Unit IV Lateral and Directional Stability

Lateral (Rolling) Dynamics

The Aircraft in Roll

The dynamics of an aircraft in roll are surprisingly complex, given the apparent simplicity of the maneuver. Of course, one person's complexity is just another person getting started. At the U.S. Navy Test Pilot School, for instance, "The classic roll mode is a heavily damped, first order, non-oscillatory mode of motion manifested in a build-up of roll rate to a steady state value for a given lateral control input." Well, ok, that sounds right.

Our Maneuvers and Flight Notes training guide describes piloting technique during aerobatic or unusual attitude rolling maneuvers. Here the emphasis is on the general characteristics of aircraft response.

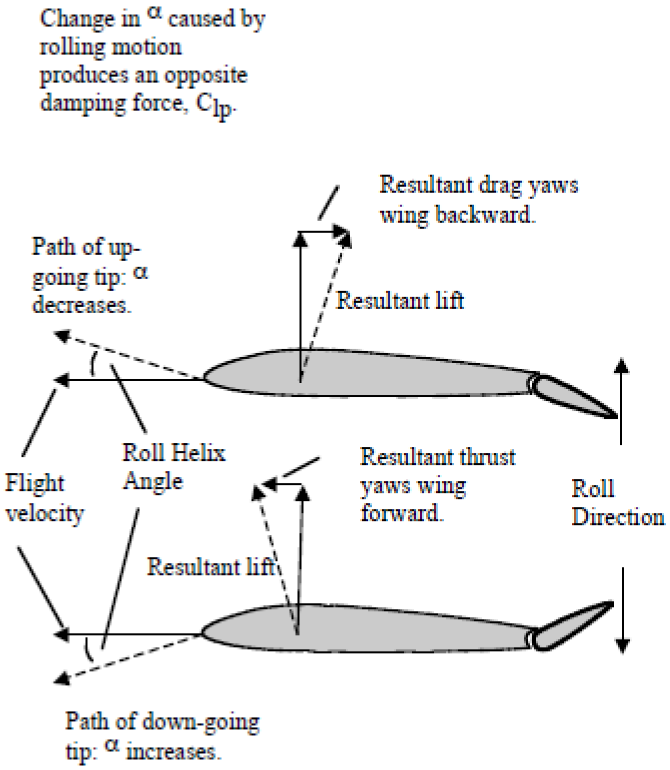


Fig. 4.1. Roll Damping, C_{lp}, Yaw due to Roll Rate, C_{np}

A roll starts with the creation of an asymmetric lift distribution along the wingspan. In the case of aileron roll control, deflecting an aileron down increases wing camber and coefficient of lift; raising the opposite aileron reduces camber and coefficient of lift. The resulting spanwise asymmetry produces a rolling moment.

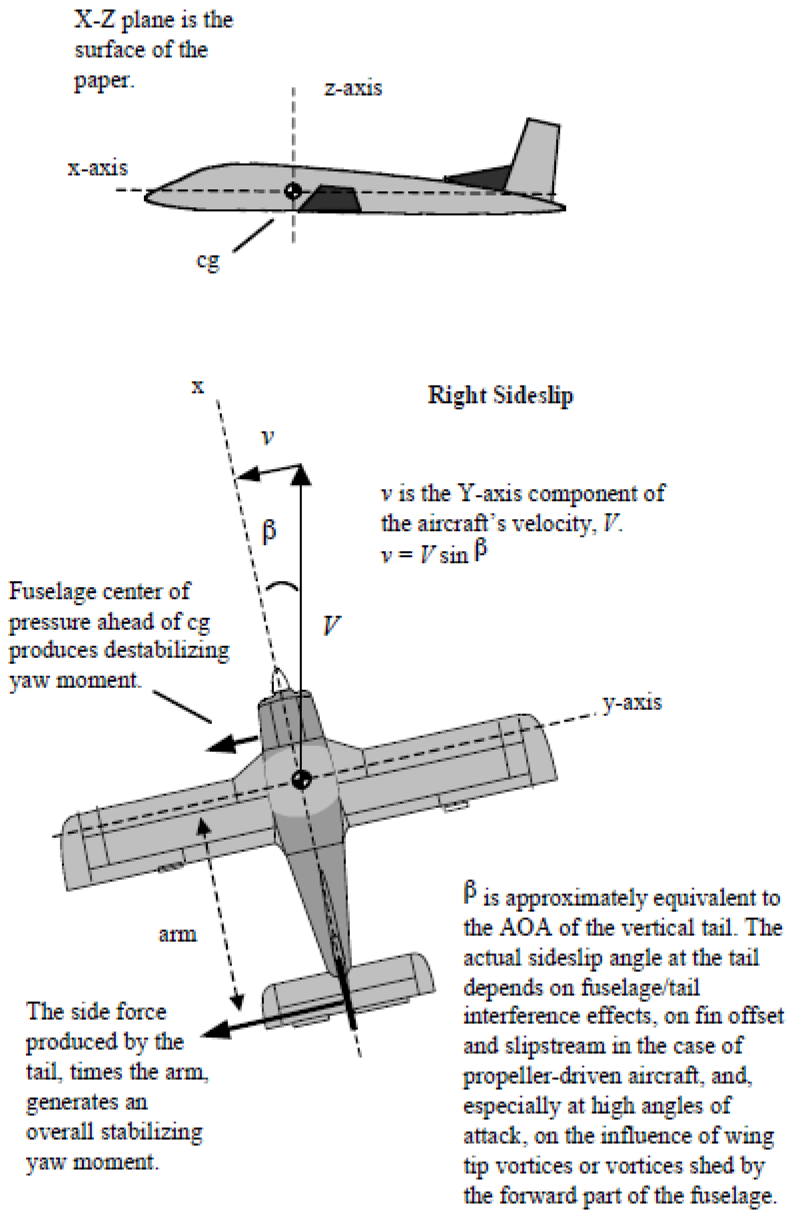
As the aircraft begins to roll in response to the moment produced by the ailerons, the lift distribution again begins to change. The rolling motion induces an angle of attack increase on the down-going wing, and an angle of attack decrease on the up-going wing (Figure 4.1). This creates an opposing aerodynamic moment, called roll damping (or rolling moment due to roll rate, C_{lp}). Roll damping increases with roll rate (and varies with other factors we'll get to). When the damping moment produced by the roll rate rises to equal the opposing moment produced by the ailerons, the roll rate becomes constant.

In Figure 1 you can see that as the airplane rolls, the lift vector tilts to accommodate itself to the new direction of the relative wind, creating new vectors of thrust and drag. As a result, the rolling motion produces adverse yaw all by itself, a yawing moment that goes away when the roll stops. This yaw due to roll rate, C_{np}, is in addition to the adverse yaw created by the displaced ailerons, and increases with coefficient of lift. Depending on wing planform, at aspect ratios above 6 or so, adverse yaw due to roll rate actually becomes more significant than that due to aileron deflection.

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

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

An aircraft is in a sideslip when its direction of motion (its velocity vector) does not lie on the xz plane of symmetry. The top drawing in Figure 4.2 defines the x-z plane, and in the bottom drawing we're looking down the z-axis. The angle between the velocity vector, V, and the x-z plane is the sideslip angle, β (pronounced "beta"). In aerodynamics notation β is positive to the right, negative to the left. (Just so there's no confusion, a -β sideslip to the left, for example, means that the nose is pointing to the right of the aircraft's actual direction of motion.)



X-Z plane is the surface of the paper.

v is the Y-axis component of the aircraft's velocity, V. $v = V \sin \beta$

Fuselage center of pressure ahead of cg produces destabilizing yaw moment.

The side force produced by the tail, times the arm, generates an overall stabilizing yaw moment.

β is approximately equivalent to the AOA of the vertical tail. The actual sideslip angle at the tail depends on fuselage/tail interference effects, on fin offset and slipstream in the case of propeller-driven aircraft, and, especially at high angles of attack, on the influence of wing tip vortices or vortices shed by the forward part of the fuselage.

Fig. 4.2. Directional Stability

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

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

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

This is also called “weathercock” stability, in honor of a much simpler invention. Figure 4.3 shows that this stabilizing yaw moment is not typically linear, but tends to decrease at high β angles. In the figure, a positive slope (rising to the right) in the $C_{n\beta}$ curve indicates directional stability. The steeper the slope the stronger is the tendency to weathercock.

Not all parts of the aircraft contribute to directional stability. Alone, the fuselage is destabilizing.

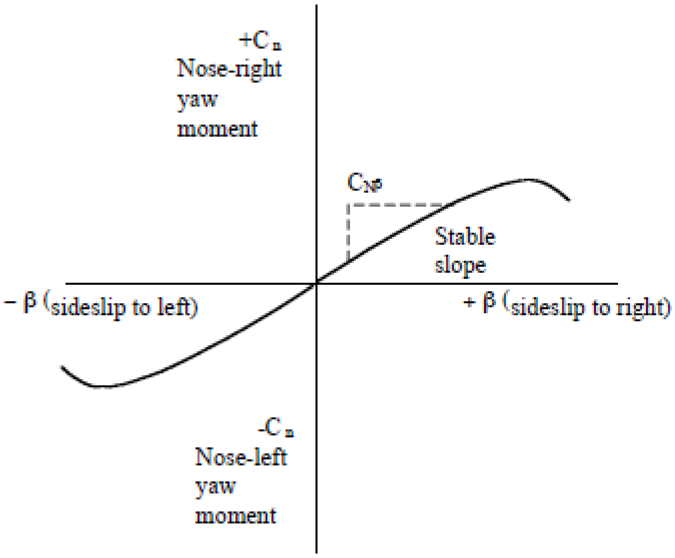


Fig. 4.3. Directional Stability Response

In subsonic flight, the center of pressure on a fuselage in a sideslip is usually somewhere forward of 25 percent of the fuselage length. Since the aircraft’s center of gravity is typically aft of this point, the fuselage alone would tend to turn broadside to the relative wind in a sideslip. Notice in Figure 4.4 how the destabilizing contribution from the fuselage levels out as β increases. Figure 4.4 breaks down the components of directional stability. A sideslip to the right (+β) produces a nose-right, stabilizing yaw moment for the entire airplane, but a destabilizing yaw to the left (-Cn) for the fuselage alone.

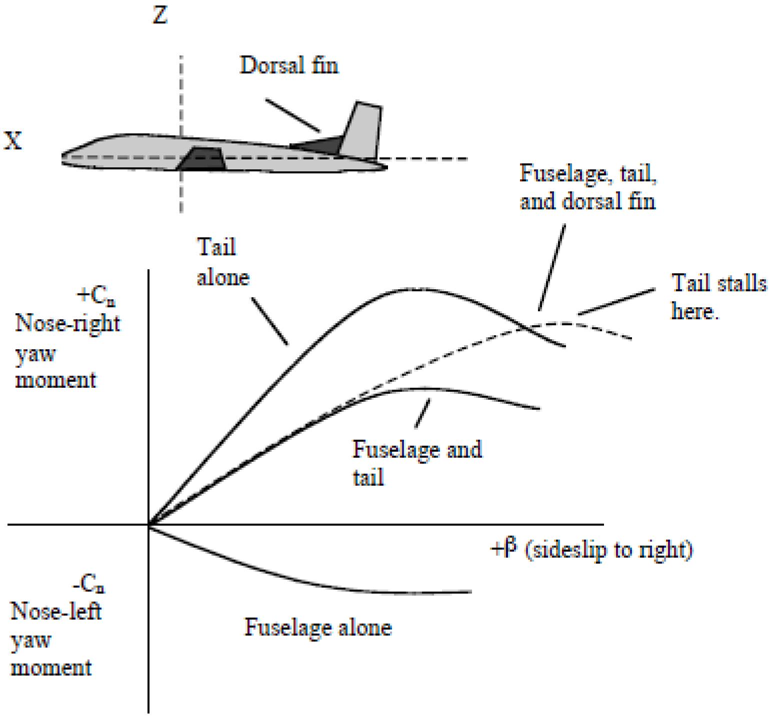


Fig. 4.4. Contributions to Directional Stability

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

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

The $C_{n\beta}$ directional stability curve for the fuselage and tail together reaches its peak when the tail stalls. You can see in Figure 4.4 that adding a dorsal fin increases the tail's effectiveness (and without adding much weight or drag). Because of its higher aspect ratio and steeper lift curve, the vertical tail proper produces strong and rapidly increasing yaw moments at lower sideslip angles, but soon stalls. But the dorsal fin, with its low aspect ratio and more gradual lift curve, goes to a higher angle of attack before stalling, and so helps the aircraft retain directional stability at higher sideslip angles. The dorsal fin can also generate a vortex that delays the vertical tail's stall.

The Fokker Dr1 triplane provides an extreme example of a low-aspect-ratio tail (there's a rough approximation in Figure 4.5). Without a fixed vertical fin, the aircraft had low directional stability. The low-aspect-ratio rudder stalled at about 30-degree deflection. The combination gave the pilot the ability to yaw the nose around rapidly if necessary to get off a shot. But in straight-ahead flight the aircraft needed constant directional attention (a typical attribute of WW-I fighters).

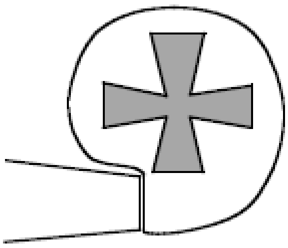


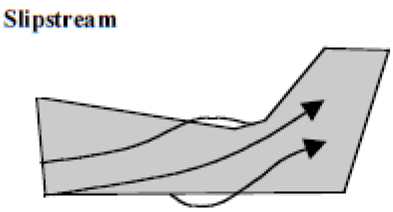
Fig. 4.5. World War I Fokker Dr1 rudder

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

Propellers and Directional Stability

Propellers ahead of the aircraft c.g. are directionally destabilizing, mostly because of slipstream effects and P-factor (Figure 4.6). Our Air Wolf is an example of an aircraft that requires lots of directional trimming (or just rudder pushing) to compensate for propeller effects as angle of attack and airspeed change. In this respect it's quite unlike a jet, say, or an aircraft with counter-rotating propellers, which typically have no associated directional trim changes.

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



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

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

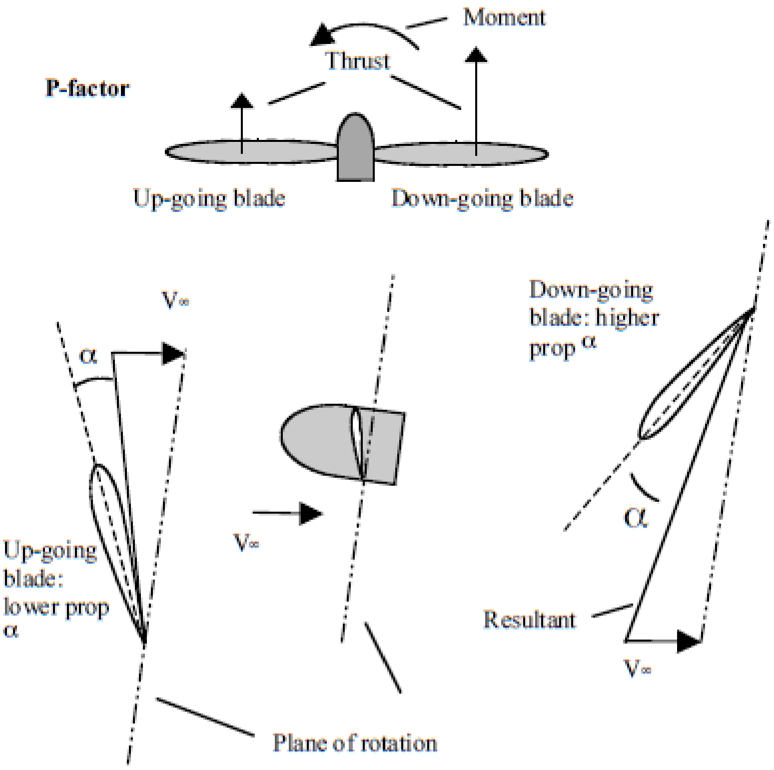
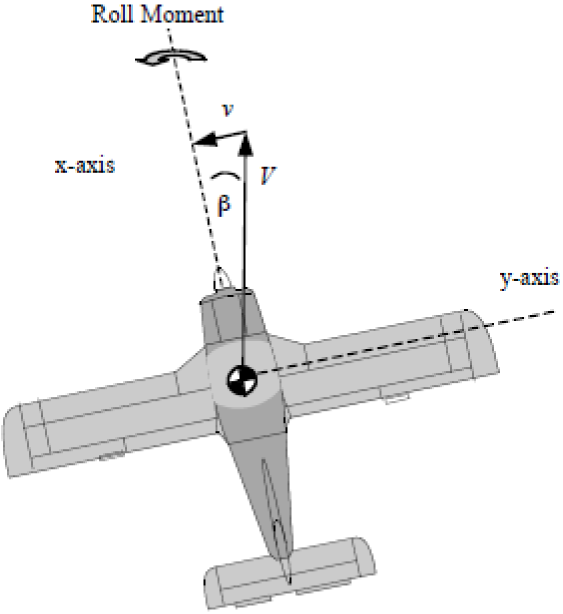


Fig. 4.6. Slipstream and P-factor

Dihedral Effect, C_{l_β}

An aircraft with dihedral effect rolls away from a sideslip (away from the velocity vector). The term describes a single behaviour with more than a single cause. Dihedral effect was observed first as resulting from actual geometric dihedral (wing tips higher than wing roots), but it's also produced by wing sweep, by a high wing location on a fuselage, and by forces acting on the vertical tail.

For convenience, Figure 4.7 illustrates sideslip angle, β, and sideslip velocity, v, velocity vector, V, plus the direction of roll. During our flight program, we'll do steady heading sideslips to assess the presence of dihedral effect. We'll press on a rudder pedal while applying opposite aileron, so that the airplane will be banked but not turning.



v is the y-axis component of the aircraft's velocity, V.
$v = V \sin \beta$

Fig. 4.7. Sideslip Angle, β

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

The interaction between sideslip and dihedral effect forms the basis of an aircraft's lateral stability. Lateral stability can't appear unless an aircraft starts to sideslip first. An aircraft with positive lateral stability rolls away from the sideslip (velocity vector) that results when a wing drops, and that usually means back toward level flight (although an aircraft with dihedral effect can go into a spiral dive if the bank angle is high and other moments prevail).

In the notation used in Figure 4.8, sideslip angle is β (beta), and the rolling moment coefficient is C_l, so the slope of the curve of rolling moment due to sideslip is $C_{l\beta}$. Since it does roll off the tongue, if we lapse into this terminology you'll know what we mean. The figure shows that the slope must be negative (descending to the right) for stability when we follow the standard sign conventions, where aircraft right is positive, left is negative. A laterally unstable aircraft tends to continue to roll toward the direction of sideslip (positive slope).

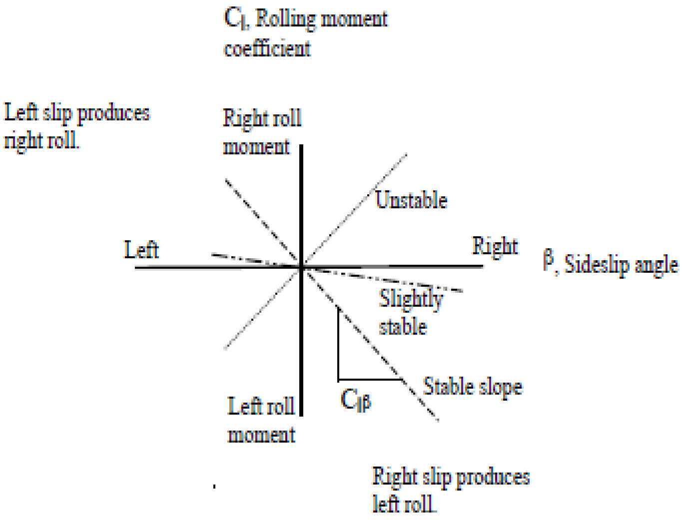


Fig. 4.8. Lateral Stability

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

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

Maintain that eye height above the ground and move back and forth in front of the aircraft, trying hard not to look too suspicious to possible representatives of the TSA. Notice how the angle of attack, α, of the near wing increases—you can see more wing bottom—while that of the far wing decreases as you change your position, as illustrated at the top of Figure 4.9. With anhedral, you'd see just the opposite.

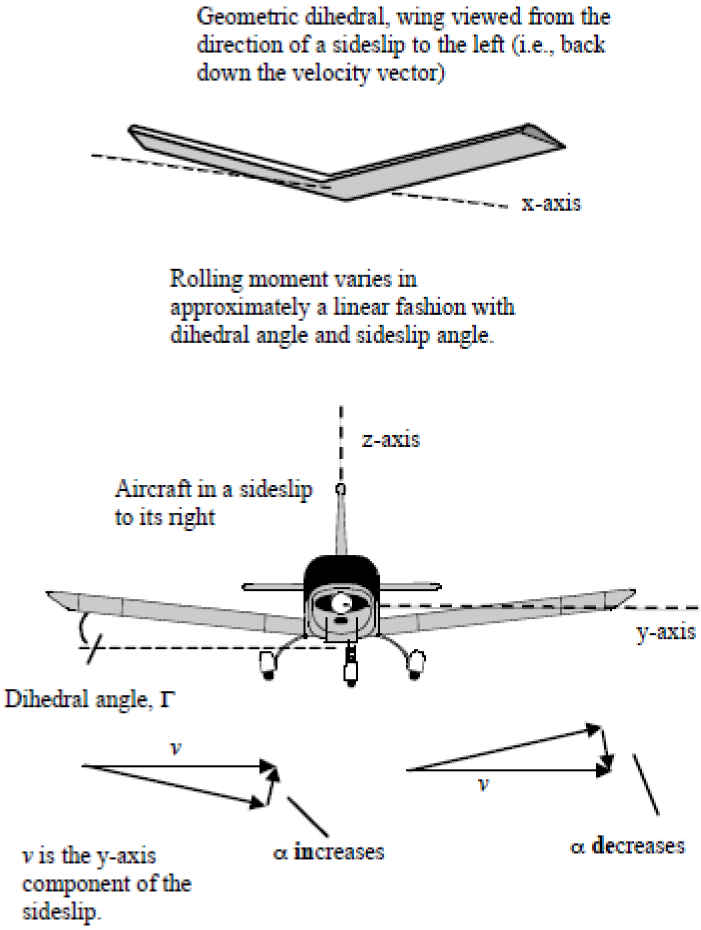


Fig. 4.9. Sideslip, Dihedral Angle, and Resulting Change in α

Figure 4.9 also presents the same idea in another way. In the lower figure, the y-axis component of sideslip, v, is in turn broken down into two vector components projected onto the aircraft's y-z plane, one parallel to and one perpendicular to the wing. On the upwind wing, the perpendicular component acts to increase the angle of attack. It does the opposite on the downwind wing. The difference produces a rolling moment.

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

Figure 4.10 shows the contributions of wing position, tail height, landing gear, and slipstream angle to dihedral effect. Wing position guides the cross flow around the fuselage in a sideslip, altering the angles of attack on the near and far wings, and thus the relative lift. This is stabilizing on a high-wing aircraft. It's destabilizing on a low wing, which is why low-wing aircraft typically require more geometric dihedral. These fuselage effects are enhanced by smooth airflow over the wing-body junction.

They're diminished by flow separation at the wing roots at the approach of a stall. A vertical tail produces a side force during a sideslip. If the tail is tall enough, so that its center of lift is a good distance above the aircraft's center of gravity, the vertical moment arm can provoke a stabilizing roll response. Landing gear, below the C.G., is destabilizing.

The bottom illustration in Figure 4.10 shows how the angle of the propwash during a sideslip creates a destabilizing condition by increasing the airflow, and thus the lift, over the downwind wing.

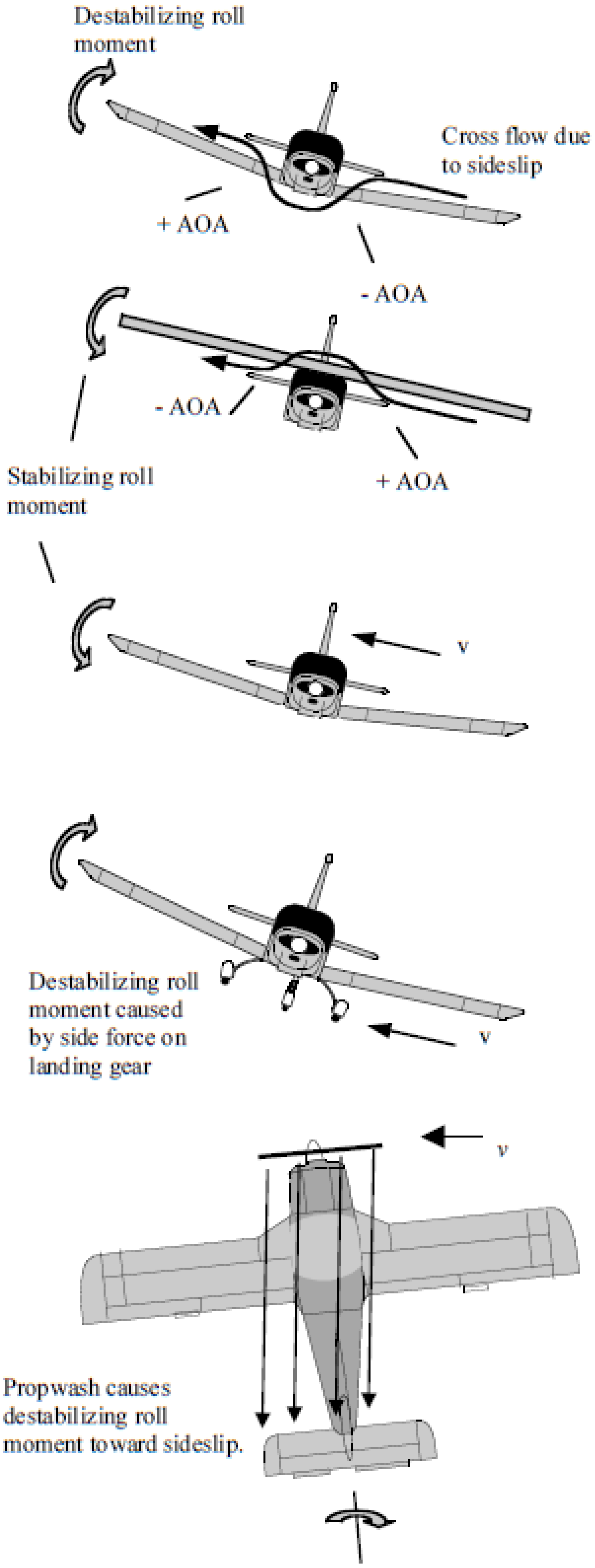


Fig. 4.10. Sideslip induced Roll

This generates a rolling moment into the sideslip. The destabilizing effect increases with the flaps down. It also increases at low airspeeds and high power settings, as the ratio of propwash velocity to freestream velocity increases and the propwash gains relatively more influence.

The propwash effect may vary somewhat, depending on the direction of the sideslip. Propeller swirl, as it's sometimes called, creates an upwash on the left wing root and a downwash on the right, leading to a difference in angle of attack between the wings and thus a rolling moment. For the aircraft at the bottom of Figure 4.10, clock-wise propeller swirl may initially generate a rolling moment to the right, which can suddenly reverse at high α, when the left wing stalls first because of its swirl-induced higher angle of attack. This is an important factor in spin departures, especially during the classic, career-ending skidding turn to final.

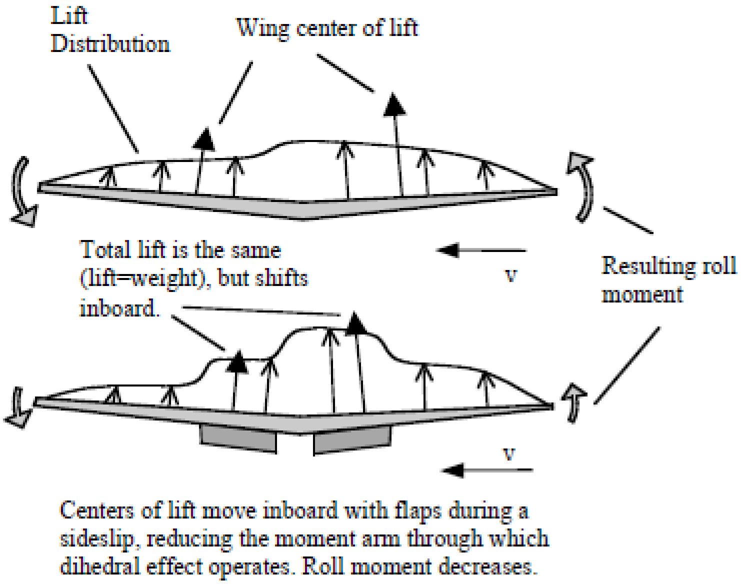


Fig. 4.11. Flap Effects

Propwash effects don't occur in jets, but flap effects do. Flaps shift the centres of lift inboard on the wings, as illustrated in Figure 4.11. This shortens the moment arms through which the lift changes caused by sideslip act, and so sideslip induced roll moments decrease.

We'll explore this effect during steady-heading sideslips by raising and lowering the flaps and watching the roll response. When the flaps go down, dihedral effect will diminish and the aircraft will start to roll in the direction of aileron input. (This demonstration is important in understanding the concept of crossover speed.) Propwash increases flap effects because of the added airflow over the flap region of the up going wing, but we can demonstrate with the prop at idle—it will just take more flap deflection.

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

Geometric Dihedral and Coefficient of Lift, C_L

The strength of geometric dihedral effect does not depend directly on aircraft coefficient of lift (you'll see the reason for the italic treatment presently). The C_L/α curve for a cambered wing in Figure 4.12 is linear up to the stall, which means that for a given change in angle of attack (produced by a sideslip) there's a given incremental difference in coefficient, until the slope starts to decline near the stall. As a result, a given sideslip angle combined with a given dihedral angle, will generate a given difference in C_L. It doesn't matter if you start at low or high C_L, as long you stay on the straight line.

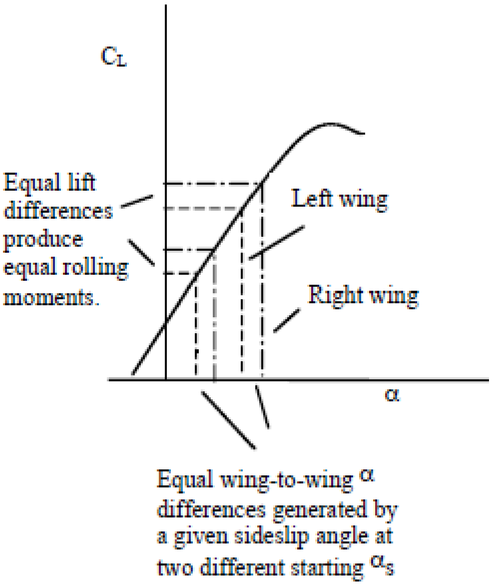


Fig. 4.12. Geometric Dihedral Effect

That difference then produces a rolling moment that varies directly with speed. If you can tolerate even more confusion, imagine that an aircraft with geometric dihedral is flying at its zero lift angle of attack (maybe during a pushover at the top of a zoom). If the airplane starts to sideslip, it will begin to roll as the angle of attack changes on each wing and a spanwise asymmetry in lift appears. Without geometric dihedral, a purely swept-wing aircraft, at zero coefficient of lift, won't roll in the same situation, because the sideslip has no influence if lift is not already being generated.

Swept-wing Dihedral Effect

Figure 4.13 shows the contribution of wing sweep angle (Λ) to dihedral effect. It's almost enough to say that in a sideslip, because of the angle of intercept, the wing toward the sideslip "gets more wind" across its span, while the opposite wing gets less. But we can gain a better understanding of swept-wing characteristics by first breaking the airflow over the wing into normal and spanwise vectors. It's the normal vector (perpendicular to the leading edge on a wing with no taper, or by convention perpendicular to the 25% chord line on a wing with taper) that does all the heavy lifting, because only the normal vector is accelerated by the curve of the wing. There's no acceleration and accompanying drop in static pressure in the spanwise direction, because there's no spanwise curve.

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

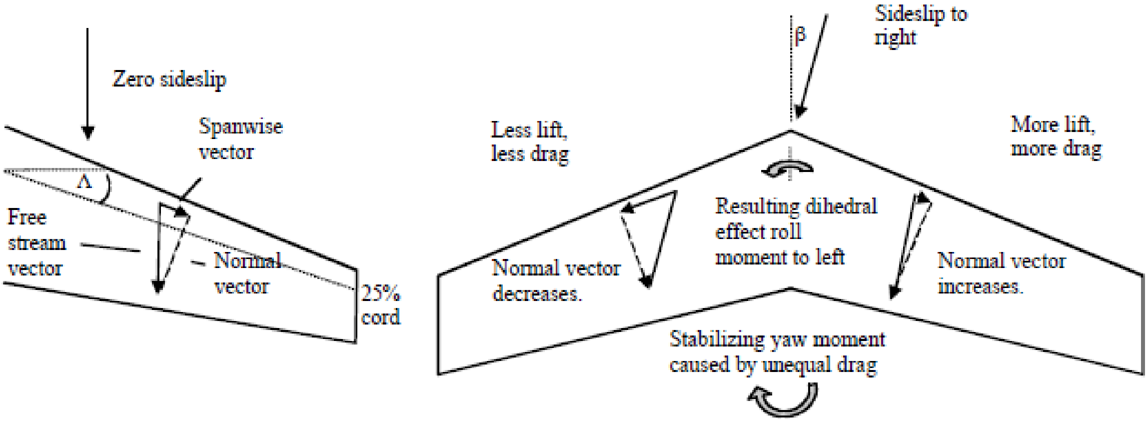


Fig. 4.13. Wing Sweep

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

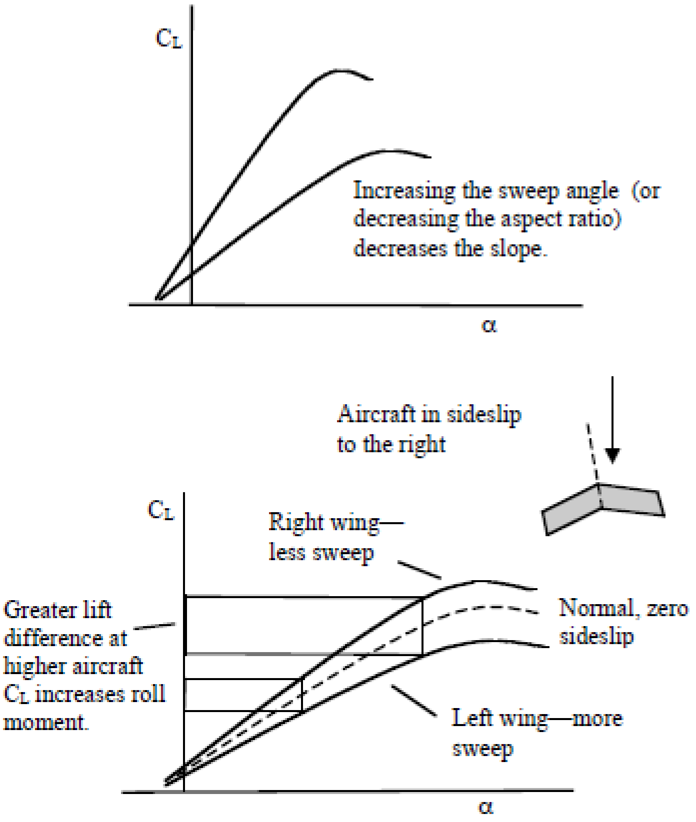


Fig. 4.14. Swept-Wing Dihedral and C_L

The relationship between sideslip and sweep angles, and subsequent rolling moment can be anticipated just from looking at Figure 4.13, but the variation in rolling moment with C_L takes explaining. The easiest approach is to think of sideslip as changing the effective sweep angle of each wing, and thus the slope of their respective C_L/α curves.

Sweep angle and slope are related as shown at the top of Figure 4.14. In a sideslip, as shown on the bottom, a swept-wing aircraft has two C_L/α curves: a steeper one than normal for the wing into the wind, and a shallower one than normal for the trailing wing.

The difference between them creates the rolling moment. Note how the difference at any given β increases with α, and therefore with C_L. Back in Figure 4.13, right, note the difference in spanwise drag during a sideslip. That difference is directionally stabilizing, and it's the reason why flying wing aircraft are swept.

Since wept-wing dihedral effect varies with lift coefficient, so does lateral stability. Aircraft with high sweep angles can have acceptable dihedral effect and lateral stability in normal cruise flight when C_L is low, but excessive dihedral effect at low speeds, or during aggressive turning maneuvers, or at high altitudes, where in each case C_L is necessarily high.

Under those conditions, sideslips can produce strong rolling moments. This can allow a pilot to accelerate a roll rate by forcing a sideslip with rudder, but also increases the potential for Dutch roll oscillation and rudder misuse. As mentioned, unlike a wing with geometric dihedral, a purely swept-wing will not roll in response to a sideslip unless it's already generating lift. There's no dihedral effect attributable to wing sweep at zero C_L. You can see that a wing possessing both geometric dihedral and sweep has a kind of multiple personality (and usually a yaw damper).

Straight Wings and Coefficient of Lift—Revisited

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

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

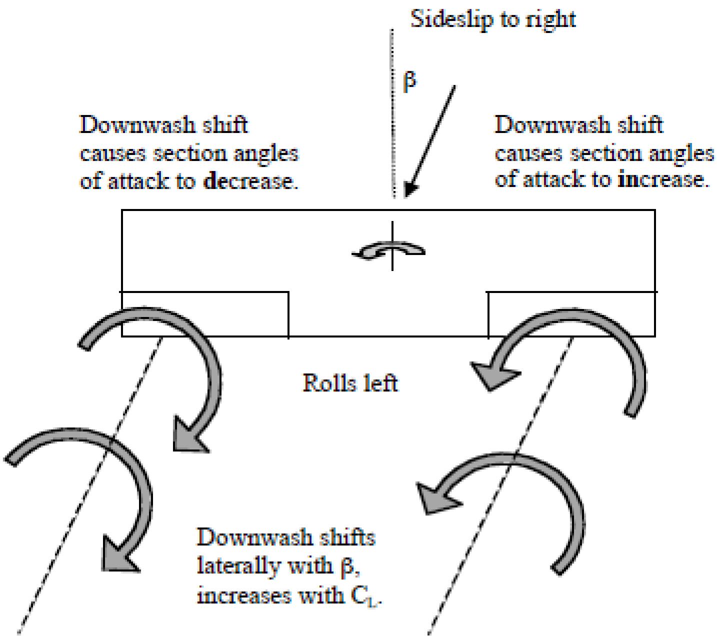


Fig. 4.15. Vortex Effects

In a sideslip the vortex flow shifts laterally, as in Figure 4.15. This changes the overall downwash distribution, shifting it to the left in the case illustrated, which in turn causes the average effective angle of attack of the left wing to be lower than it would from dihedral geometry alone. The average effective angle of attack on the right wing becomes higher. The result is a rolling moment to the left (a moment that would theoretically occur even if the wing had zero dihedral—as long as lift is being produced).

Since downwash strength is a function of C_L, pulling or pushing on the stick will affect roll moment due to sideslip in a manner similar to the swept-wing example already described. (Our trainers' rectangular planforms tend to promote strong tip vortices. Other straight-wing planforms with different lift distributions might not be as effective.) Pushing and pulling on the stick during a sideslip also causes the aircraft to pitch around its y wind axis (as opposed to body axis), which introduces a roll as described in Figure 4.20. The effect would be in the same direction as the downwash phenomenon just mentioned, and the two might easily be confused.

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

Sideslip and Roll Rate

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

1. Increasing C_L (by pulling back on the control) will increase rolling moment due to sideslip and yaw rate. Decreasing C_L (by pushing forward) will decrease rolling moment due to sideslip and yaw rate. We'll explore the implications of this during our flight program. (See roll due to yaw rate, and y-wind-axis roll, farther on.)
2. A laterally stable aircraft rolling with aileron toward the direction of a sideslip/velocity vector will experience a decrease in roll rate in proportion to the opposing rolling moment the sideslip produces. An aircraft rolling with aileron away from the direction of a sideslip/velocity vector will experience an increase in roll rate. You'll discover this effect when we start rolling the training aircraft through 360 degrees and begin using rudder-controlled sideslips to augment roll rates.

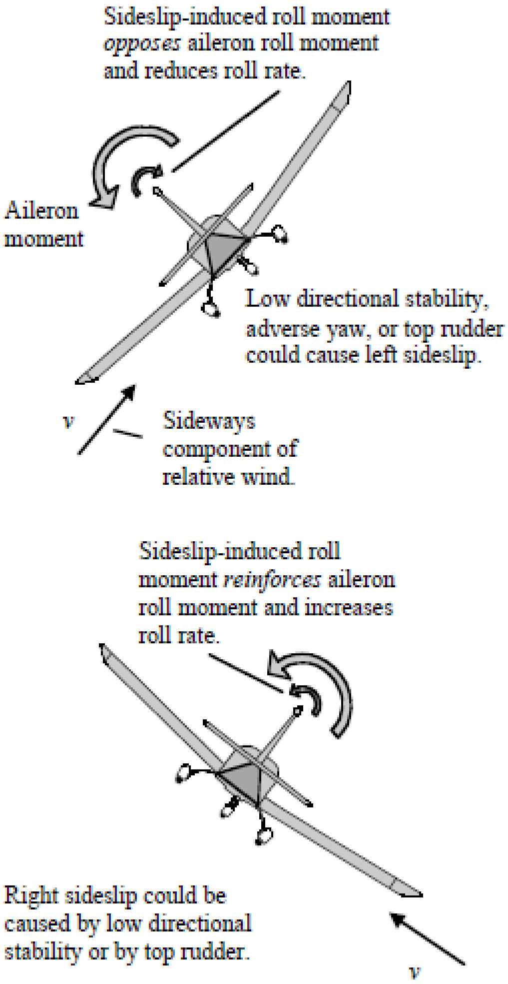


Fig. 4.16. Sideslip and Roll Rate

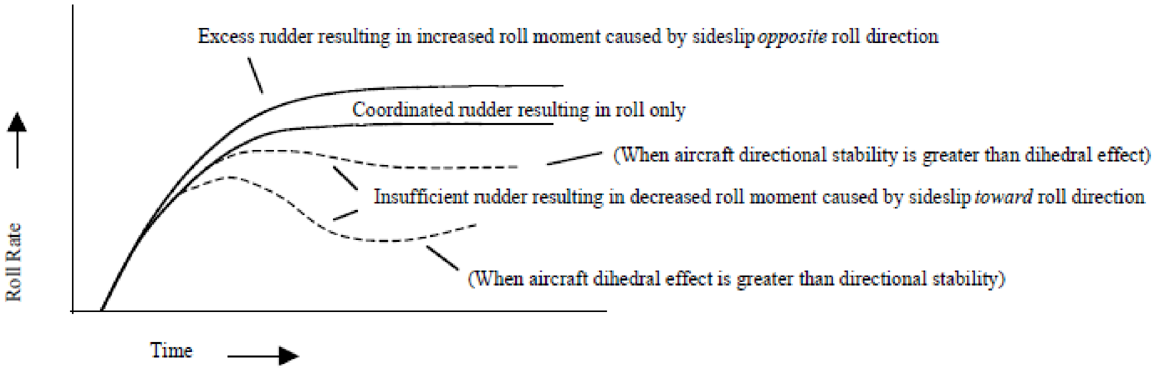


Fig. 4.17. Dihedral Effect, Rudder Use, Roll Rate

Figure 4.16 describes the link between sideslip direction and roll rate at two points during a 360 degree roll to the left, and Figure 4.17 plots roll rate against time, given differences in rudder use, dihedral effect, and directional stability.

Aerobatic Aircraft and Dihedral Effect

High-performance aerobatic airplanes usually have little or no geometric dihedral, and so very little lateral stability through dihedral effect. One can't always know what the designer had in mind, but the absence of dihedral allows aircraft to roll faster in the presence of opposing sideslips, and makes them easier to fly to competition standards because roll rate and rudder deflection remain essentially independent.

It's possible to use the rudder to keep the nose up during the last quarter of a slow roll (when an aircraft that's rolling left, say, and going through the second knife edge is side slipping to the right) without having to change aileron deflection to keep the roll rate from accelerating. These desirable characteristics for smooth aerobatic flying actually make an aircraft less suitable for unusual-attitude training. Most aircraft do exhibit lateral stability, and the resulting characteristics are important to understand. For one thing, lateral stability allows you to roll an aircraft with rudder using normal directional input should you lose the primary roll control—the ailerons.

Absent dihedral effect and unaccompanied by aileron, rudder deflection alone in some aerobatic aircraft will produce a roll opposite the expected direction. For example, right rudder, instead of rolling the aircraft right by dihedral effect (and roll due to yaw rate), slowly rolls it to the left, as in Figure 4.18. Roll due to rudder is caused by the vertical tail's centre of lift being above the aircraft's centre of gravity.

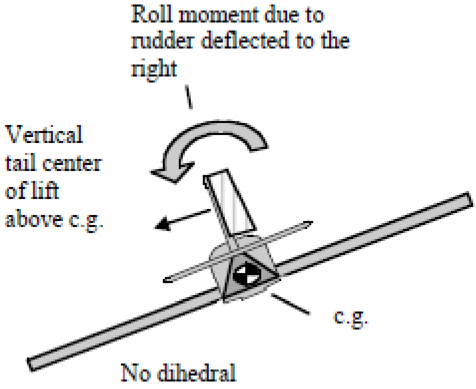


Fig. 4.18. Roll due to Rudder, $C_{l_{\delta_r}}$

A moment arm results. The effect could be particularly evident in a zero-dihedral, low-wing aircraft, when a sideslip generated by rudder deflection also produces an accompanying, destabilizing roll due to cross flow. (Check back to Figure 4.10, top. Low wing is destabilizing.) The first time you try to unfold a map while using your feet to keep the wings level in an aircraft that behaves like this, you're in for a surprise.

If you actually lost your ailerons you might regain some positive dihedral effect and roll due to yaw rate by slowing down and increasing the coefficient of lift. Also, slowing down will raise the nose, and so place the tail lower and decrease the vertical distance between its centre of lift and the C.G., reducing the moment arm. Perhaps the aircraft would then respond in the normal way. It may be possible (as in the Giles G-200, for example) to control an aircraft by using roll due to rudder, but it's not the sort of thing that happens intuitively. Aileron failure is typically catastrophic in an aircraft without dihedral effect. That's one reason why pre-flight inspection of the lateral control system in a zero-dihedral aerobatic aircraft (for integrity of the linkages, and for items that could cause jams like loose change, nuts, bolts, screwdrivers, hotel pens—your mechanic has horror stories and probably a collection of preserved examples) is so important. The same, of course, goes for elevator and rudder systems.

Here’s a related phenomenon: Next time you fly the swept-wing MiG-15, notice that rudder deflection produces a roll in the expected direction until you get past about Mach 0.86, but then the response reverses—left rudder causing the right wing to drop, for example. A sideslip, as pointed out in Figures 4.13 and 4.14, reduces the sweep of one wing and increases the sweep of the other, relative to the free stream. The reduction in the effective sweep of the right wing, caused by pressing the left rudder, can send the right wing past critical Mach number, causing shock airflow separation and a wing drop. If you’re pulling g, the effect can happen at a lower speed because of the acceleration of the airflow over the wing caused by the higher angle of attack. Response to the rudder returns to normal at about Mach 0.95.

Roll Due to Yaw Rate, C_{l_r}

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

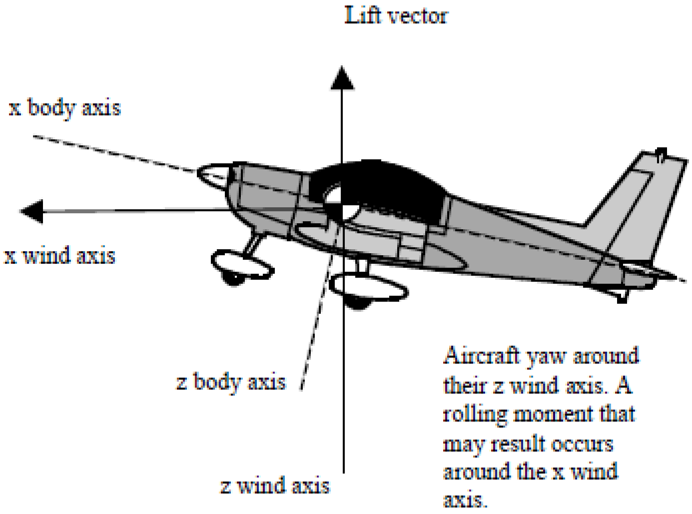
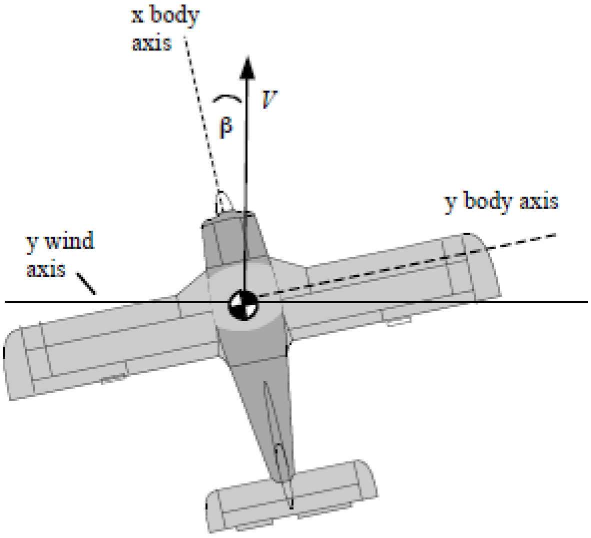


Fig. 4.19. Aircraft Yaw Around Z Wind Axis

When you enter a sideslip by pressing the rudder, some percentage of the roll moment generated is caused by dihedral effect, and some by roll due to yaw rate. Once a given sideslip angle is reached and held and yaw rate disappears, dihedral effect provides the remaining rolling moment. Like the dihedral effects described above, roll due to yaw rate increases with coefficient of lift, C_L. For rectangular wings, the value for the rolling moment coefficient per unit of yaw rate, C_{l_r}, is about 0.25 times C_L, on average. Wingtip washout, and/or flap deployment, reduces C_{l_r}.

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

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



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

Fig. 4.20. Aircraft Pitch Around Y Wind Axis

Adverse Yaw, $C_{n_{\delta_a}}$

Aerodynamic coupling effects keep rolling from being a one-degree-of-freedom proposition. Rolling moments come with yawing moments attached, and those yawing moments affect roll behaviour.

Induced drag increases when an aileron goes down, decreases when an aileron goes up. The result is usually an adverse yawing moment, opposite the direction of roll. In the absence of a sufficient counteracting yaw moment—supplied in part by the aircraft's inherent directional stability, in part by aileron design, and in the remainder by coordinated rudder—the aircraft will begin to sideslip.

The velocity vector will shift from the plane of symmetry toward the roll direction if too little coordinating rudder is applied, and shift opposite the roll direction if the rudder gets too emphatic an in-turn boot.

In a perfectly coordinated, ball-centred roll and turn, with adverse yaw properly countered by rudder deflection, the "instantaneous" velocity vector remains on the plane of symmetry, as Figure 4.21 describes.

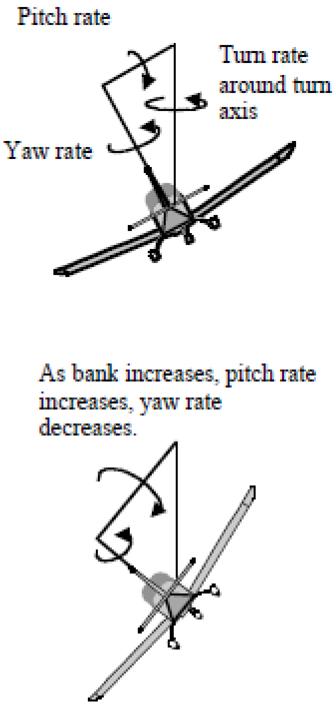


Fig. 4.21. Relative Yaw and Pitch Rates. Constant- Altitude Turn

The rudder deflection necessary to handle adverse yaw depends on the ratio of yaw moment to roll moment the ailerons produce. While the ratio is basically a function of the aileron system design, it increases with coefficient of lift, C_L. This means that as airspeed goes down, the need for rudder coordination becomes greater. The nature of induced drag rise at high angles of attack is the major reason, since induced drag increases as the square of the coefficient of lift. As the drag curve becomes steeper, a given aileron deflection produces a greater difference in induced drag across the span, and the yaw/roll ratio increases. Differential or Frise ailerons, initially designed to reduce aileron forces, also reduce adverse yaw by increasing the drag of the up-going aileron. Another factor is the reduction in directional stability caused by the disrupted fuselage wake at angles of attack approaching stall. Because energy is removed from the free stream, more rudder deflection is needed as weathercock stability goes down in the tired-out air.

Configuration is also important. Partial-span flaps cause an aircraft to fly at a more nose-down angle for a given overall coefficient of lift. As a result, the aileron portion of the wing experiences a relative washout and generates a lower local coefficient of lift than when the flaps are up. That lower local coefficient translates into less adverse yaw. Flaps also reduce dihedral effect, so the sideslip that does occur has less effect on roll.

Aeroelastic Aileron Reversal

At high speeds, aeroelastic deformation also puts a cap on roll rates. The down aileron produces a twisting moment on the wing, which forces the leading edge to deflect downward, reducing the angle of attack (Figure 4.22). This reduces lift and consequently rolling moment. Roll rate then starts going down and at a certain speed, V_R, when the decrease in lift due to twisting equals the increase in lift due to aileron deflection, the ailerons will no longer create a normal rolling moment. Beyond this speed "aileron reversal" occurs. A down-going aileron then produces a down-going wing.

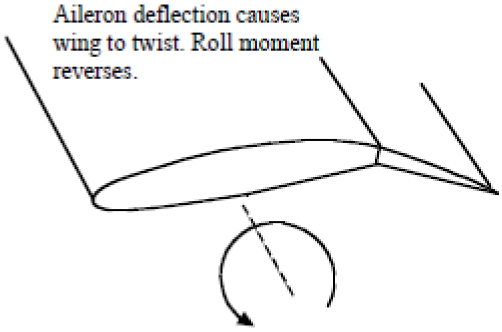


Fig. 4.22. Aileron Reversal

One of the cures for aileron reversal, not surprisingly, is to increase the torsional stiffness of the wing (at the expense of added weight). On swept wings it's necessary to increase the bending stiffness because the geometry of a swept wing causes it to twist as it bends. Moving the ailerons inboard or extending their span inboard also helps raise V_R on a swept wing. Spoilers are another option, as mentioned.

Weathercock effect

Whenever an airplane, originally flying with zero sideslip, develops a sideslip (β), the vertical tail tends to bring it back to the original position of zero sideslip.

This effect is similar to that of the vane attached to the weathercock which is used to indicate the direction of wind and is located on top of buildings in meteorological departments and near airports (Figure 4.23). When the vane is at an angle of attack, it produces lift on itself and consequently a moment about its hinge. This moment becomes zero only when the vane is aligned with the wind direction.

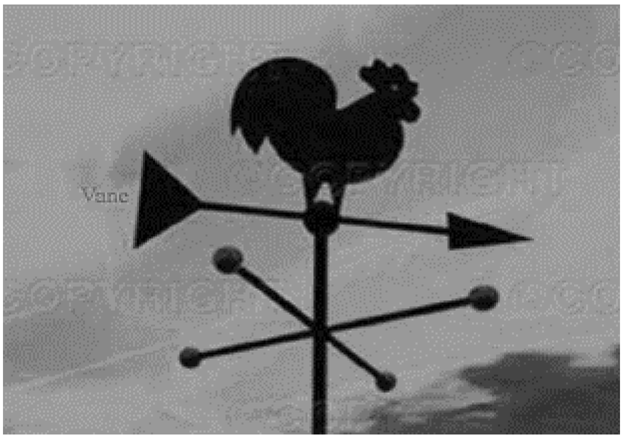


Fig. 4.23. Weathercock or weather vane

Hence, the vane is always directed in a way that the arrow points in the direction opposite to that of the wind. The action of vertical tail on the airplane is also similar to that of the vane and helps in aligning the airplane axis with wind direction. Hence, the directional stability is also called weathercock stability.