

Flightlab Ground School

10. Spins

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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.

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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

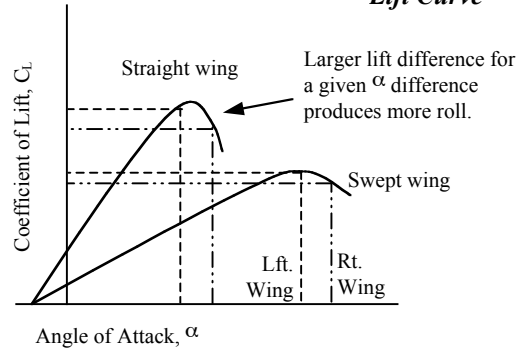
After World War II, a new generation of jet fighter aircraft appeared with swept wings and with their mass distributed more along the fuselage axis, and less along the span (fuselage loaded). This changed for the worse the governing aerodynamic and inertial relationships that determined their stall/spin 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 asymmetically, 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

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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

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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.

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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

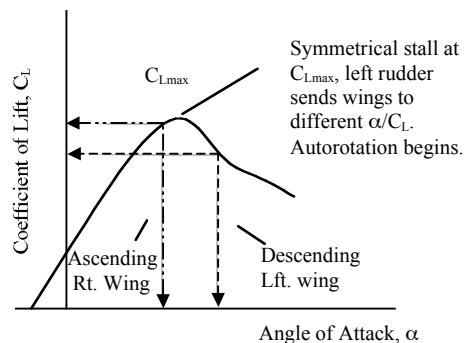
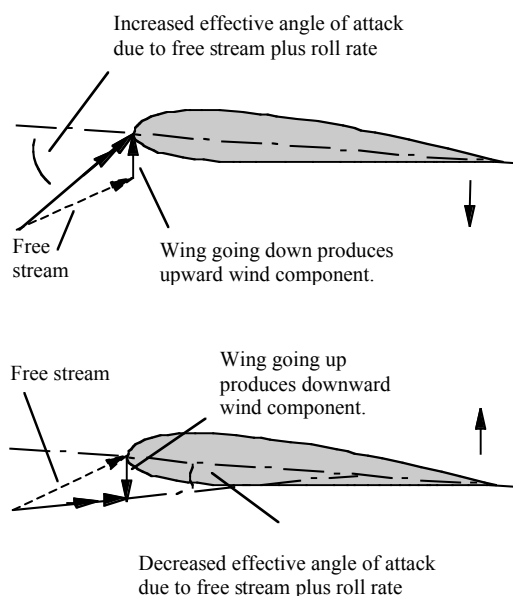


Figure 3
Roll-induced Angle of Attack



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.

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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.

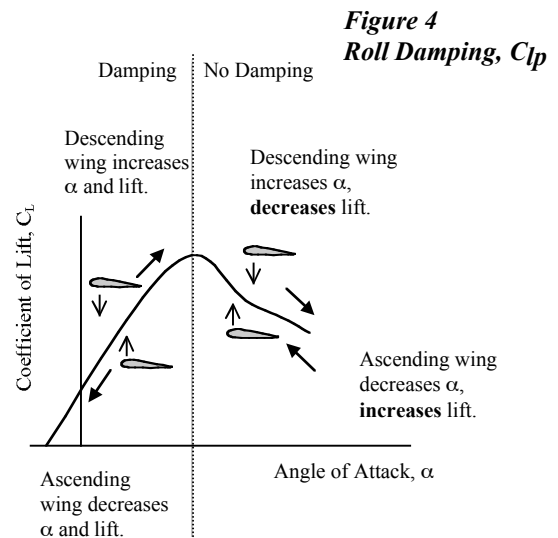
If a wing operates on the right side of the C_L/α curve, past stall, a downward roll still produces an increase in α , but now accompanied by a decrease in C_L , as we've seen. There's no damping effect. Just the reverse—the wing continues to fall. Roll damping turns unstable when the slope of the C_L/α 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.)



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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

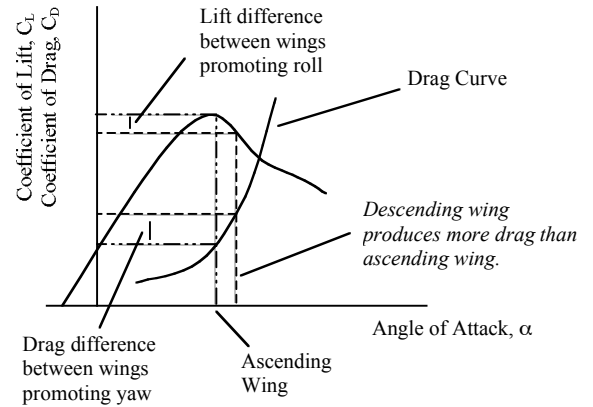
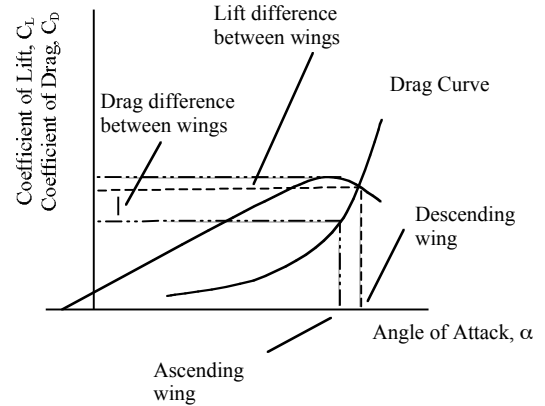


Figure 6
Swept-Wing
Lift & Drag



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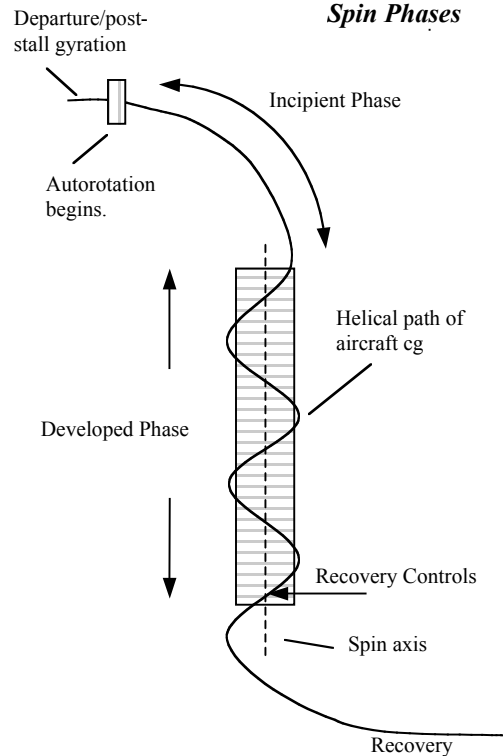
Spin Phases

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.

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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.

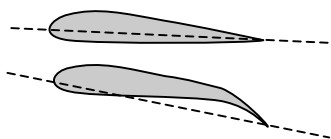
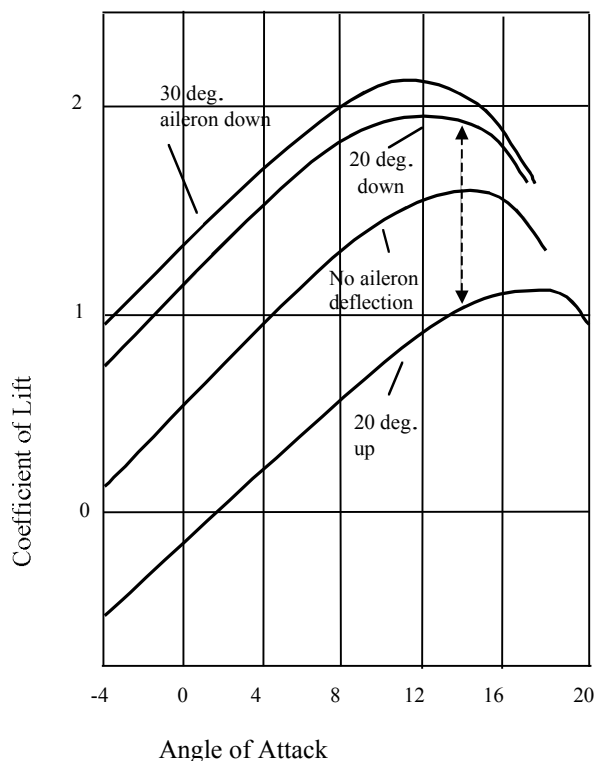


Figure 8. Aileron deflection shifts lift curve. (LS(1)-0417 wing)



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

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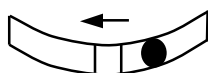
the region of roll damping. The lift of the area increases, but its contribution to damping—its resistance to autorotation—drops out!

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.)

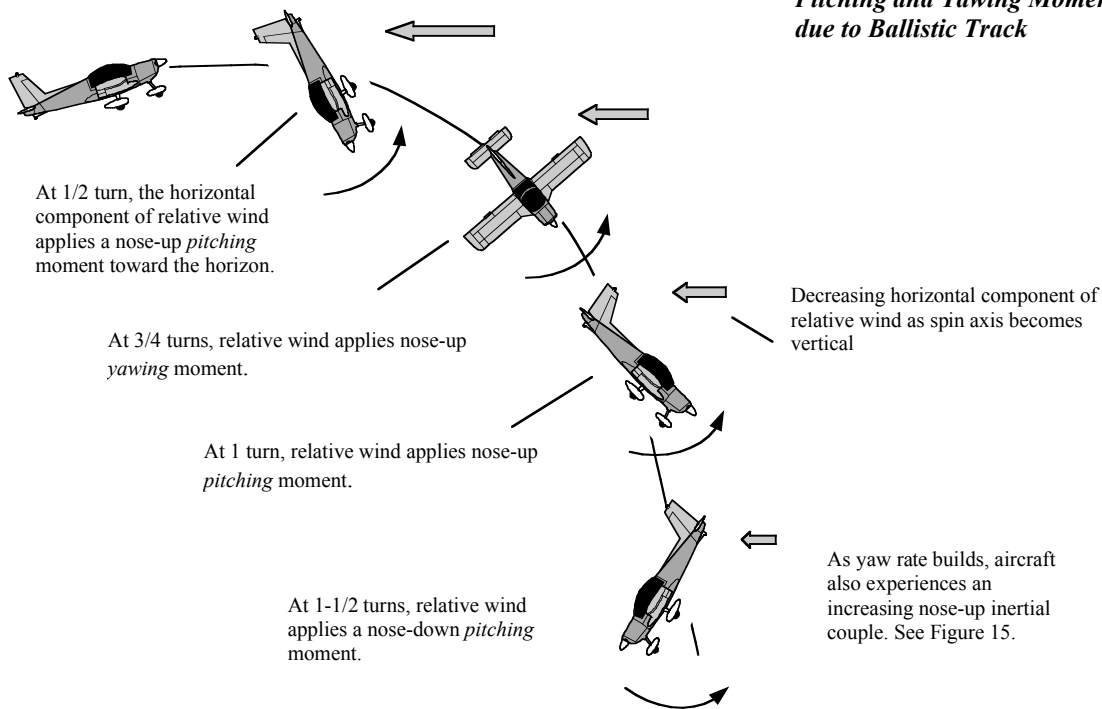
The displaced ball is predictive. It tells you which direction a departure will go. During a spin it's an unreliable indicator of spin direction—unlike a turn needle, which is reliable upright or inverted. The aircraft symbol in a turn coordinator is reliable only in upright spins.

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.

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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

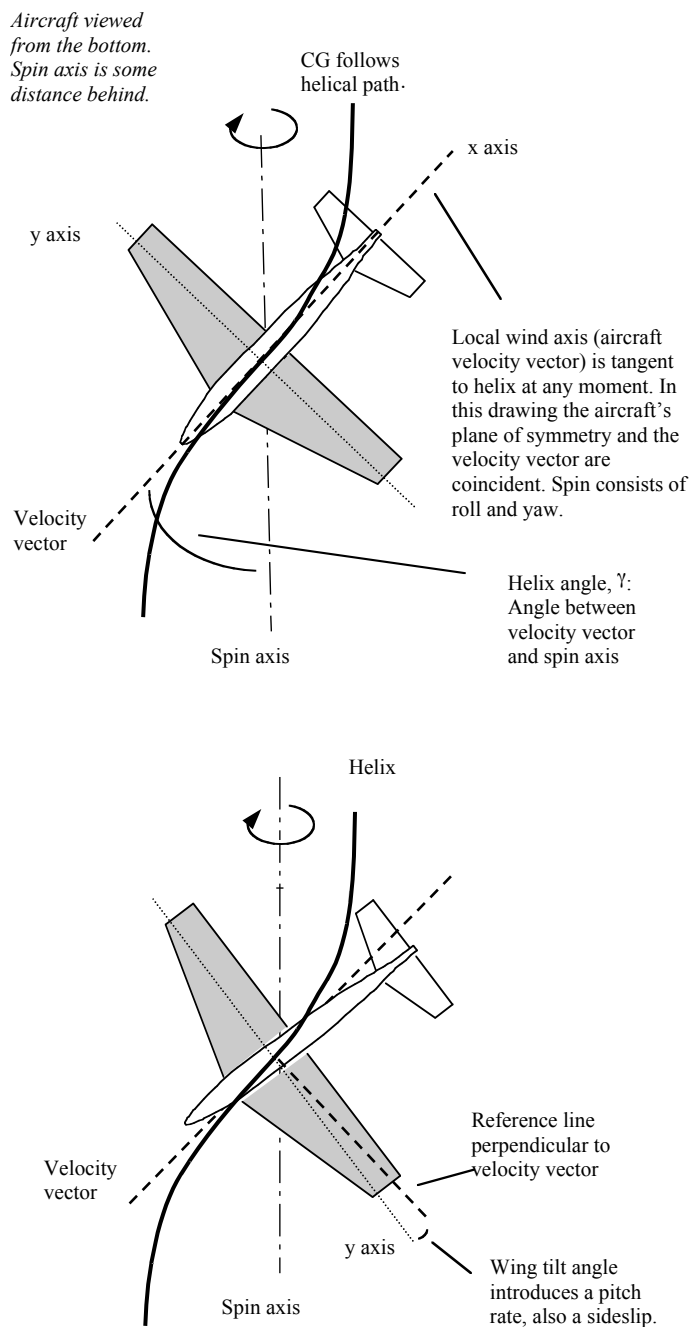
In a steady, developed spin, aerodynamic and inertia forces come into balance. Yaw, roll and pitch rates settle down to constant values. Angle of attack, descent rate, and pitch attitude do the same. In the case of oscillatory developed spins, which never settle down, the rates may fluctuate around average 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

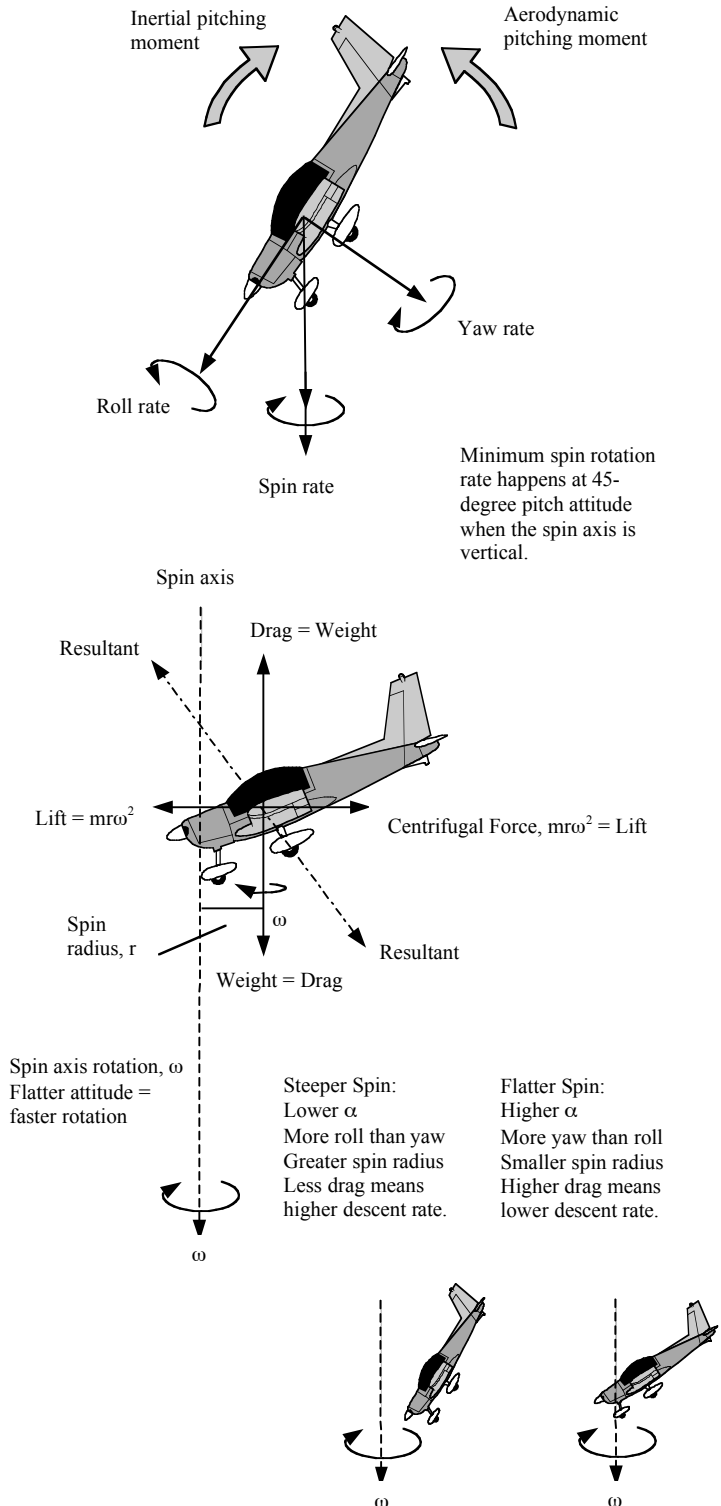
Figure 11 shows some of the characteristics of flat versus steep spins. In the example shown, for simplification the spin consists of roll and yaw only—no pitch rate. In an equilibrium state, the aerodynamic pitching moments, which are nose down, are opposite to and equal the nose up inertia moments (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.)

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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.

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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

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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.

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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.

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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.

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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:

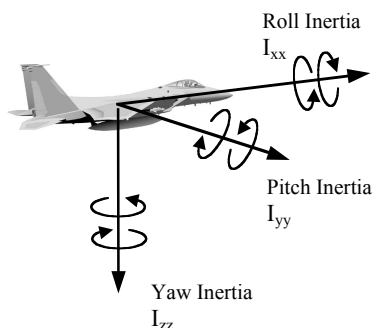
A moment causes rotation about an axis.

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

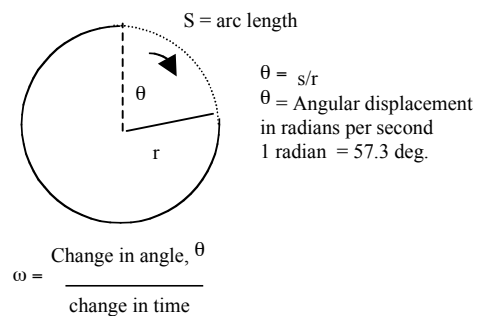
$$\text{Angular momentum} = I\omega$$

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).

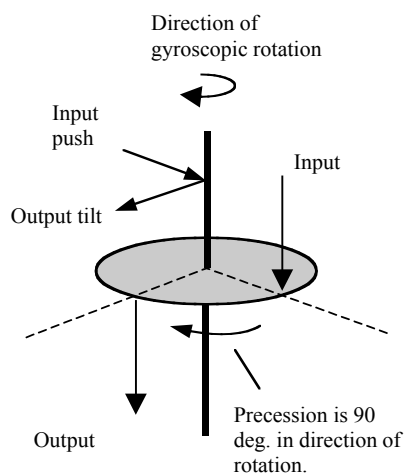
ω = angular velocity



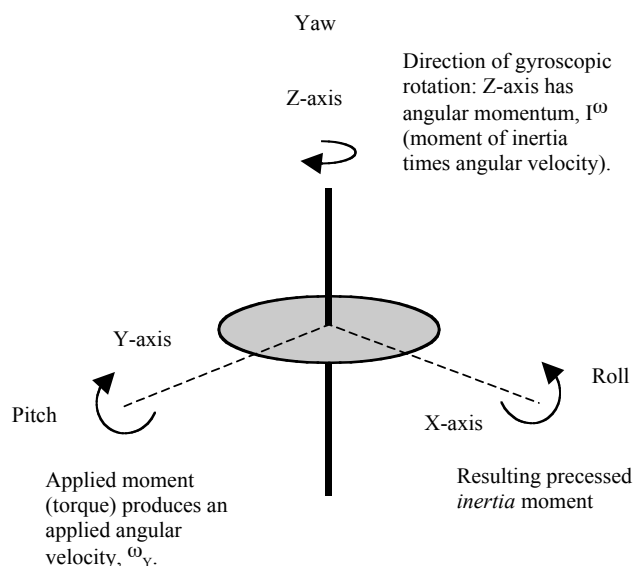
Every point on the line has the same *angular* velocity. Its *tangential* velocity is proportional to its distance from the axis.

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.

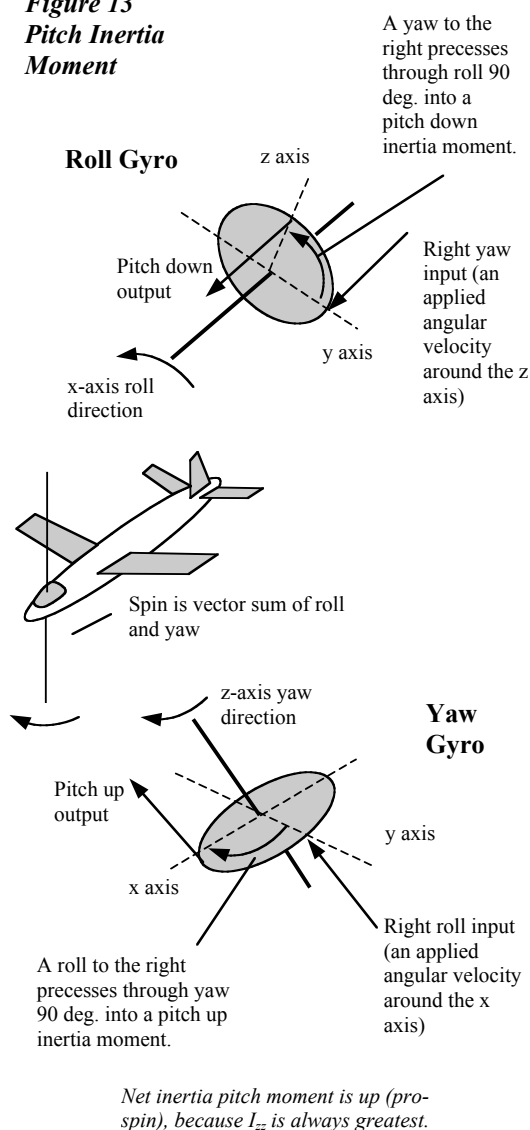
Take, for example, *pitch inertia moment*. Imagine an aircraft rolling and yawing in a spin to the right, as in Figure 13, top. It has an angular momentum in roll (equal to I_{xx} times angular velocity in roll, p). Since it's also yawing to the right, it has an applied angular velocity around the yaw 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.

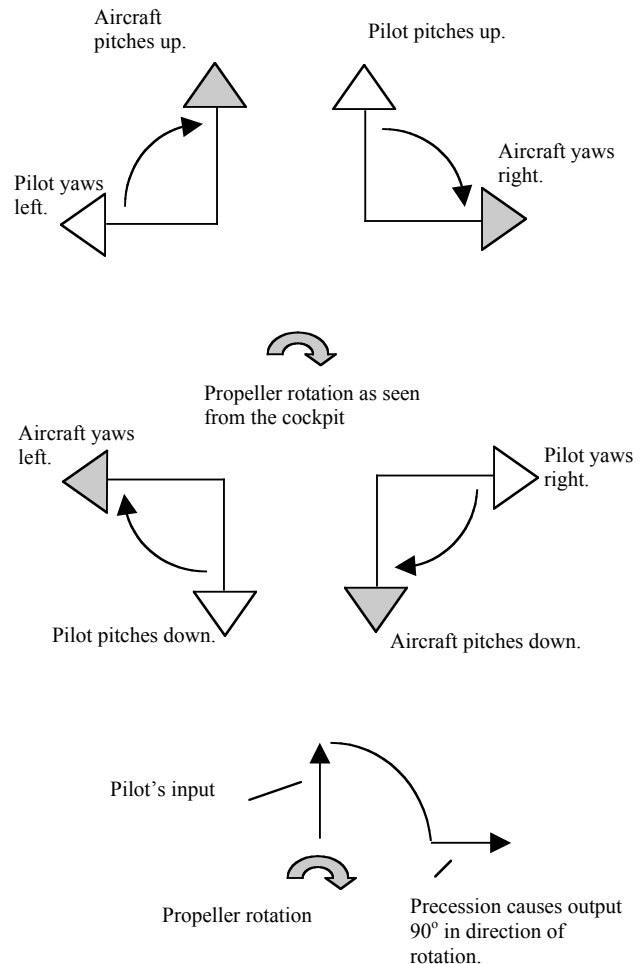
The effects of propeller gyroscopics are most evident in aircraft with heavy props and rather low directional and longitudinal stabilities, whenever the aircraft yaws or pitches rapidly at high prop rpm and low airspeed. It also helps if the prop is a substantial distance from the aircraft center of 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.

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*.

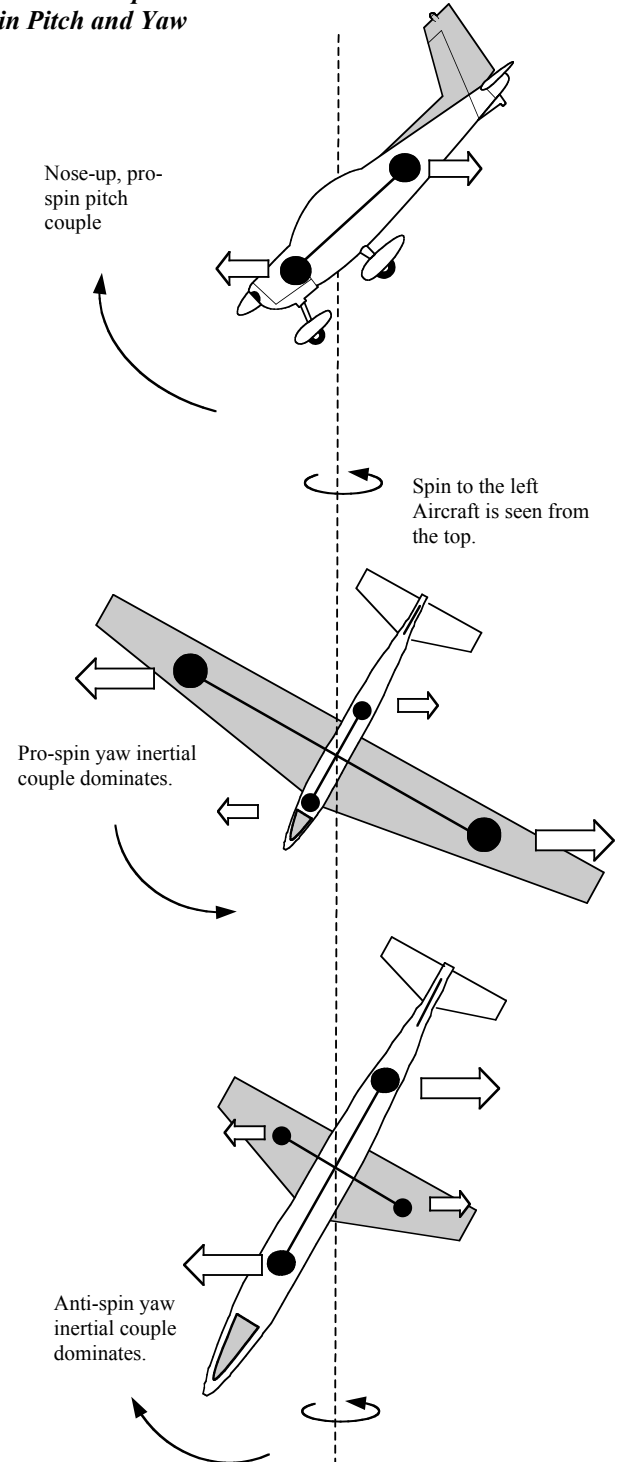
By itself the *fuselage couple tends to drive the nose up, flattening the spin attitude* (a pro-spin pitch couple).

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.

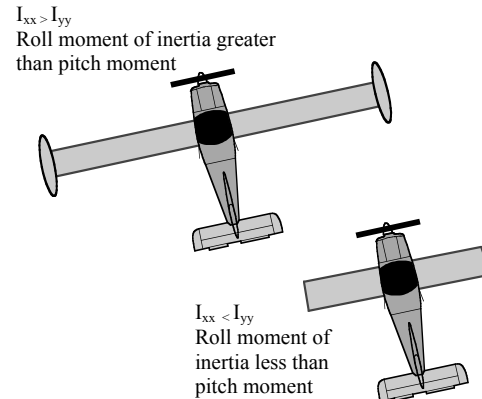
Remember that in the aerodynamics sign system positive values are up and/or to the right, negative values are down and/or to the left. (Remember from algebra that a negative times a negative equals a positive; a negative times a positive equals a negative; and a positive times a positive equals a positive.)

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.

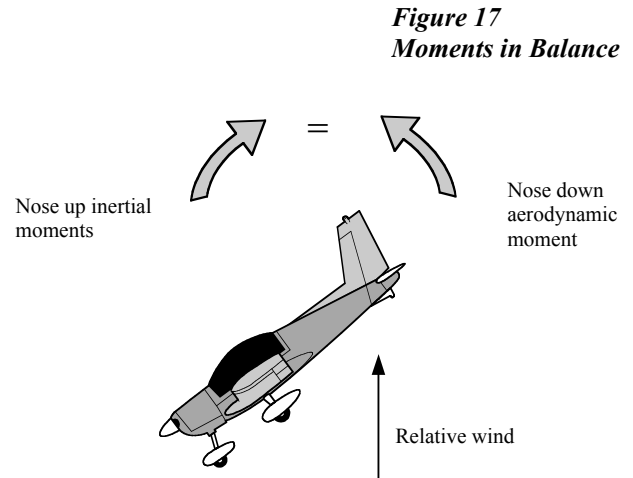
Spins

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.

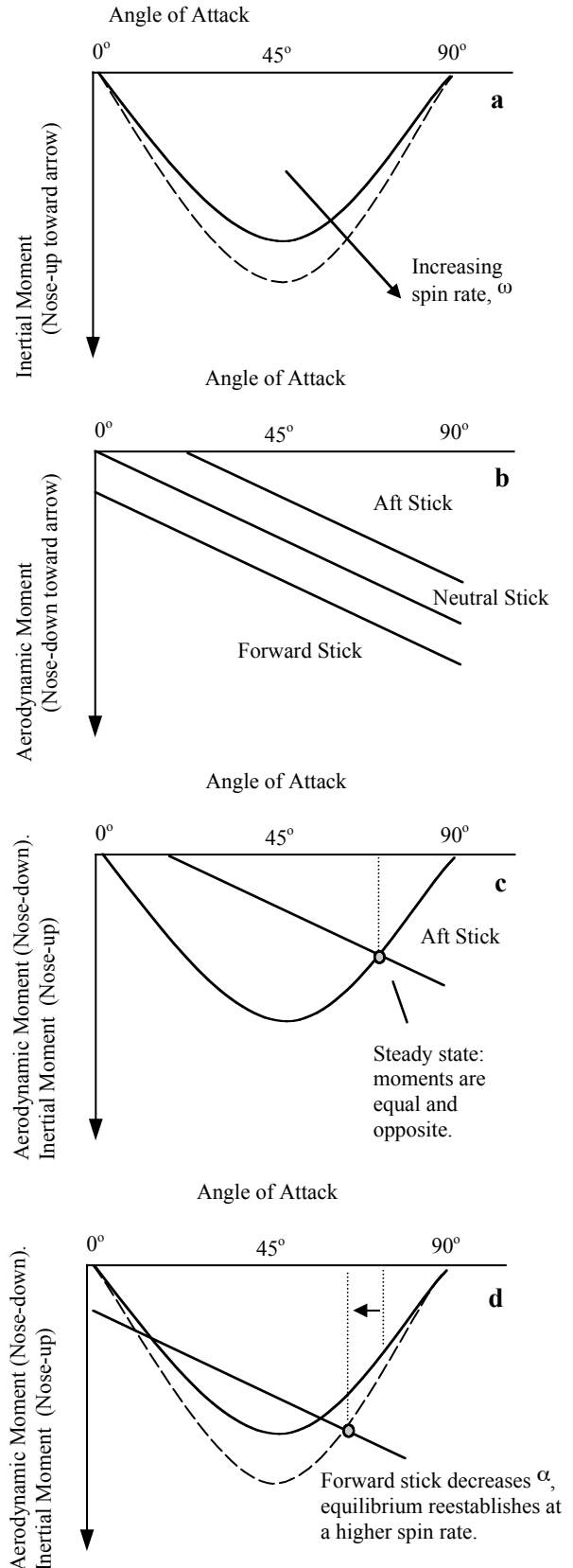
Figure 18b shows aerodynamic pitching moment, which is always nose down, plotted against angle of attack. Note the increase in aerodynamic moment as angle of attack increases and/or as the stick moves from aft to forward.

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