitude, indicating that the recommendation given in the *Aeronautical Information Manual* that pilots fly above the glide path of the preceding aircraft may not always ensure protection.

Circulation is a measure of the angular momentum of the air in the surrounding flow field, and defines the strength of a vortex. That strength is directly proportional to the weight of the generating aircraft and inversely proportional

to its velocity and wingspan (speed and span reduce the vortex).

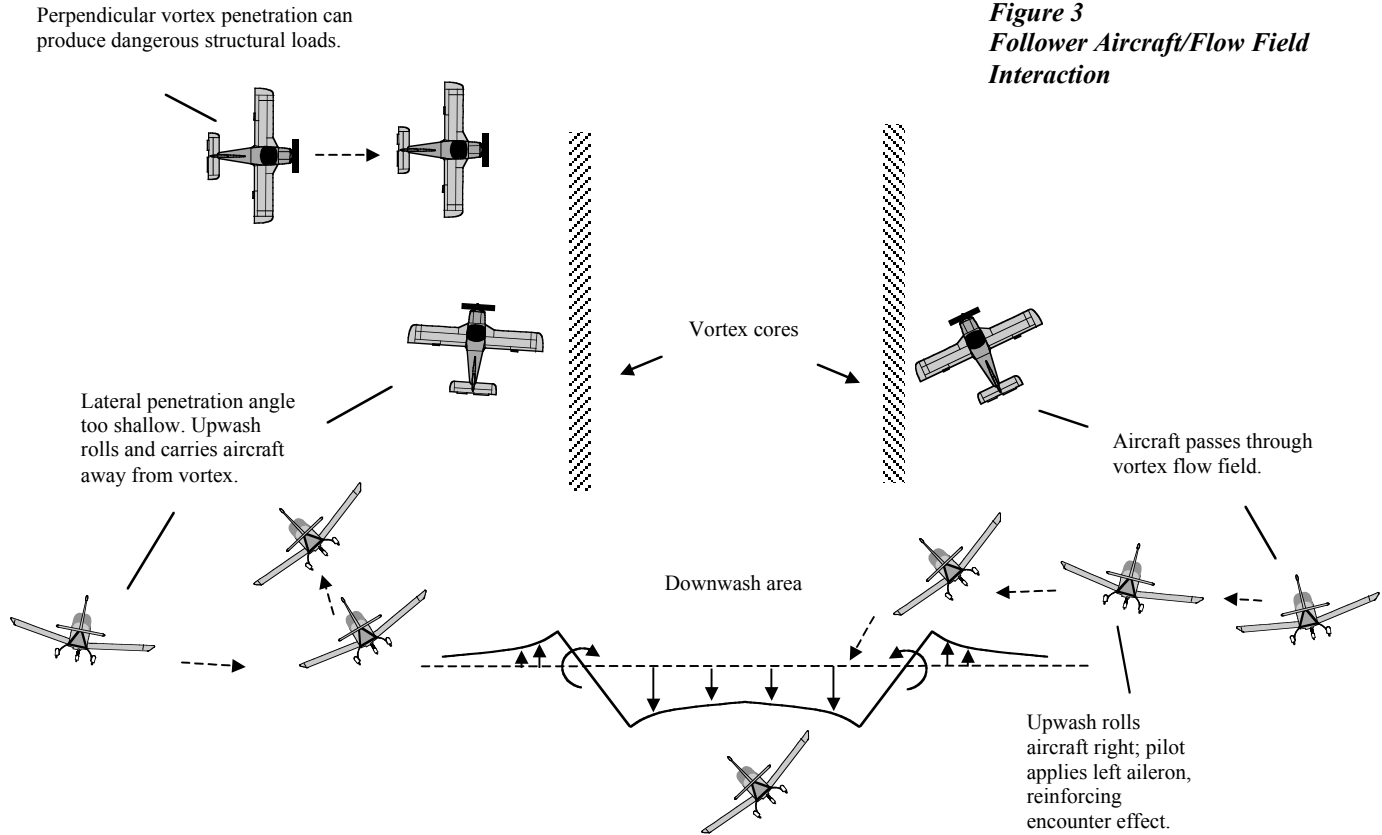
Size and strength of the flow field determine the risk to the follower. A hazardous situation can occur when the leading aircraft is landing at its maximum landing weight, and the follower aircraft is operating at minimum weight—and therefore with minimum roll inertia.

When the follower aircraft has a large span, the encounter forces are distributed over a greater lateral distance. The induced rolling moments build up more gradually and are less intense relative to the aircraft’s aileron control power.

Studies have shown that a follower aircraft with the same span as the generating aircraft will typically have enough maximum aileron control power to handle wake-induced rolling moments. Pilots, however, consider the need for maximum control inputs as unacceptably hazardous.

Vortex Wake Turbulence

Figure 3
Follower Aircraft/Flow Field
Interaction



Simulations, wind tunnel studies, and in-flight research demonstrate that penetrating a vortex core is unlikely. Depending on the follower aircraft's intercept angle, speed, and inertia, the flow field tends to roll the aircraft away from the vortex. In a more serious encounter, the aircraft can be carried over the core and through the downwash between the generator's wingtips (Figure 3, right).

Because penetrating, let alone staying within, the vortex core is unlikely, pilots shouldn't conclude from an initial, rapid roll acceleration (or from upset training) that continuing to roll the aircraft through 360 degrees in the vortex direction constitutes an automatic recovery procedure. Although that type of recovery could become necessary when a small aircraft follows a heavy one, the probability is low that a roll excursion will go that far.

Pilots often inadvertently reinforce the rolling moments generated by a vortex encounter. For example, an aircraft entering the right-hand vortex from the outside will experience an abrupt

rolling moment to the right, as in Figure 3. Responding with left aileron will reinforce the vortex-induced rolling moment once the left wing passes the core and enters the downwash area.

The interaction between the vortex flow field and the aircraft's vertical tail produces yawing moments that often result in Dutch roll oscillation, especially with swept-wing aircraft. Pilots trying to settle the aircraft down tend to get their control inputs out of phase and instead amplify the oscillation.

According to the Flight Safety Foundation, the especially bad news is that more than two-thirds of all wake vortex accidents and reported incidents happen over the runway threshold.

Vortex Wake Turbulence

Flightlab Ground School

13. A Selective Summary of Certification Requirements FAR Parts 23 & 25

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The Federal Aviation Regulation Part 23 Airworthiness Standards covers normal, utility, aerobatic, and commuter category airplanes. According to section 23.3:

“(a) The normal category is limited to airplanes that have a seating configuration, excluding pilot seats, of nine or less, a maximum certificated takeoff weight of 12,500 pounds or less, and intended for nonacrobatic operation. Nonacrobatic operation includes:

- (1) Any maneuver incident to normal flying;
- (2) Stalls (except whip stalls); and
- (3) Lazy eights, chandelles, and steep turns, in which the angle of bank is not more than 60 degrees.

(b) The utility category is limited to airplanes that have a seating configuration, excluding pilot seats, of nine or less, a maximum certificated takeoff weight of 12,500 pounds or less, and intended for limited acrobatic operation. Airplanes certificated in the utility category may be used in any of the operations covered under paragraph (a) of this section and in limited acrobatic operations. Limited acrobatic operation includes:

- (1) Spins (if approved for the particular type of airplane); and
- (2) Lazy eights, chandelles, and steep turns, or similar maneuvers, in which the angle of bank is more than 60 degrees but not more than 90 degrees.

(c) The acrobatic category is limited to airplanes that have a seating configuration, excluding pilot seats, of nine or less, a maximum certificated takeoff weight of 12,500 pounds or less, and intended for use without restrictions, other than those shown to be necessary as a result of required flight tests.

(d) The commuter category is limited to propeller-driven, multiengine airplanes that have a seating configuration, excluding pilot seats, of 19 or less, and a maximum certificated takeoff weight of 19,000 pounds or less. The commuter category operation is limited to any maneuver incident to normal flying, stalls (except whip stalls), and steep turns, in which the angle of bank is not more than 60 degrees.

(e) Except for commuter category, airplanes may be type certificated in more than one category if the requirements of each requested category are met.”

FAR Part 25 contains the airworthiness standards for transport category airplanes.

We’ve reproduced some of the regulations that pertain to maneuvers we fly in the course, and that set the baseline for aircraft behavior. You’ll see that the standards are not always the same in both parts. If you really want to enter the belly of the beast, Parts 23 and 25 are available online.

Certification Requirements

Far 23	FAR 25
Controllability and Maneuverability	Controllability and Maneuverability
<p>§23.147 Directional and lateral control.</p> <p>(a) For each multiengine airplane, it must be possible, while holding the wings level within five degrees, to make sudden changes in heading safely in both directions. This ability must be shown at $1.4 V_{S1}$ with heading changes up to 15 degrees, except that the heading change at which the rudder force corresponds to the limits specified in §23.143 need not be exceeded, with the --</p> <p>(1) Critical engine inoperative and its propeller in the minimum drag position;</p> <p>(2) Remaining engines at maximum continuous power;</p> <p>(3) Landing gear --</p> <p>(i) Retracted; and</p> <p>(ii) Extended; and</p> <p>(4) Flaps retracted.</p> <p>(b) For each multiengine airplane, it must be possible to regain full control of the airplane without exceeding a bank angle of 45 degrees, reaching a dangerous attitude or encountering dangerous characteristics, in the event of a sudden and complete failure of the critical engine, making allowance for a delay of two seconds in the initiation of recovery action appropriate to the situation, with the airplane initially in trim, in the following condition:</p> <p>(1) Maximum continuous power on each engine;</p> <p>(2) The wing flaps retracted;</p> <p>(3) The landing gear retracted;</p> <p>(4) A speed equal to that at which compliance with §23.69(a) has been shown; and</p> <p>(5) All propeller controls in the position at which compliance with §23.69(a) has been shown.</p> <p>(c) For all airplanes, it must be shown that the airplane</p>	<p>§25.147 Directional and lateral control.</p> <p>(a) <i>Directional control; general.</i> It must be possible, with the wings level, to yaw into the operative engine and to safely make a reasonably sudden change in heading of up to 15 degrees in the direction of the critical inoperative engine. This must be shown at $1.4V_{S1}$ for heading changes up to 15 degrees (except that the heading change at which the rudder pedal force is 150 pounds need not be exceeded), and with --</p> <p>(1) The critical engine inoperative and its propeller in the minimum drag position;</p> <p>(2) The power required for level flight at $1.4 V_{S1}$, but not more than maximum continuous power;</p> <p>(3) The most unfavorable center of gravity;</p> <p>(4) Landing gear retracted;</p> <p>(5) Flaps in the approach position; and</p> <p>(6) Maximum landing weight.</p> <p>(b) <i>Directional control; airplanes with four or more engines.</i> Airplanes with four or more engines must meet the requirements of paragraph (a) of this section except that --</p> <p>(1) The two critical engines must be inoperative with their propellers (if applicable) in the minimum drag position;</p> <p>(2) [Reserved]</p> <p>(3) The flaps must be in the most favorable climb position.</p> <p>(c) <i>Lateral control; general.</i> It must be possible to make 20° banked turns, with and against the inoperative engine, from steady flight at a speed equal to $1.4 V_{S1}$, with --</p> <p>(1) The critical engine inoperative and its propeller (if applicable) in the minimum drag position;</p> <p>(2) The remaining engines at maximum continuous power;</p> <p>(3) The most unfavorable center of gravity;</p>

Certification Requirements

is safely controllable without the use of the primary lateral control system in any all-engine configuration(s) and at any speed or altitude within the approved operating envelope. It must also be shown that the airplane's flight characteristics are not impaired below a level needed to permit continued safe flight and the ability to maintain attitudes suitable for a controlled landing without exceeding the operational and structural limitations of the airplane. If a single failure of any one connecting or transmitting link in the lateral control system would also cause the loss of additional control system(s), compliance with the above requirement must be shown with those additional systems also assumed to be inoperative.

[Doc. No. 27807, 61 FR 5188, Feb. 9, 1996]

§23.155 Elevator control force in maneuvers.

(a) The elevator control force needed to achieve the positive limit maneuvering load factor may not be less than:

(1) For wheel controls, $W/100$ (where W is the maximum weight) or 20 pounds, whichever is greater, except that it need not be greater than 50 pounds; or

(2) For stick controls, $W/140$ (where W is the maximum weight) or 15 pounds, whichever is greater, except that it need not be greater than 35 pounds.

(b) The requirement of paragraph (a) of this section must be met at 75 percent of maximum continuous power for reciprocating engines, or the maximum continuous power for turbine engines, and with the wing flaps and landing gear retracted --

(1) In a turn, with the trim setting used for wings level

(4) Landing gear (i) retracted and (ii) extended;

(5) Flaps in the most favorable climb position; and

(6) Maximum takeoff weight.

(d) *Lateral control; airplanes with four or more engines.*

Airplanes with four or more engines must be able to make 20° banked turns, with and against the inoperative engines, from steady flight at a speed equal to 1.4 V_{S1} , with maximum continuous power, and with the airplane in the configuration prescribed by paragraph (b) of this section.

(e) *Lateral control; all engines operating.* With the engines operating, roll response must allow normal maneuvers (such as recovery from upsets produced by gusts and the initiation of evasive maneuvers). There must be enough excess lateral control in sideslips (up to sideslip angles that might be required in normal operation), to allow a limited amount of maneuvering and to correct for gusts. Lateral control must be enough at any speed up to V_{FC}/M_{FC} to provide a peak roll rate necessary for safety, without excessive control forces or travel.

[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-42, 43 FR 2321, Jan. 16, 1978; Amdt. 25-72, 55 FR 29774, July 20, 1990]

Certification Requirements

flight at V_O ; and

(2) In a turn with the trim setting used for the maximum wings level flight speed, except that the speed may not exceed V_{NE} or V_{MO}/M_{MO} , whichever is appropriate.

(c) There must be no excessive decrease in the gradient of the curve of stick force versus maneuvering load factor with increasing load factor.

[Amdt. 23-14, 38 FR 31819, Nov. 19, 1973; 38 FR 32784, Nov. 28, 1973, as amended by Amdt. 23-45, 58 FR 42158, Aug. 6, 1993; Amdt. 23-50, 61 FR 5189 Feb. 9, 1996]

[\[TOP\]](#)

§23.157 Rate of roll.

(a) *Takeoff*. It must be possible, using a favorable combination of controls, to roll the airplane from a steady 30-degree banked turn through an angle of 60 degrees, so as to reverse the direction of the turn within:

(1) For an airplane of 6,000 pounds or less maximum weight, 5 seconds from initiation of roll; and

(2) For an airplane of over 6,000 pounds maximum weight,

$$(W+500)/1,300$$

seconds, but not more than 10 seconds, where W is the weight in pounds.

(b) The requirement of paragraph (a) of this section must be met when rolling the airplane in each direction with --

(1) Flaps in the takeoff position;

(2) Landing gear retracted;

(3) For a single-engine airplane, at maximum takeoff power; and for a multiengine airplane with the critical engine inoperative and the propeller in the minimum drag position, and the other engines at maximum takeoff power; and

(4) The airplane trimmed at a speed equal to the greater of $1.2 V_{S1}$ or $1.1 V_{MC}$, or as nearly as possible in trim for

Certification Requirements

<p>straight flight.</p> <p>(c) <i>Approach</i>. It must be possible, using a favorable combination of controls, to roll the airplane from a steady 30-degree banked turn through an angle of 60 degrees, so as to reverse the direction of the turn within:</p> <p>(1) For an airplane of 6,000 pounds or less maximum weight, 4 seconds from initiation of roll; and</p> <p>(2) For an airplane of over 6,000 pounds maximum weight,</p> $(W+2,800)/2,200$ <p>seconds, but not more than 7 seconds, where W is the weight in pounds.</p> <p>(d) The requirement of paragraph (c) of this section must be met when rolling the airplane in each direction in the following conditions --</p> <p>(1) Flaps in the landing position(s);</p> <p>(2) Landing gear extended;</p> <p>(3) All engines operating at the power for a 3 degree approach; and</p> <p>(4) The airplane trimmed at V_{REF}.</p> <p>[Amdt. 23-14, 38 FR 31819, Nov. 19, 1973, as amended by Amdt. 23-45, 58 FR 42158, Aug. 6, 1993; Amdt. 23-50, 61 FR 5189, Feb. 9, 1996]</p> <p style="text-align: center;">Stability</p> <p>§23.171 General.</p> <p>The airplane must be longitudinally, directionally, and laterally stable under §§23.173 through 23.181. In addition, the airplane must show suitable stability and control "feel" (static stability) in any condition normally encountered in service, if flight tests show it is necessary for safe operation.</p> <p>§23.173 Static longitudinal stability.</p>	<p style="text-align: center;">Stability</p> <p>§25.171 General.</p> <p>The airplane must be longitudinally, directionally, and laterally stable in accordance with the provisions of §§25.173 through 25.177. In addition, suitable stability and control feel (static stability) is required in any condition normally encountered in service, if flight tests show it is necessary for safe operation.</p> <p>[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-7, 30 FR 13117, Oct. 15, 1965]</p>
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Certification Requirements

<p>§23.173 Static longitudinal stability.</p> <p>Under the conditions specified in §23.175 and with the airplane trimmed as indicated, the characteristics of the elevator control forces and the friction within the control system must be as follows:</p> <p>(a) A pull must be required to obtain and maintain speeds below the specified trim speed and a push required to obtain and maintain speeds above the specified trim speed. This must be shown at any speed that can be obtained, except that speeds requiring a control force in excess of 40 pounds or speeds above the maximum allowable speed or below the minimum speed for steady unstalled flight, need not be considered.</p> <p>(b) The airspeed must return to within the tolerances specified for applicable categories of airplanes when the control force is slowly released at any speed within the speed range specified in paragraph (a) of this section. The applicable tolerances are --</p> <p>(1) The airspeed must return to within plus or minus 10 percent of the original trim airspeed; and</p> <p>(2) For commuter category airplanes, the airspeed must return to within plus or minus 7.5 percent of the original trim airspeed for the cruising condition specified in §23.175(b).</p> <p>(c) The stick force must vary with speed so that any substantial speed change results in a stick force clearly perceptible to the pilot.</p> <p>[Doc. No. 4080, 29 FR 17955, Dec. 18, 1964, as amended by Amdt. 23-14, 38 FR 31820 Nov. 19, 1973; Amdt. 23-34, 52 FR 1828, Jan. 15, 1987]</p> <p>§23.177 Static directional and lateral stability.</p> <p>(a) The static directional stability, as shown by the tendency to recover from a wings level sideslip with the rudder free, must be positive for any landing gear and flap position appropriate to the takeoff, climb, cruise, approach, and landing configurations. This must be shown with symmetrical power up to maximum continuous power, and at speeds from $1.2 V_{S1}$ up to the maximum allowable speed for the condition being investigated. The angle of sideslip for these tests must be appropriate to the type of airplane. At larger angles of sideslip, up to that at which full rudder is used or a control force limit in §23.143 is reached, whichever occurs first, and at speeds from $1.2 V_{S1}$ to V_O, the rudder</p>	<p>§25.173 Static longitudinal stability.</p> <p>Under the conditions specified in §25.175, the characteristics of the elevator control forces (including friction) must be as follows:</p> <p>(a) A pull must be required to obtain and maintain speeds below the specified trim speed, and a push must be required to obtain and maintain speeds above the specified trim speed. This must be shown at any speed that can be obtained except speeds higher than the landing gear or wing flap operating limit speeds or <i>VFC/MFC</i>, whichever is appropriate, or lower than the minimum speed for steady unstalled flight.</p> <p>(b) The airspeed must return to within 10 percent of the original trim speed for the climb, approach, and landing conditions specified in §25.175 (a), (c), and (d), and must return to within 7.5 percent of the original trim speed for the cruising condition specified in §25.175(b), when the control force is slowly released from any speed within the range specified in paragraph (a) of this section.</p> <p>(c) The average gradient of the stable slope of the stick force versus speed curve may not be less than 1 pound for each 6 knots.</p> <p>(d) Within the free return speed range specified in paragraph (b) of this section, it is permissible for the airplane, without control forces, to stabilize on speeds above or below the desired trim speeds if exceptional attention on the part of the pilot is not required to return to and maintain the desired trim speed and altitude.</p> <p>[Amdt. 25-7, 30 FR 13117, Oct. 15, 1965]</p> <p>§25.177 Static lateral-directional stability.</p> <p>(a)-(b) [Reserved]</p> <p>(c) In straight, steady sideslips, the aileron and rudder control movements and forces must be substantially proportional to the angle of sideslip in a stable sense; and the factor of proportionality must lie between limits found necessary for safe operation throughout the range of sideslip angles appropriate to the operation of the airplane. At greater angles, up to the angle at which full rudder force of 180 pounds is obtained, the rudder pedal forces may not reverse; and increased rudder deflection must be needed for increased angles of sideslip. Compliance with this paragraph must be demonstrated for all landing gear and flap positions and symmetrical power conditions at speeds from $1.2 V_{S1}$ to</p>
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Certification Requirements

<p>pedal force must not reverse.</p> <p>(b) The static lateral stability, as shown by the tendency to raise the low wing in a sideslip, must be positive for all landing gear and flap positions. This must be shown with symmetrical power up to 75 percent of maximum continuous power at speeds above $1.2 V_{S1}$ in the take off configuration(s) and at speeds above $1.3 V_{S1}$ in other configurations, up to the maximum allowable speed for the configuration being investigated, in the takeoff, climb, cruise, and approach configurations. For the landing configuration, the power must be that necessary to maintain a 3 degree angle of descent in coordinated flight. The static lateral stability must not be negative at $1.2 V_{S1}$ in the takeoff configuration, or at $1.3 V_{S1}$ in other configurations. The angle of sideslip for these tests must be appropriate to the type of airplane, but in no case may the constant heading sideslip angle be less than that obtainable with a 10 degree bank, or if less, the maximum bank angle obtainable with full rudder deflection or 150 pound rudder force.</p> <p>(c) Paragraph (b) of this section does not apply to acrobatic category airplanes certificated for inverted flight.</p> <p>(d) In straight, steady slips at $1.2 V_{S1}$ for any landing gear and flap positions, and for any symmetrical power conditions up to 50 percent of maximum continuous power, the aileron and rudder control movements and forces must increase steadily, but not necessarily in constant proportion, as the angle of sideslip is increased up to the maximum appropriate to the type of airplane. At larger slip angles, up to the angle at which full rudder or aileron control is used or a control force limit contained in §23.143 is reached, the aileron and rudder control movements and forces must not reverse as the angle of sideslip is increased. Rapid entry into, and recovery from, a maximum sideslip considered appropriate for the airplane must not result in uncontrollable flight characteristics.</p> <p>[Doc. No. 27807, 61 FR 5190, Feb. 9, 1996]</p> <p>§23.181 Dynamic stability.</p> <p>(a) Any short period oscillation not including combined lateral-directional oscillations occurring between the stalling speed and the maximum allowable speed appropriate to the configuration of the airplane must be heavily damped with the primary controls --</p>	<p>VFE, VLE, or VFC/MFC, as appropriate.</p> <p>(d) The rudder gradients must meet the requirements of paragraph (c) at speeds between V_{MO}/M_{MO} and V_{FC}/M_{FC} except that the dihedral effect (aileron deflection opposite the corresponding rudder input) may be negative provided the divergence is gradual, easily recognized, and easily controlled by the pilot.</p> <p>[Amdt. 25-72, 55 FR 29774, July 20, 1990; 55 FR 37607, Sept. 12, 1990]</p> <p>§25.181 Dynamic stability.</p> <p>(a) Any short period oscillation, not including combined lateral-directional oscillations, occurring between $1.2 V_S$ and maximum allowable speed appropriate to the configuration of the airplane must be heavily damped with the primary controls --</p>
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Certification Requirements

<p>(1) Free; and</p> <p>(2) In a fixed position.</p> <p>(b) Any combined lateral-directional oscillations ("Dutch roll") occurring between the stalling speed and the maximum allowable speed appropriate to the configuration of the airplane must be damped to 1/10 amplitude in 7 cycles with the primary controls --</p> <p>(1) Free; and</p> <p>(2) In a fixed position.</p> <p>(c) If it is determined that the function of a stability augmentation system, reference §23.672, is needed to meet the flight characteristic requirements of this part, the primary control requirements of paragraphs (a)(2) and (b)(2) of this section are not applicable to the tests needed to verify the acceptability of that system.</p> <p>(d) During the conditions as specified in §23.175, when the longitudinal control force required to maintain speeds differing from the trim speed by at least plus and minus 15 percent is suddenly released, the response of the airplane must not exhibit any dangerous characteristics nor be excessive in relation to the magnitude of the control force released. Any long-period oscillation of flight path, phugoid oscillation, that results must not be so unstable as to increase the pilot's workload or otherwise endanger the airplane.</p> <p>[Amdt. 23-21, 43 FR 2318, Jan. 16, 1978, as amended by Amdt. 23-45, 58 FR 42158, Aug. 6, 1993]</p>	<p>(1) Free; and</p> <p>(2) In a fixed position.</p> <p>(b) Any combined lateral-directional oscillations ("Dutch roll") occurring between 1.2 V_S and maximum allowable speed appropriate to the configuration of the airplane must be positively damped with controls free, and must be controllable with normal use of the primary controls without requiring exceptional pilot skill.</p> <p>[Amdt. 25-42, 43 FR 2322, Jan. 16, 1978, as amended by Amdt. 25-72, 55 FR 29775, July 20, 1990; 55 FR 37607, Sept. 12, 1990]</p>
<p style="text-align: center;">Stalls</p> <p>§23.201 Wings level stall.</p> <p>(a) It must be possible to produce and to correct roll by unreversed use of the rolling control and to produce and to correct yaw by unreversed use of the directional control, up to the time the airplane stalls.</p> <p>(b) The wings level stall characteristics must be demonstrated in flight as follows. Starting from a speed at least 10 knots above the stall speed, the elevator control must be pulled back so that the rate of speed reduction will not exceed one knot per second until a</p>	<p style="text-align: center;">Stalls</p> <p>§25.201 Stall demonstration.</p> <p>(a) Stalls must be shown in straight flight and in 30 degree banked turns with --</p> <p>(1) Power off; and</p> <p>(2) The power necessary to maintain level flight at 1.6 V_{S1} (where V_{S1} corresponds to the stalling speed with flaps in the approach position, the landing gear retracted, and maximum landing weight).</p>

Certification Requirements

<p>stall is produced, as shown by either:</p> <p>(1) An uncontrollable downward pitching motion of the airplane;</p> <p>(2) A downward pitching motion of the airplane that results from the activation of a stall avoidance device (for example, stick pusher); or</p> <p>(3) The control reaching the stop.</p> <p>(c) Normal use of elevator control for recovery is allowed after the downward pitching motion of paragraphs (b)(1) or (b)(2) of this section has unmistakably been produced, or after the control has been held against the stop for not less than the longer of two seconds or the time employed in the minimum steady slight speed determination of §23.49.</p> <p>(d) During the entry into and the recovery from the maneuver, it must be possible to prevent more than 15 degrees of roll or yaw by the normal use of controls.</p> <p>(e) Compliance with the requirements of this section must be shown under the following conditions:</p> <p>(1) <i>Wing flaps</i>. Retracted, fully extended, and each intermediate normal operating position.</p> <p>(2) <i>Landing gear</i>. Retracted and extended.</p> <p>(3) <i>Cowl flaps</i>. Appropriate to configuration.</p> <p>(4) <i>Power</i>:</p> <p>(i) Power off; and</p> <p>(ii) 75 percent of maximum continuous power. However, if the power-to-weight ratio at 75 percent of maximum continuous power result in extreme nose-up attitudes, the test may be carried out with the power required for level flight in the landing configuration at maximum landing weight and a speed of 1.4 V_{SO}, except that the power may not be less than 50 percent of maximum continuous power.</p> <p>(5) <i>Trim</i>. The airplane trimmed at a speed as near 1.5 V_{S1} as practicable.</p> <p>(6) <i>Propeller</i>. Full increase r.p.m. position for the power off condition.</p> <p>[Doc. No. 27807, 61 FR 5191, Feb. 9, 1996]</p>	<p>landing weight).</p> <p>(b) In each condition required by paragraph (a) of this section, it must be possible to meet the applicable requirements of §25.203 with --</p> <p>(1) Flaps, landing gear, and deceleration devices in any likely combination of positions approved for operation;</p> <p>(2) Representative weights within the range for which certification is requested;</p> <p>(3) The most adverse center of gravity for recovery; and</p> <p>(4) The airplane trimmed for straight flight at the speed prescribed in §25.103(b)(1).</p> <p>(c) The following procedures must be used to show compliance with §25.203;</p> <p>(1) Starting at a speed sufficiently above the stalling speed to ensure that a steady rate of speed reduction can be established, apply the longitudinal control so that the speed reduction does not exceed one knot per second until the airplane is stalled.</p> <p>(2) In addition, for turning flight stalls, apply the longitudinal control to achieve airspeed deceleration rates up to 3 knots per second.</p> <p>(3) As soon as the airplane is stalled, recover by normal recovery techniques.</p> <p>(d) The airplane is considered stalled when the behavior of the airplane gives the pilot a clear and distinctive indication of an acceptable nature that the airplane is stalled. Acceptable indications of a stall, occurring either individually or in combination, are --</p> <p>(1) A nose-down pitch that cannot be readily arrested;</p> <p>(2) Buffeting, of a magnitude and severity that is a strong and effective deterrent to further speed reduction; or</p> <p>(3) The pitch control reaches the aft stop and no further increase in pitch attitude occurs when the control is held full aft for a short time before recovery is initiated. [Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-84, 60 FR 30750, June 9, 1995]</p>
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Certification Requirements

<p>§23.203 Turning flight and accelerated turning stalls.</p> <p>Turning flight and accelerated turning stalls must be demonstrated in tests as follows:</p> <p>(a) Establish and maintain a coordinated turn in a 30 degree bank. Reduce speed by steadily and progressively tightening the turn with the elevator until the airplane is stalled, as defined in §23.201(b). The rate of speed reduction must be constant, and --</p> <p>(1) For a turning flight stall, may not exceed one knot per second; and</p> <p>(2) For an accelerated turning stall, be 3 to 5 knots per second with steadily increasing normal acceleration.</p> <p>(b) After the airplane has stalled, as defined in §23.201(b), it must be possible to regain wings level flight by normal use of the flight controls, but without increasing power and without --</p> <p>(1) Excessive loss of altitude;</p> <p>(2) Undue pitchup;</p> <p>(3) Uncontrollable tendency to spin;</p> <p>(4) Exceeding a bank angle of 60 degrees in the original direction of the turn or 30 degrees in the opposite direction in the case of turning flight stalls;</p> <p>(5) Exceeding a bank angle of 90 degrees in the original direction of the turn or 60 degrees in the opposite direction in the case of accelerated turning stalls; and</p> <p>(6) Exceeding the maximum permissible speed or allowable limit load factor.</p> <p>(c) Compliance with the requirements of this section must be shown under the following conditions:</p> <p>(1) <i>Wing flaps</i>: Retracted, fully extended, and each intermediate normal operating position;</p> <p>(2) <i>Landing gear</i>: Retracted and extended;</p> <p>(3) <i>Cowl flaps</i>: Appropriate to configuration;</p>	<p>§25.203 Stall characteristics.</p> <p>(a) It must be possible to produce and to correct roll and yaw by unreversed use of the aileron and rudder controls, up to the time the airplane is stalled. No abnormal nose-up pitching may occur. The longitudinal control force must be positive up to and throughout the stall. In addition, it must be possible to promptly prevent stalling and to recover from a stall by normal use of the controls.</p> <p>(b) For level wing stalls, the roll occurring between the stall and the completion of the recovery may not exceed approximately 20 degrees.</p> <p>(c) For turning flight stalls, the action of the airplane after the stall may not be so violent or extreme as to make it difficult, with normal piloting skill, to effect a prompt recovery and to regain control of the airplane. The maximum bank angle that occurs during the recovery may not exceed --</p> <p>(1) Approximately 60 degrees in the original direction of the turn, or 30 degrees in the opposite direction, for deceleration rates up to 1 knot per second; and</p> <p>(2) Approximately 90 degrees in the original direction of the turn, or 60 degrees in the opposite direction, for deceleration rates in excess of 1 knot per second.</p> <p>[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-84, 60 FR 30750, June 9, 1995]</p>
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Certification Requirements

<p>(4) <i>Power</i>:</p> <p>(i) Power off; and</p> <p>(ii) 75 percent of maximum continuous power. However, if the power-to-weight ratio at 75 percent of maximum continuous power results in extreme nose-up attitudes, the test may be carried out with the power required for level flight in the landing configuration at maximum landing weight and a speed of $1.4 V_{SO}$, except that the power may not be less than 50 percent of maximum continuous power.</p> <p>(5) <i>Trim</i>: The airplane trimmed at a speed as near $1.5 V_{S1}$ as practicable.</p> <p>(6) <i>Propeller</i>. Full increase rpm position for the power off condition.</p> <p>[Amdt. 23-14, 38 FR 31820, Nov. 19, 1973, as amended by Amdt. 23-45, 58 FR 42159, Aug. 6, 1993; Amdt. 23-50, 61 FR 5191, Feb. 9, 1996]</p> <p>§23.207 Stall warning.</p> <p>(a) There must be a clear and distinctive stall warning, with the flaps and landing gear in any normal position, in straight and turning flight.</p> <p>(b) The stall warning may be furnished either through the inherent aerodynamic qualities of the airplane or by a device that will give clearly distinguishable indications under expected conditions of flight. However, a visual stall warning device that requires the attention of the crew within the cockpit is not acceptable by itself.</p> <p>(c) During the stall tests required by §23.201(b) and §23.203(a)(1), the stall warning must begin at a speed exceeding the stalling speed by a margin of not less than 5 knots and must continue until the stall occurs.</p> <p>(d) When following procedures furnished in accordance with §23.1585, the stall warning must not occur during a takeoff with all engines operating, a takeoff continued with one engine inoperative, or during an approach to landing.</p> <p>(e) During the stall tests required by §23.203(a)(2), the stall warning must begin sufficiently in advance of the</p>	<p>§25.207 Stall warning.</p> <p>(a) Stall warning with sufficient margin to prevent inadvertent stalling with the flaps and landing gear in any normal position must be clear and distinctive to the pilot in straight and turning flight.</p> <p>(b) The warning may be furnished either through the inherent aerodynamic qualities of the airplane or by a device that will give clearly distinguishable indications under expected conditions of flight. However, a visual stall warning device that requires the attention of the crew within the cockpit is not acceptable by itself. If a warning device is used, it must provide a warning in each of the airplane configurations prescribed in paragraph (a) of this section at the speed prescribed in paragraph (c) of this section.</p> <p>(c) The stall warning must begin at a speed exceeding the stalling speed (i.e., the speed at which the airplane stalls or the minimum speed demonstrated, whichever is applicable under the provisions of §25.201(d)) by seven percent or at any lesser margin if the stall warning has enough clarity, duration, distinctiveness, or similar properties.</p> <p>[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-7, 30 FR 13118, Oct. 15, 1965; Amdt. 25-42, 43 FR 2322, Jan. 16, 1978]</p>
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Certification Requirements

stall for the stall to be averted by pilot action taken after the stall warning first occurs.

(f) For acrobatic category airplanes, an artificial stall warning may be mutable, provided that it is armed automatically during takeoff and rearmed automatically in the approach configuration.

[Amdt. 23-7, 34 FR 13087, Aug. 13, 1969, as amended by Amdt. 23-45, 58 FR 42159, Aug. 6, 1993; Amdt. 23-50, 61 FR 5191, Feb. 9, 1996]

Spinning

§23.221 Spinning.

(a) *Normal category airplanes.* A single-engine, normal category airplane must be able to recover from a one-turn spin or a three-second spin, whichever takes longer, in not more than one additional turn after initiation of the first control action for recovery, or demonstrate compliance with the optional spin resistant requirements of this section.

(1) The following apply to one turn or three second spins:

(i) For both the flaps-retracted and flaps-extended conditions, the applicable airspeed limit and positive limit maneuvering load factor must not be exceeded;

(ii) No control forces or characteristic encountered during the spin or recovery may adversely affect prompt recovery;

(iii) It must be impossible to obtain unrecoverable spins with any use of the flight or engine power controls either at the entry into or during the spin; and

(iv) For the flaps-extended condition, the flaps may be retracted during the recovery but not before rotation has ceased.

(2) At the applicant's option, the airplane may be demonstrated to be spin resistant by the following:

(i) During the stall maneuver contained in §23.201, the pitch control must be pulled back and held against the

§25.351 Yaw maneuver conditions.

The airplane must be designed for loads resulting from the yaw maneuver conditions specified in paragraphs (a) through (d) of this section at speeds from V_{MC} to V_D . Unbalanced aerodynamic moments about the center of gravity must be reacted in a rational or conservative manner considering the airplane inertia forces. In computing the tail loads the yawing velocity may be assumed to be zero.

(a) With the airplane in unaccelerated flight at zero yaw, it is assumed that the cockpit rudder control is suddenly displaced to achieve the resulting rudder deflection, as limited by:

(1) The control system on control surface stops; or

(2) A limit pilot force of 300 pounds from V_{MC} to V_A and 200 pounds from V_C/M_C to V_D/M_D , with a linear variation between V_A and V_C/M_C .

(b) With the cockpit rudder control deflected so as always to maintain the maximum rudder deflection available within the limitations specified in paragraph (a) of this section, it is assumed that the airplane yaws to the overswing sideslip angle.

(c) With the airplane yawed to the static equilibrium sideslip angle, it is assumed that the cockpit rudder control is held so as to achieve the maximum rudder deflection available within the limitations specified in paragraph (a) of this section.

(d) With the airplane yawed to the static equilibrium sideslip angle of paragraph (c) of this section, it is assumed that the cockpit rudder control is suddenly returned to neutral.

[Amdt. 25-91, 62 FR 40704, July 29, 1997]

Certification Requirements

stop. Then, using ailerons and rudders in the proper direction, it must be possible to maintain wings-level flight within 15 degrees of bank and to roll the airplane from a 30 degree bank in one direction to a 30 degree bank in the other direction;

(ii) Reduce the airplane speed using pitch control at a rate of approximately one knot per second until the pitch control reaches the stop; then, with the pitch control pulled back and held against the stop, apply full rudder control in a manner to promote spin entry for a period of seven seconds or through a 360 degree heading change, whichever occurs first. If the 360 degree heading change is reached first, it must have taken no fewer than four seconds. This maneuver must be performed first with the ailerons in the neutral position, and then with the ailerons deflected opposite the direction of turn in the most adverse manner. Power and airplane configuration must be set in accordance with §23.201(e) without change during the maneuver. At the end of seven seconds or a 360 degree heading change, the airplane must respond immediately and normally to primary flight controls applied to regain coordinated, unstalled flight without reversal of control effect and without exceeding the temporary control forces specified by §23.143(c); and

(iii) Compliance with §§23.201 and 23.203 must be demonstrated with the airplane in uncoordinated flight, corresponding to one ball width displacement on a slip-skid indicator, unless one ball width displacement cannot be obtained with full rudder, in which case the demonstration must be with full rudder applied.

(b) *Utility category airplanes.* A utility category airplane must meet the requirements of paragraph (a) of this section. In addition, the requirements of paragraph (c) of this section and §23.807(b)(7) must be met if approval for spinning is requested.

(c) *Acrobatic category airplanes.* An acrobatic category airplane must meet the spin requirements of paragraph (a) of this section and §23.807(b)(6). In addition, the following requirements must be met in each configuration for which approval for spinning is requested:

(1) The airplane must recover from any point in a spin up to and including six turns, or any greater number of turns for which certification is requested, in not more than one and one-half additional turns after initiation of the first control action for recovery. However, beyond three turns, the spin may be discontinued if spiral

Certification Requirements

<p>characteristics appear.</p> <p>(2) The applicable airspeed limits and limit maneuvering load factors must not be exceeded. For flaps-extended configurations for which approval is requested, the flaps must not be retracted during the recovery.</p> <p>(3) It must be impossible to obtain unrecoverable spins with any use of the flight or engine power controls either at the entry into or during the spin.</p> <p>(4) There must be no characteristics during the spin (such as excessive rates of rotation or extreme oscillatory motion) that might prevent a successful recovery due to disorientation or incapacitation of the pilot.</p> <p>[Doc. No. 27807, 61 FR 5191, Feb. 9, 1996]</p>	
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Certification Requirements