Module – 4

STABILITY AND CONTROL – LATERAL AND DIRECTIONAL

Syllabus:

Lateral and directional static & dynamic stability: - Coupling between rolling and yawing moments. Steady heading slide slip. Definition of Roll stability. Adverse yaw effects. Aileron reversal. Regulations, test techniques and method of data reduction.

4.1 Static Lateral –Directional Stability Theory and Flight Test Methods

A study of lateral-directional stability is a study of the reaction of the airplane when its flight path deviates from the plane of symmetry. The angle that the plane of symmetry makes with the relative wind is called the sideslip angle β. The angle that the plane of symmetry makes with some fixed reference is called the yaw angle ψ. The yaw angle is positive when the nose is displaced to the right of the reference, while sideslip is positive when the relative wind is coming from the right side of the airplane. The sideslip can be compared to the angle of attack, while the yaw angle is similar to the pitch angle. Also, like angle of attack and pitch, the two will only always agree in magnitude in the wind tunnel. It should be noted that it is possible to have yaw without sideslip, and to have yaw rates and moments without sideslip. It might also be noted that sideslip acts in a different plane than does the angle of attack and its effects are quite different. In lateral-directional stability and control a sideslip will not only generate a yawing moment, but it will also generate rolling moments and side-force. This is considerably different from the longitudinal case where a change in angle of attack only generates a pitching moment. Also, where angle of attack has great usefulness to the pilot, sideslip has little use except for crosswind landing situations.[1–3]

4.1.1 Federal Aviation Administration Regulations

Both CAR 3 and FAR Part 23 contain requirements for lateral-directional stability.

4.1.2 Theory

Since sideslip is a factor in both lateral and directional stability, these items are generally measured in steady sideslips. Since in a steady sideslip there is no acceleration we can write the equations of motion as follows:

Rolling moment equation:[1]

$$C_{l_\beta}\beta + C_{l_{\delta_r}}\delta_r + C_{l_{\delta_a}}\delta_a = 0 \qquad (28.1)$$

where

C_{l_β} = rolling moment coefficient due to sideslip

$C_{l_{\delta_r}}$ = rolling moment coefficient due to rudder deflection

δ_r = rudder deflection

$C_{l_{\delta_a}}$ = rolling moment coefficient due to aileron deflection

δ_a = aileron deflection

Yawing moment equation:[1]

$$C_{n_\beta}\beta + C_{n_{\delta_r}}\delta_r + C_{n_{\delta_a}}\delta_a = 0 \tag{28.2}$$

where

C_{n_β} = yawing moment coefficient due to sideslip

$C_{n_{\delta_r}}$ = yawing moment coefficient due to rudder deflection

$C_{n_{\delta_a}}$ = yawing moment coefficient due to aileron deflection

Side-force equation:[1]

$$C_{Y_\beta}\beta + C_{Y_{\delta_r}}\delta_r + C_{Y_{\delta_a}}\delta_a + C_L\phi = 0 \tag{28.3}$$

where

C_{Y_β} = side-force coefficient due to sideslip

$C_{Y_{\delta_r}}$ = side-force coefficient due to rudder deflection

$C_{Y_{\delta_a}}$ = side-force coefficient due to aileron deflection

ϕ = bank angle

As can be seen from these three equations, all have a mixture of lateral and directional coefficients, and treatment of lateral-directional stability and control cannot be as simple as for longitudinal stability and control. It is, however, of some benefit to discuss them separately and that will be the approach here.

4.1.2.1 Directional Stability

In examining Eq. (28.2), which is essentially the directional stability equation, we can see that the first term in the equation is the sideslip term. This is quite proper since the problem of directional stability is essentially that of insuring that the airplane maintains zero sideslip. Directional stability then is "weathercock" stability and involves the moments generated about the vertical axis.[3] Directional stability also has a closer comparison with longitudinal stability than does lateral stability. If we view the airplane from the top we can see that the fuselage, vertical tail, nacelles, and power all act about the vertical axis much in the same way that the fuselage, horizontal tail, nacelles, and power act about the lateral axis. Only the wing contributions differ. Like longitudinal stability, the static directional stability is a result of the contribution of the components of the airplane.[3] Although the contributions of the components are sometimes related, it is much easier to study them separately.

The vertical tail is the primary contributor to directional stability.[3] When the airplane is placed in a sideslip the vertical tail experiences a change in angle of attack. This change in angle of attack causes the vertical tail to generate a force in the direction, which rotates the airplane so as to reduce the sideslip.[3]

This side-force can be expressed by the nondimensional derivative $C_{Y_{\beta_V}}$ (Ref. 1).

$$C_{Y_{\beta_V}} = -a_V\left(1 - \frac{d\sigma}{d\beta}\right)\eta_V \frac{S_V}{S_W} \qquad (28.4)$$

where
a_V = lift curve slope of the vertical tail
$d\sigma/d\beta$ = change in side wash σ with change in sideslip β. This factor is caused by interference of other parts of the airplane
η_V = vertical tail efficiency factor q_V/q

The yawing moment due to the vertical tail is a function of the side-force due to the vertical tail and the length of the vertical from the c.g. or:[2]

$$C_{n_{\beta_V}} = -C_{Y_{\beta_V}} \frac{l_V}{b} \qquad (28.5)$$

where
l_V = tail arm, or length of the vertical tail a.c. from the c.g.

In studying the last two equations, we can see that the directional stability contribution of the vertical tail is controlled by three main factors: 1) the tail arm, 2) the lift curve slope, and 3) the vertical tail area.

Once the airplane has progressed to the flight test stage, a modification of the tail arm is not likely, since it would probably require a major redesign of the fuselage. It is, however, probably one of the more powerful parameters in the equation.

The vertical tail lift curve slope is somewhat easier to modify during flight test. For instance, the addition of a dorsal fin (Fig. 28.1)[3] will reduce the vertical tail aspect ratio and cause the vertical tail to stall at a higher sideslip angle. A ventral fin (Fig. 28.2) will increase the vertical tail aspect ratio and steepen the lift curve slope. The ventral fin also lowers the center of pressure of the vertical tail which will reduce the roll with yaw caused by the vertical tail.[7]

The vertical tail area can also be changed with dorsal and ventral fins, so they are handy gimmicks to use during flight test. The contribution of the wing to directional stability is small. Sweeping the wings improves the contribution, but it is still small when compared to other components.

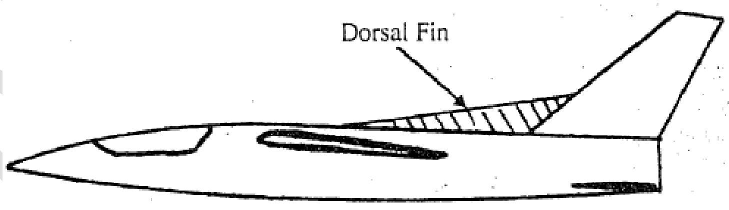


Fig. 28.1 Aircraft with dorsal fin.[3]

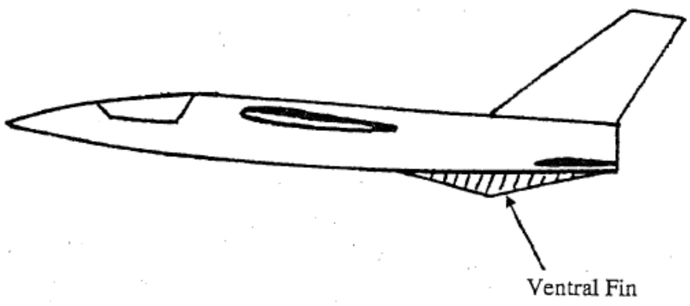


Fig. 28.2 Aircraft with ventral fin.

The fuselage and nacelles provide a large contribution that is generally destabilizing.[3] This destabilizing influence is similar to the longitudinal case except that in this case the up-wash and down-wash of the wing are not a factor. Therefore, the destabilizing influence of the fuselage is not as great in this case as it is in the longitudinal case.

The power and propeller fin effects on directional stability are similar to the effects of these items on longitudinal stability, i.e., generally destabilizing.[3]

Freeing the rudder has the same effects on directional stability as it does on longitudinal stability, i.e., a reduction in stability.[3]

High Mach numbers also reduce directional stability due to the reduction of the vertical tail lift curve slope with increasing Mach number.[3,7] This is one of the reasons that today's high-speed fighters have twin vertical tails.

In the category of minor contributors to directional stability are the roll control devices such as ailerons and spoilers. Because ailerons produce more induced drag on the up-going wing than on the down-going wing, they tend to increase sideslip and have a destabilizing effect. This effect is called adverse yaw. Spoilers, on the other hand, produce additional drag on the down-going wing and, therefore, reduce sideslip or cause proverse yaw.[1]

4.1.2.2 Lateral (Roll) Stability

Static lateral stability is not comparable to either longitudinal or directional stability even though it does have an effect on directional stability. Lateral stability is a study of the effects of sideslip on the rolling moments of an airplane. If positive sideslip provides a negative rolling moment and vice versa, then the airplane is said to possess positive lateral stability. If a sideslip produces no rolling moment then the airplane possesses neutral lateral stability. A positive sideslip producing a positive rolling moment and vice versa is described as negative lateral stability. We can say then that when an airplane tries to roll away from the sideslip it has positive lateral stability, and if it rolls into the sideslip it has negative lateral stability.[3]

It is generally desirable only to have weak positive lateral stability. This is because excessive roll due to sideslip complicates such tasks as crosswind takeoffs and landings where it is necessary to sideslip.[3] Also, strong positive lateral stability increases roll-yaw coupling, which is undesirable for certain

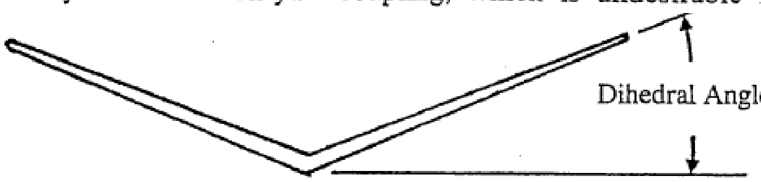


Fig. 28.3 Wing dihedral.[3]

tracking tasks such as instrument approaches and strafing runs.

If the above is the case, what methods do we have for increasing or decreasing lateral stability? Once the aircraft reaches the flight test stage we have very few. The designer, on the other hand, has several options that may be used during the design stage. To evaluate these options let us examine the contributions of the various airplane components to lateral stability.

The wing is the primary contributor to lateral stability.[3] This is accomplished by the use of geometric dihedral (Fig. 28.3).[3] A wing with dihedral will develop stable rolling moments with sideslip because the dihedral causes the "wing into" the sideslip to have an increased angle of attack while the opposite wing has a decreased angle of attack (Fig. 28.4). It is for this reason that lateral stability is sometimes referred to as dihedral effect.

Aft sweep in a wing also creates favorable rolling moments with sideslip.[1,3,7] This is also due to the differences in angle of attack experienced due to an effective reduction in sweep of the wing "into the wind" and an effective increase in sweep of the opposite wing (Fig. 28.5).[3] This effect increases as angle of attack increases and presents a significant roll-yaw coupling problem for high performance, highly swept wing airplanes.[2]

The fuselage, or location of the wing on the fuselage, is a major contributor to lateral stability. This is essentially caused by the effect of the fuselage on

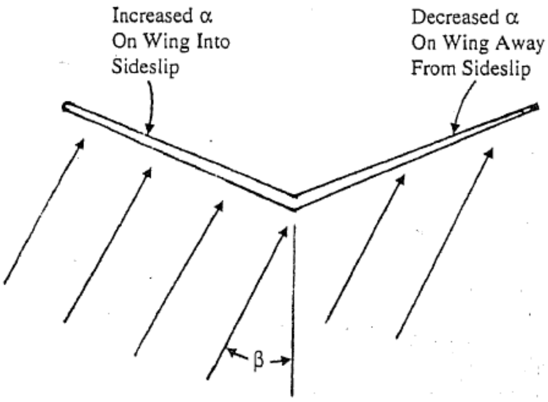


Fig. 28.4 Effects of dihedral during sideslips.

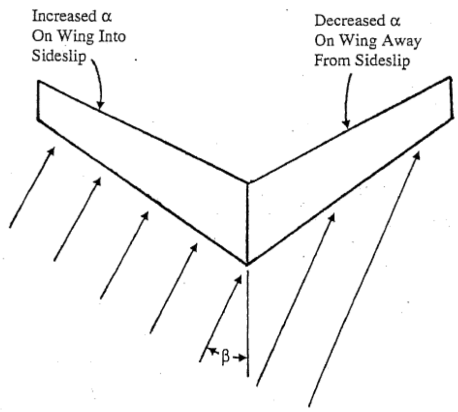


Fig. 28.5 Effects of wing sweep on lateral stability.[3]

the wing angle of attack. A fuselage below the wing creates the positive lateral stability while a fuselage above the wing creates negative lateral stability (Fig. 28.6).[3,7] This is such a strong effect that low-wing airplanes require 3–4 deg more dihedral than do high-wing airplanes.

The vertical tail also contributes to lateral stability.[3] The side-force acting on the vertical tail during a sideslip acts at some distance from the longitudinal axis. This creates a rolling moment that is favorable for conventional tail configurations.[7] It is possible to make this moment zero or even unfavorable by placing part or all of the vertical tail below the longitudinal axis.

The propeller slipstream also contributes to lateral stability. Due to the fact that during a sideslip the slipstream flows mostly over the wing "away from the wind," it creates a destabilizing rolling moment. This moment is greater when the flaps are down (Fig. 28.7)[1] and, as a result, the power approach configuration is generally critical for lateral stability.[1]

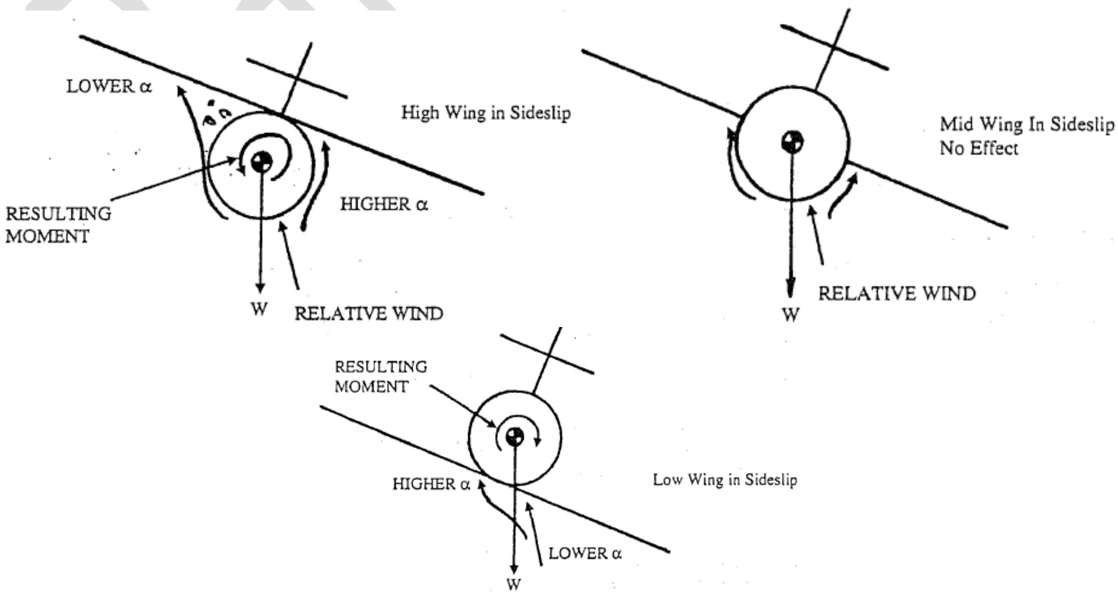


Fig. 28.6 Effects of fuselage locations on lateral stability.

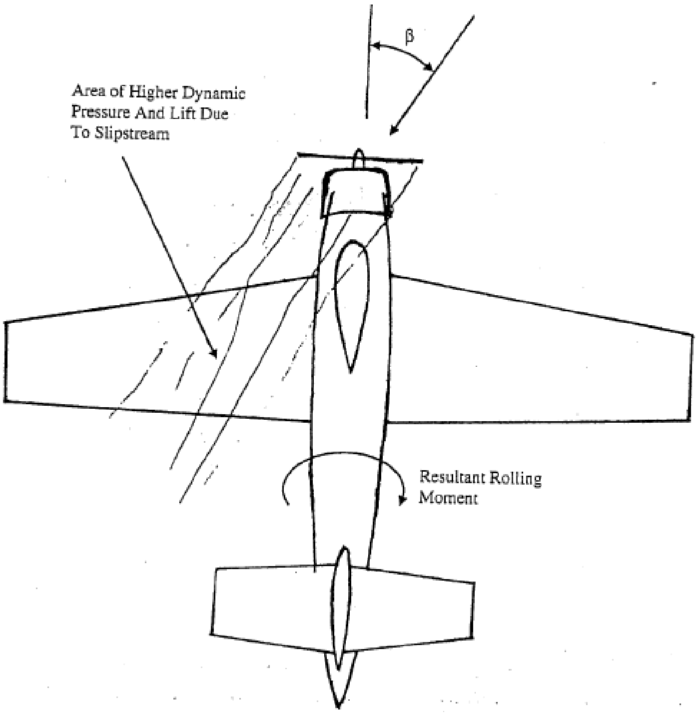


Fig. 28.7 Slipstream effects during sideslip.[1]

4.1.2.3 Side Force

Side-force can be generated by many parts of the airplane; however, the two main contributors are the vertical tail and an inclination of the lift vector. In a steady sideslip it is the side-force that causes the lateral translation. This lateral translation is very useful in countering drift due to crosswinds in takeoff, landing, and target tracking situations. If side-force is generated in a sideslip, it creates the roll-yaw coupling problems that make the piloting task difficult. This is one reason that considerable effort is now being expended on direct side-force control through auxiliary surfaces on the wings or fuselage. As can be seen from Eq. (28.3), the side-force is very dependent on bank angle due to the inclination of the lift vector. This makes a plot of bank angle vs sideslip an important plot in determining side-force.

4.1.3 Flight Test Methods

From the lateral-directional stability theory one can see that more information regarding the capabilities of the airplane can be gained from measuring the quantities of control displacements, forces, bank angle, and sideslip, along with aircraft test weight while the aircraft is in a steady heading sideslip. This technique will also allow the extraction of some lateral-directional stability derivatives for use by the stability and control group in addition to providing the information needed for aircraft certification. However, the steady heading sideslip method requires more complex instrumentation than that required by the FARs and the advisory circular. Those methods can be used to show compliance to the regulations with minimum instrumentation.

4.1.3.1 Steady Heading Sideslips

The steady heading sideslip is performed by first trimming to hands-off flight in all three axis (providing three axis trim is available) at the test airspeed. In order to minimize altitude loss in power-off tests, one should start at the lowest trim airspeed at the highest altitude. The aircrew should approach large sideslip angles at this lowest airspeed with some caution as large sideslip may cause one wing to stall resulting in a snap roll departure. Once trimmed, the steady heading sideslip is entered in one direction using about 0.25 full rudder deflection. Once stabilized, data is recorded. The sideslip is then increased to 0.5 full rudder deflection, stabilized in a steady heading and data again recorded. This process is continued using 0.75 full deflection and full rudder deflection. Once completed in one sideslip direction, the testing is repeated in the opposite direction. Seldom does one find that propeller-driven airplanes are symmetrical left and right. This will be especially true if there is a fuel unbalance. Therefore, initial testing should be conducted with a symmetrical fuel loading. Since AC 23-8A requests testing with a maximum allowed fuel unbalance, the critical sideslips should be repeated with that unbalance. These tests should be repeated in even increments of airspeed throughout the required range and in the specified configurations of landing gear, flaps, and power.

The data to be recorded during these tests consist of sideslip $\hat{\beta}$, bank angle ϕ, aircraft weight at the time of the data point, rudder position δ_r and force F_r, aileron position δ_a and force F_a, and elevator position δ_e and force F_s. Elevator position and force are recorded to determine if the aircraft has a tendency to tuck or pitch up with sideslip. Although this pitching information is not required by the FARs it is worthwhile information. Since there are several parameters to record, it is best to record this data with an automatic recording device. The data may be hand recorded, but accuracy and test time suffer, and the pilot may experience fatigue from stabilizing the airplane in the many sideslips. Once data are recorded, they are corrected for instrument error and plotted as shown in Fig. 28.8. Most lateral-directional stability data are nonlinear. This is due to separation from various parts of the airplane during the sideslip. The propeller slipstream will cause this separation to be different depending upon the direction of sideslip resulting in plots that are not symmetrical.

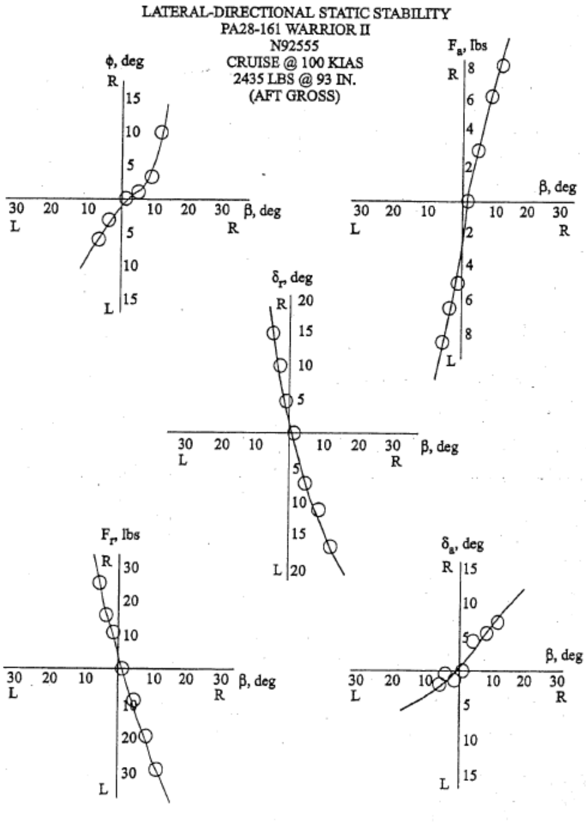


Fig. 28.8 Steady heading sideslip data.

4.1.3.2 FAA Directional and Lateral Methods

The lateral stability test method prescribed by the FAA in AC 23-8A is essentially the same as the steady heading sideslip described above. The difference comes when the airplane is incapable of performing a steady heading sideslip with 10 deg of bank. In that case, 10 deg of bank is used with full rudder and the aircraft is allowed to turn. Compliance with the regulation is demonstrated in the lateral stability test using the FAA method if when the aileron is released the wings tend to return to level. Note that they only have to have a *tendency* to return to level. As one can see, this test only collects qualitative data and does not provide the data that can be obtained from a fully instrumented steady heading sideslip.

Directional stability tests as prescribed by the FAA consist of wing-level sideslips to determine if, when the rudder is released, the aircraft returns to straight flight. Care should be taken in any of the test methods that full control deflections are not used above the maneuvering speed V_A. The directional stability test using the FAA method also only provides qualitative data. However, that is sufficient to show compliance with the regulation.

4.2 Dynamic Lateral –Directional Stability Theory and Flight Test Methods

In our past discussions on lateral-directional stability and control, we have separated the lateral and directional responses. This was convenient for the discussion of the static cases, but in free flight the responses are coupled. For the dynamic case, we have to consider this coupling and the effects that the airplane's inertia have on it.

4.2.1 Federal Aviation Administration Regulations

The FAA Regulations from their early days have only addressed the motions both longitudinal and lateral-directional that are of such short period as to couple with the pilots reaction time. As a result, motions like the spiral do not appear in the FAA Regulations.

4.2.2 Theory

4.2.2.1 Spiral Mode

The spiral mode of motion is a very gentle mode even when divergent and is easily controlled by the pilot.[6,7,8] If divergent, the spiral mode may present a problem for the pilot under instrument conditions when his/her attention is diverted from flying the airplane. The spiral mode can be described as a bank angle increase or decrease after a bank angle disturbance from wings level flight. The spiral mode can be either convergent, divergent, or neutral. This is dependent on the sign of the following combination of derivatives:[4,5]

$$L_\beta N_r - N_\beta L_r$$

If this combination is positive then the spiral mode will be convergent. If it is negative the spiral mode will diverge. This indicates that strong directional stability N_β tends to make the spiral mode divergent while strong positive lateral stability tends to make it converge. If the combination is zero then the spiral mode is neutral.[4,5]

The rate at which the spiral mode converges or diverges is a function of airspeed. At low airspeeds the rate is high while at high airspeeds it is low.[4]

4.2.2.1 Dutch Roll Mode

The Dutch roll mode can be described as a lateral-directional oscillation. The oscillation is generally convergent, but the rate at which it converges is quite significant to the pilot's opinion of the airplane. It is desirable to have the motion heavily damped since a near neutral oscillation would make any tracking task difficult due to the fact that the pilot will excite it with any lateral-directional control input. In addition, if the oscillation is not heavily damped, atmospheric turbulence will excite it and make the ride of the airplane unpleasant. The Dutch roll mode is not a totally nuisance mode, however, since the pilot may use this mode of motion to generate sideslip changes for straight flight in crosswind landings. It is also the mode of motion used to control bank angle with the rudder.[4]

Since Dutch roll is a coupled motion there are no simple methods for determining the frequency and damping ratio of the Dutch roll mode. If we assume that both L_β and L_r are zero then we can arrive at an equation that gives a rough approximation of the undamped natural frequency of the motion.[4]

$$\omega_{n_{DR}} \cong M\sqrt{C_{n_\beta}\frac{\gamma P_a S b}{2I_{zz}}} \tag{29.2}$$

where
M = Mach number
γ = a constant, 1.4 for air
P_a = absolute pressure in pounds per square foot
I_{zz} = moment of inertia in yaw

If we evaluate this equation we can learn several things about the Dutch roll undamped natural frequency. First, we can see that it varies directly with Mach number. The higher the Mach number the higher the frequency. It also varies directly with directional stability C_{n_β}. In this case the directional stability can be equated to the spring in the spring-mass-damper system. Increasing the spring stiffness $+C_{n_\beta}$ increases the frequency. This equation also shows that as altitude increases (lower P_a) the frequency decreases. We can also see that as moment of inertia in yaw increases the frequency decreases. We would then expect airplanes with engines on the wing and tip tanks to have a low Dutch roll frequency if all else is equal.[4]

In all studies of dynamic motions, both the frequency and the damping ratio are important. In order to come up with Dutch roll damping ratio we have to make another simplifying assumption. In addition to the assumptions made to obtain the frequency equation, we must also assume that the side-force due to sideslip is equal to the yawing moment due to yaw rate or $Y_\beta = N_r$. If this is done we can arrive at the following equation for Dutch roll damping:[4]

$$\zeta_{DR} = C_{n_r}\sqrt{\frac{\rho S b^3}{8C_{n_\beta} I_{zz}}} \tag{29.3}$$

where
C_{n_r} = yaw rate damping coefficient

Again, by a study of this equation we can reach several conclusions about Dutch roll damping. First, we can see that as yaw rate damping C_{n_r} increases, Dutch roll damping increases. The yaw rate damping acts like the damper in the spring-mass-damper system. We can also see that the Dutch roll damping decreases as altitude increases. This is the reason that most high-altitude airplanes have artificial yaw damping. Increasing directional stability decreases Dutch roll damping. Although an increase in yawing moment of inertia reduces the frequency, it also reduces damping. One other item might be noted about Dutch roll damping: neither airspeed nor Mach number appears in this equation and neither affects damping.[4]

The equations we have just evaluated only consider the case where there is no roll present in the motion, just a wagging of the tail. Dutch roll is in fact a coupled motion and the amount of roll present with the yawing, or the ratio of roll to yaw ϕ/β is very important in how the pilot perceives the Dutch roll characteristics of the airplane.[7] Generally, more damping is required when the ϕ/β ratio is increased.

4.2.3 Flight Test Methods for Evaluating Dynamic Lateral-Directional Stablity

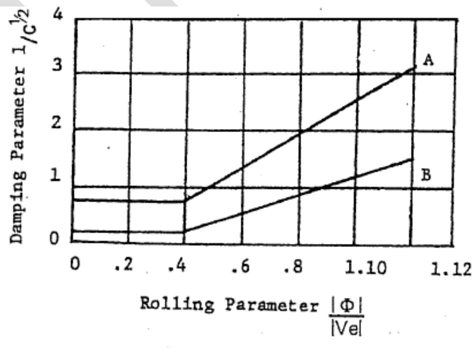
Since the roll mode is evaluated during rolling performance and lateral control power evaluations, we will only discuss methods for evaluating the spiral and Dutch roll modes.

The FARs do not contain any requirements for the spiral; however, they do contain damping requirements for the Dutch roll modes. Military specification MIL-F-8785B does contain requirements for both Dutch roll (in Sec. 3.4.1) and spiral (in Sec. 3.4.2).[8]

The requirements for Dutch roll are stated as functions of the damping parameter $1/C_{1/2}$ and the rolling parameter $|\phi|/|\beta|$; see Fig. 29.8 (Ref. 8).

The damping parameter $1/C_{1/2}$ is a function of the number of cycles for the motion to damp to half-amplitude or $C_{1/2}$. This value is a function of the Dutch roll damping.[5]

$$C_{1/2} = 0.1104 \frac{\sqrt{1-\zeta_{DR}^2}}{\zeta_{DR}} \qquad (29.4)$$



1. All Airplanes – $1/C_{1/2}$ Should be less than curve A, and Residual Motion should not be objectional.

2. Airplanes in firing or bombing configuration $1/C_{1/2}$ Should be 1.73 or curve A whichever is higher.

3. Airplanes with Yaw Dampers $1/C_{1/2}$ At least .24 with damper inoperative in all configurations. In P.A. Configuration at Least Curve B

Fig. 29.8 Military specification requirements for Dutch roll.[8]

This is approximately equal to:[5,8]

$$C_{1/2} \approx \frac{0.11}{\zeta_{DR}} \tag{29.5}$$

The damping ratio can be found from flight test data using methods described in Refs. 4 and 5. Once the damping ratio is known, we can also determine the undamped natural frequency $\omega_{n_{DR}}$ by using the damped natural frequency ω_D and the following equation:[5]

$$\omega_{n_{DR}} = \frac{\omega_{D_{DR}}}{\sqrt{1 - \zeta_{DR}^2}} \tag{29.6}$$

The rolling parameter $|\phi|/|V_e|$ is a function of the roll-to-sideslip ratio ϕ/β (Refs. 5 and 8).

$$\frac{|\phi|}{|V_e|} = \frac{57.3}{V_e}\left(\frac{|\phi|}{|\beta|}\right) \tag{29.7}$$

Both the number of cycles to damp to half-amplitude and the roll-to-sideslip ratio can be obtained from visual observation of the aircraft wing tip during the oscillation.[4] However, a more accurate method is to record the parameters of sideslip β, bank angle ϕ, and rudder deflection δ_r on an oscillograph or other tracing vs time. We may then determine such items as damping ratio, undamped natural frequency, and rolling parameter very accurately.

To excite the Dutch roll for test purposes there are several methods. The two most common methods are rudder kicks and the doublet input.

In the rudder kicks method the rudder is depressed and released rapidly, and the resultant Dutch roll oscillation observed. The problem with this method is that it also tends to excite the spiral mode causing a wing to drop.[4]

A better method is called the doublet input. In this case the rudder is moved both left and right in phase with the natural motion of the airplane and then returned to neutral or the trimmed condition before being released. This method tends to excite the Dutch roll mode well without exciting the spiral mode.[4]

The tests for the spiral mode along with the requirements are very simple. The military specification for the spiral mode is that after a small disturbance it should take at least 20 s for the bank angle to double.

To perform this test the lateral control is held fixed while the aircraft is banked 5 deg with the rudder. The rudder is then returned to trim and all controls released. Timing is started upon control release and bank angle ϕ vs time is recorded.[4]

4.3 Adverse Yaw

To understand what adverse yaw is, we need to first explain the axes of motion for an airplane. An aircraft in flight can rotate around three different axes, as illustrated below.

First, the aircraft nose can rotate up and down about the y-axis, a motion known as pitch. Pitch control is typically accomplished using an elevator on the horizontal tail.

Second, the wingtips can rotate up and down about the x-axis, a motion known as roll. Roll control is usually provided using ailerons located at each wingtip.

Finally, the nose can rotate left and right about the z-axis, a motion known as yaw. Yaw control is most often accomplished using a rudder located on the vertical tail.

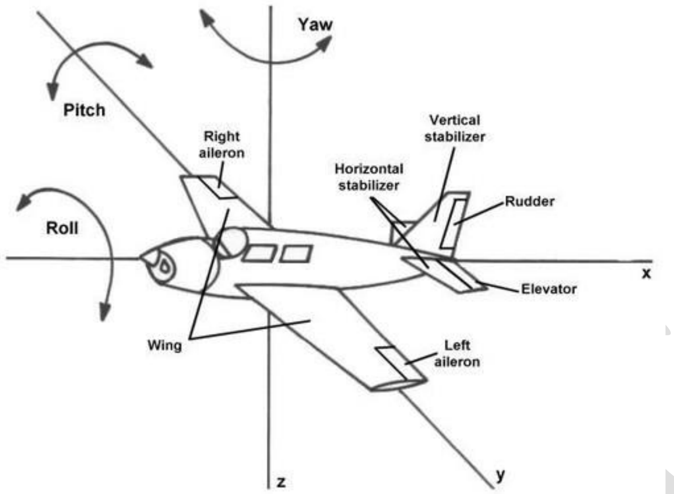


Fig: Aircraft axis system

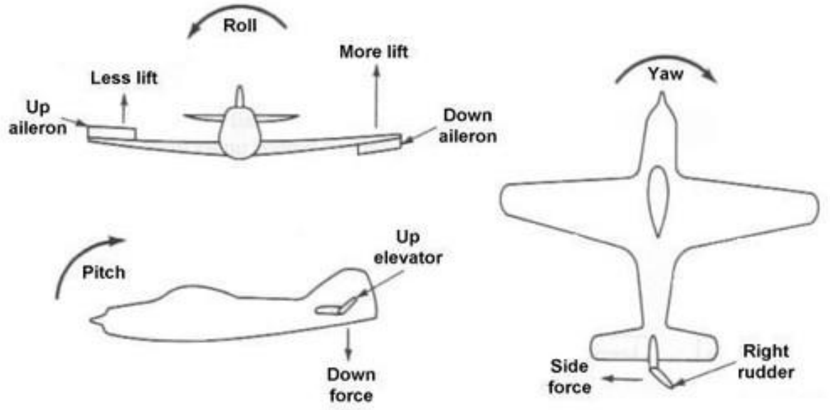


Fig: Effects caused by aileron deflection

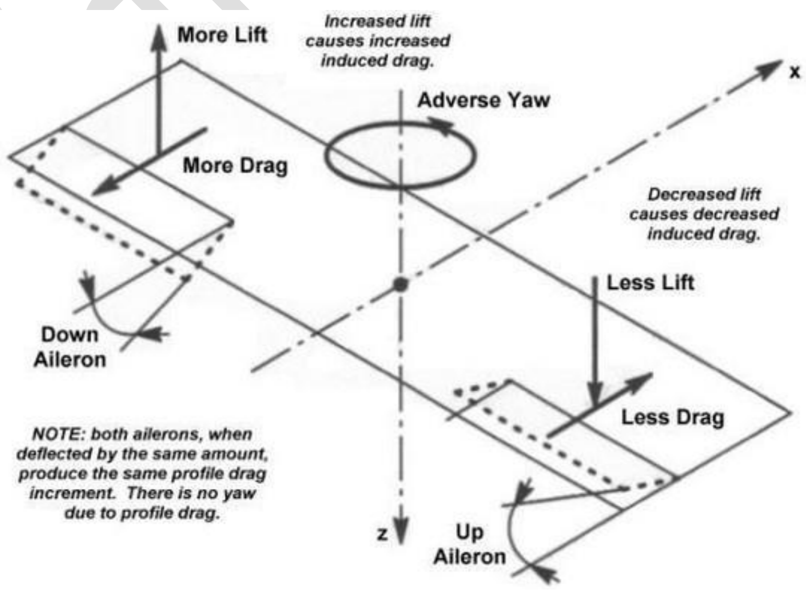


Fig: Effects caused by aileron deflection

However, the effect of one control surface is not always limited to just pitch, roll, or yaw alone. When the deflection of one control surface affects more than one of these orientations, we say that the orientations are coupled. The most important of these coupled interactions is adverse yaw. To better understand the concept, let's study a picture of what happens when the pilot deflects the ailerons to roll the aircraft.

As you can see, the aircraft rolls because one aileron is deflected downward while the other is deflected upward. Lift increases on the wing with the downward-deflected aileron because the deflection effectively increases the camber of that portion of the wing. Conversely, lift decreases on the wing with the upward-deflected aileron since the camber is decreased. The result of this difference in lift is that the wing with more lift rolls upward to create the desired rolling motion.

Unfortunately, drag is also affected by this aileron deflection. More specifically, two types of drag, called induced drag and profile drag, are increased when ailerons are deployed. Induced drag is a form of drag that is induced by any surface that generates lift. The more lift a surface produces the more induced drag it will cause (for a given wingspan and wing area). Thus, the wing on which the aileron is deflected downward to generate more lift also experiences more induced drag than the other wing. Profile drag includes all other forms of drag generated by the wing, primarily skin friction and pressure drag. This profile drag increases on both wings when the ailerons are deflected, but the increase is equal when the ailerons are deflected by the same amount. However, the induced drag on each side is not equal, and a larger total drag force exists on the wing with the down aileron. This difference in drag creates a yawing motion in the opposite direction of the roll. Since the yaw motion partially counteracts the desired roll motion, we call this effect adverse yaw.

4.4 Aileron Reversal

A number of aircraft, when flying near their maximum speed, are subject to an important aeroelastic phenomenon. No real structure is ideally rigid, and it has static and dynamic flexibility. Wings are usually produced from aerospace materials such as aluminum and composite materials and have structures which are flexible. This flexibility causes the wing to be unable to maintain its geometry and integrity, especially in high-speed flight operations. This phenomenon, which is referred to as aileron reversal, negatively influences the aileron effectiveness.

Consider the right section of a flexible wing with a downward-deflected aileron to create a negative rolling moment. At subsonic speeds, the increment in aerodynamic load due to aileron deflection has a centroid somewhere near the middle of the wing chord. At supersonic speeds, the control load acts mainly on the deflected aileron itself, and hence has its centroid even further to the rear. If this load centroid is behind the elastic axis of the wing structure, then a nose-down twist (α_{twist}) of the main wing surface (about the y-axis) results. The purpose of this deflection was to raise the right wing section. However, the wing twist reduces the wing angle of attack, and leads to a reduction of the lift on the right section of the wing (Figure 12.16). In extreme cases, the down-lift due to aeroelastic twist will exceed the commanded up-lift, so the net effect is reversed. This change in the lift direction will consequently generate a positive rolling moment.

This undesired rolling moment implies that the aileron has lost its effectiveness and the roll control derivative $C_{l_{\delta A}}$ has changed its sign. Such a phenomenon is referred to as aileron reversal. This phenomenon poses a significant constraint on the aileron design. In addition, the structural design of the wing must examine this aeroelasticity effect of the aileron deflection. The aileron reversal often occurs at high speeds. Most high-performance aircraft have an aileron reversal speed beyond which the ailerons lose their effectiveness. The F-14 fighter aircraft experiences aileron reversal at high speed.

Clearly, such aileron reversal is not acceptable within the flight envelope, and must be considered during the design process. A number of solutions for this problem are: (i) make the wing stiffer, (ii) limit the range of aileron deflections at high speed, (iii) employ two sets of ailerons – one set at the inboard wing section for high-speed flight and one set at the outboard wing section for high-speed flight, (iv) reduce the aileron chord, (v) use a spoiler for roll control, and (vi) move the ailerons toward the wing inboard section. The transport aircraft Boeing 747 has three different types of roll control device: inboard ailerons, outboard ailerons, and spoilers. The outboard ailerons are disabled except in low-speed flights when the flaps are also deflected. Spoilers are essentially flat plates of about 10–15% chord located just ahead of the flaps. When the spoilers are raised,

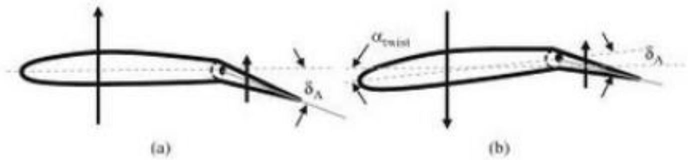


Figure 12.16 Aileron reversal. (a) An ideal and desired aileron; (b) An aileron with aileron reversal

Previous exam questions:

1. (10AE831 – June/July 2018)

a. Describe the spiral, roll and dutch roll motions of aircraft with neat diagrams. (10M)

b. Explain the flight test method for evaluating the dynamic directional stability. (10M)

2. (10AE831 – June/July 2017)

a. Explain steady heading sideslip method for determining lateral directional static stability. (10M)

b. Explain directional stability. (10M)

3. (06AE831 – June/July 2011)

a. Write the equations of motion for steady side slip. (10M)

b. Explain steady heading sideslip method for determining lateral directional static stability. (10M)

4. (06AE831 – May/June 2010)

a. Explain steady heading sideslip method for determining lateral directional static stability. (10M)

b. Explain the flight test method for evaluating the dynamic directional stability. (10M)