Chapter 3

Static Stability and Control

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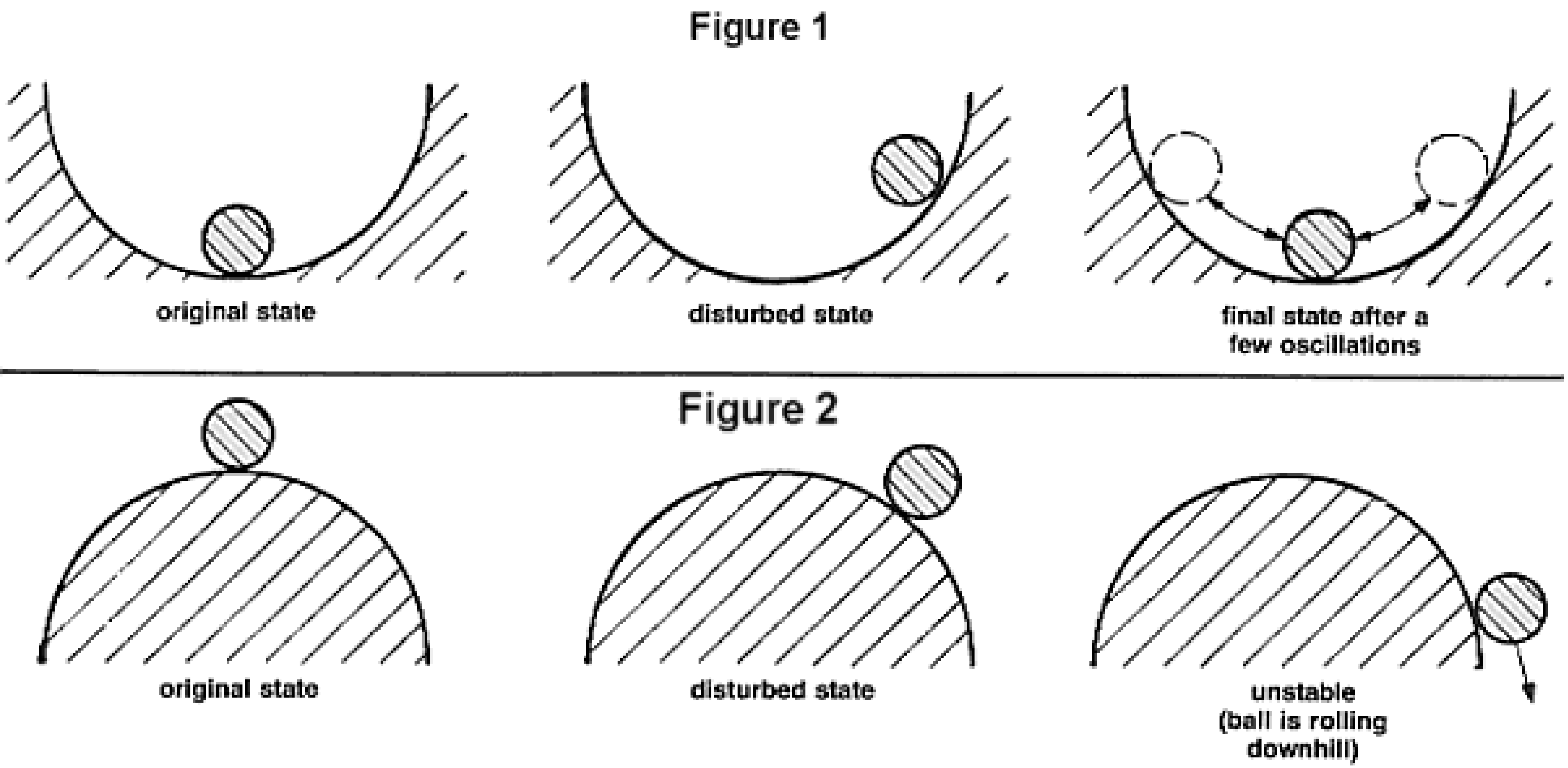
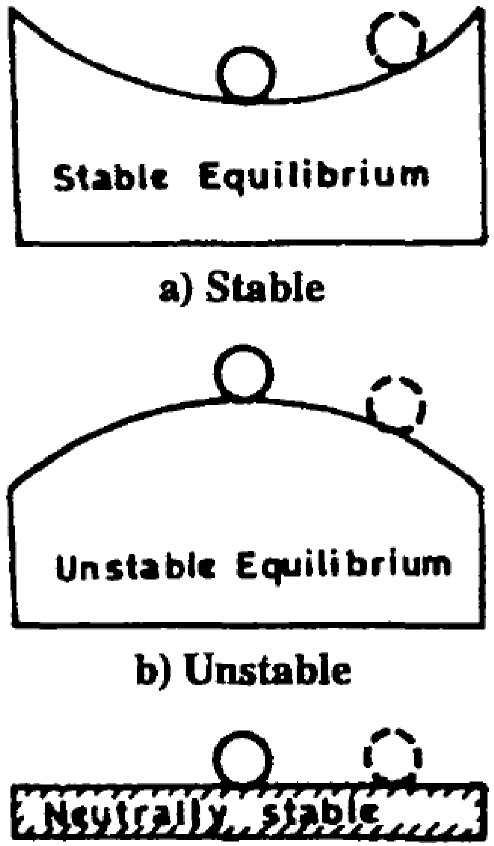
Contents

1. Concept of Equilibrium and Stability

- The airplane is a dynamic system with six degrees of freedom, three in translation and three in rotation. In general, airplane motion is characterized by three linear and three angular accelerations under the action of gravitational, inertial, and aerodynamic and propulsive forces and moments.
- However, a significant portion of the airplane's flight envelope consists of steady flight conditions such as cruise, climb, or glide. For such flight conditions, the principles of static equilibrium can be applied.
- Equilibrium states can be classified as stable, unstable, and neutrally stable.
- For steady flight in vertical plane, i.e. longitudinal stability scenario, the concept of static stability is explained in terms of the direction of the pitching moment, or location of the center of pressure with respect to the position of the center of gravity.

1. Concept of Equilibrium and Stability



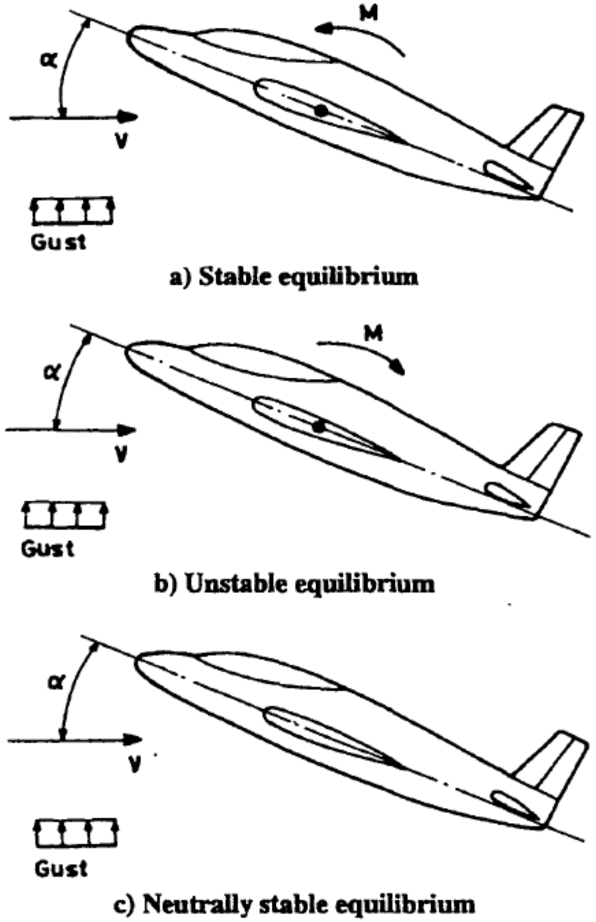


Various forms of equilibrium.

1. Concept of Equilibrium and Stability

- For a steady level flight in vertical plane, L = W and T= D. If the airplane is disturbed in angle of attack , the response could be one of the three types, namely- stable, unstable and neutrally stable.
- The disturbance could be in form of a vertical gust, air turbulence, or a rapid movement of the elevator.

- The induced **nose-down** pitching moment M is stabilizing because it tends to restore the airplane to its original angle of attack.
- The induced **nose-up** pitching moment is destabilizing because it tends to increase the angle of attack and stall the airplane.
- When the induced pitching moment is zero, the airplane will assume a new angle of attack depending on the magnitude of the disturbance.



Various forms of equilibrium in pitch.

1. Concept of Equilibrium and Stability

Stability criteria

- The criterion for longitudinal or pitch stability can be expressed mathematically as,

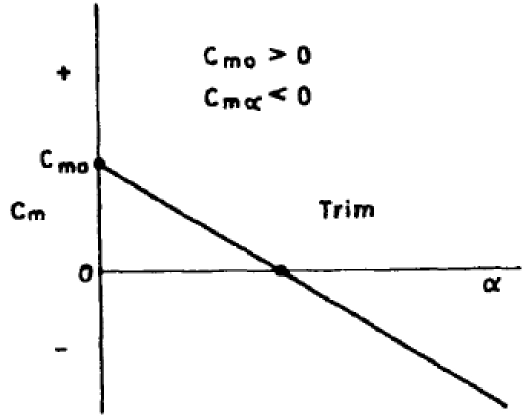
$$\frac{dM}{d\alpha} < 0 \quad \textbf{Or,} \quad \frac{dC_m}{d\alpha} < 0$$

- Where, $C_m = M/(qSc)$.

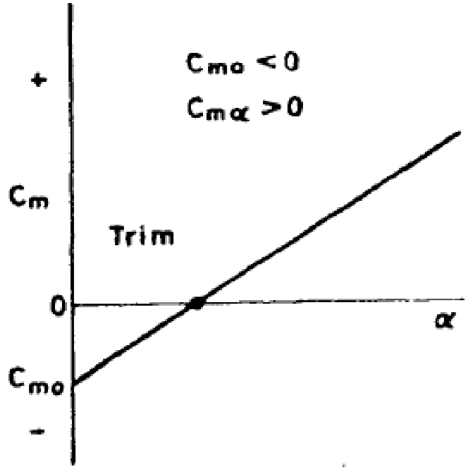
- The equilibrium condition in pitch is usually called **trim condition**. For pitch trim, the net pitching moment about the center of gravity is zero.
- **For an airplane to be flyable, it must be capable of trimming at all values of angle of attack within the permissible range of angle of attack.**

  - To establish a stable pitch trim the necessary and sufficient conditions are,

$$C_{mo} > 0 \quad \textbf{and,} \quad \frac{dC_m}{d\alpha} < 0$$



a) Stable equilibrium



b) Unstable equilibrium

1. Concept of Equilibrium and Stability

Stability criteria

- If, $C_{m\alpha} < 0$ **but,** $C_{mo} < 0$

  … the aircraft cannot be trimmed.

- On the contrary, if, $C_{m\alpha} > 0$ **but,** $C_{mo} < 0$

  … the airplane is flyable, but it is statically unstable.

- However, with proper feedback control, such an airplane can be made closed-loop stable.
- For, $C_{m\alpha} = 0$ **and,** $C_{mo} = 0$

  … the airplane is neutrally stable.

- The following assumptions can be made for the study of an open-loop stability of an airplane:
  - The airplane has a vertical plane of symmetry, i.e., it has a symmetric geometry and mass distribution with respect to this plane.
  - Deflection of longitudinal controls like elevators do not generate side force, rolling, or yawing moments. Similarly, deflection of the lateral-directional controls like ailerons or rudders do not produce lift or pitching moments.
  - Aerodynamic forces and moments vary linearly with aerodynamic/control variables.
  - Total forces and moments acting on the airplane are equal to the sum of forces/moments on individual components.
- With these assumptions, longitudinal and lateral-directional motions of the aircraft can be decoupled and studied separately.

Stability criteria

- With the previous four assumptions, **longitudinal and lateral-directional motions of the aircraft can be decoupled and studied separately**.
- The stability analysis requires evaluation/estimation of the contributions of fuselage, wing, and tail surfaces to static longitudinal and lateral-directional stabilities.

- The net aerodynamic force or moment coefficient is equal to the sum of the individual contributions from fuselage, wing and tail surfaces.

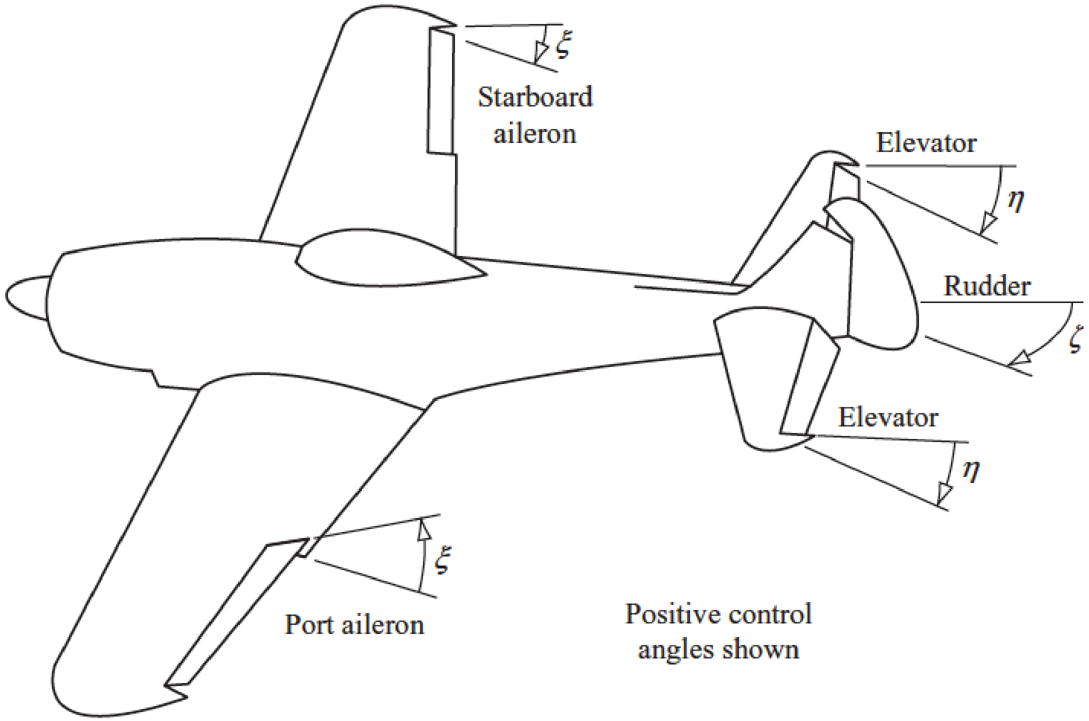
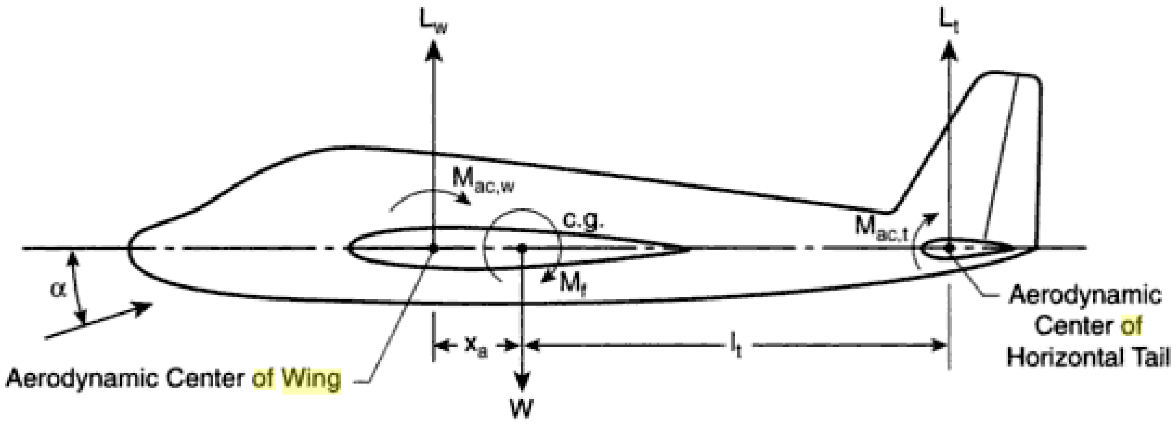


Figure 2.11 *Aerodynamic controls notation.*

2. Static Longitudinal Stability

➢ The net aerodynamic force or moment coefficient is equal to the sum of the individual contributions from fuselage, wing and tail surfaces.



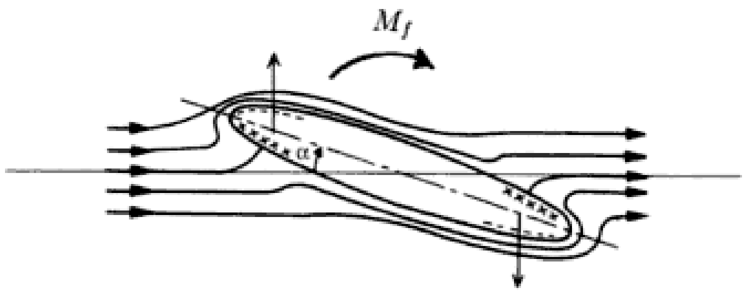
$$M_{cg} = \underbrace{M_f}_{\text{Fuselage Contribution}} + \underbrace{M_{ac,w} + L_w x_a}_{\text{Wing Contribution}} + \underbrace{M_{ac,t} - L_t l_t}_{\text{Tail Contribution}}$$

Forces and moments acting on an airplane (wing, fuselage and horizontal tail surfaces) in steady unaccelerated flight.

Fuselage contribution

➢ The pressure distribution over a streamlined body at an angle of attack yields a zero net force accompanied by a pure couple that is of destabilizing nature, i.e., both lift and drag are equal to zero, but the pitching moment is nonzero.

➢ Mathematically, this is equivalent to zero lift (normal force) acting at an infinite distance from the body so that the product (pitching moment) is finite.



Ideal fluid flow over an airplane fuselage.

➢Generally, **the fuselage contribution to static longitudinal stability is quite significant and is of a destabilizing nature**.

Wing contribution

- **Aerodynamic center**
  - For linear range of AOA, the wing pitching-moment coefficient can be expressed as: $$C_m = C_{mo} + \xi C_l$$
  - The parameter ξ is an empirical constant that depends on the location of the **moment reference point**.
  - For a cambered airfoil at zero-lift AOA, a pure couple is acting on the airfoil, C_{mo}, which is independent of the moment reference point.
  - The sign of ξ depends of the location of the moment reference point- **if it's close to the leading edge the incremental lift caused by the angle of attack acts aft of the moment reference point, and the associated pitching moment will be negative**.

- Thus, for negative pitching moment, $\xi < 0$.
- On the other hand, if the moment reference point is located close to the trailing edge, then the incremental lift acts ahead of the moment reference point, and the corresponding incremental pitching moment is positive; hence $\xi > 0$.
- Therefore, there must be some point on the chordline where $\xi = 0$ so that the incremental pitching moment caused by the AOA and pitching-moment coefficients remains constant with respect to the AOA and equal to C_{mo}.
- This point is called the aerodynamic center. In other words, all the incremental lift caused by angle of attack acts at the aerodynamic center, i.e., $C_{mac} = C_{mo}$.
- For symmetrical airfoils, $C_{mac} = C_{mo} = 0$.

2. Static Longitudinal Stability

Wing contribution

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- The concept of aerodynamic center is helpful in the study of airplane stability and control because it is sufficient to specify the pitching-moment coefficient at any one angle of attack.
- At low speeds, the aerodynamic center can be assumed to lie at the quarter chord point. At high-speeds it moves aft, like CP does.
- The exact location of the aerodynamic center can be determined if given the lift, drag, and pitching-moment coefficients about any reference point along the chord line. $C_m = C_{mac} - \bar{x}_{ac} C_l$

- If the slope is positive, then $\mathbf{x_{ac}}$ is negative, implying that the aerodynamic center is located ahead of the moment reference point.

$$\bar{x}_{ac} = -\frac{dC_m}{dC_l}$$

2. Static Longitudinal Stability

Wing contribution

- For a linear range of angle of attack, the relation between the locations of center of pressure and aerodynamic center can be obtained as follows:

$$\overline{x}_{cp} = \overline{x}_{ac} - \frac{C_{mo}}{C_l}$$

- Thus, the location of the aerodynamic center relative to the center of pressure depends on the sign of $\mathbf{C_{mo}}$. For positively cambered airfoils, $\mathbf{C_{mo}}$ < 0 so that the center of pressure is aft of the aerodynamic center.
- However, as the AOA increases, the center of pressure moves towards the aerodynamic center.

- The nature of wing contribution depends on the relative distance between the wing aerodynamic center and the center of gravity.
- If the aerodynamic center is ahead of the center of gravity, which is generally the case for low-speed general aviation planes, the wing contribution is destabilizing.
- For modern high-speed airplanes with swept-back wings, the wing aerodynamic center is usually aft of the center of gravity, and wing contribution is stabilizing.
- The wing contribution can be expressed as

$$C_{m,w} = C_{mac,w} + \overline{x}_a C_{L,w} \qquad C_{L,w} = a_w \alpha_w$$

- Here, x_a is considered positive if the center of gravity is aft of the aerodynamic center and vice versa.

2. Static Longitudinal Stability

Wing contribution

- For conventional airplanes with wing ahead of the horizontal stabilizers, the wing angle of attack is approximately equal to the airplanes angle of attack, i.e. $\boldsymbol{\alpha_w = \alpha}$.
- For canard airplane, the angle of attack of the wing may be smaller than the airplane angle of attack because of the airplane downwash.
- The fuselage interference effects on the wing are generally small for configurations with large wing-span-to-body-diameter ratios typified by conventional long range subsonic airplanes. For such configurations, **lift-curve slope of the wing in the presence of the fuselage can be assumed to be equal to that of an isolated wing**.

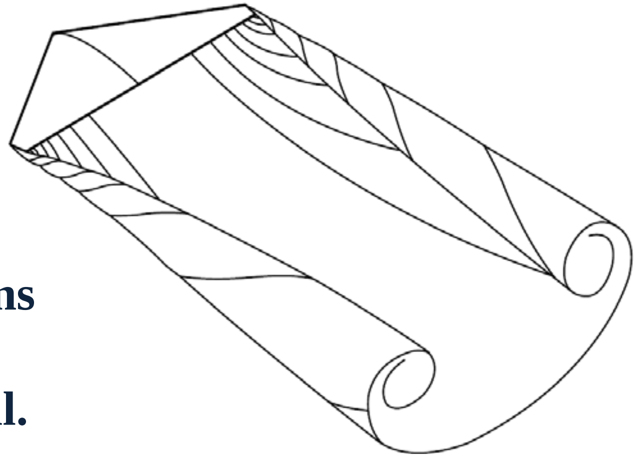
Wing-Fuselage contribution

- For configurations with relatively large values of wing-span-to-body-diameter ratios, the mutual interference effects between the wing and the body are small and can be ignored.
- **For such cases, the contributions of the wing and fuselage can be individually determined and added together to give the wing-body contribution**.
- However, for configurations with small wing-span-to-body-diameter ratio, the mutual interference effects between wing and fuselage are quite significant. Therefore, for such configurations, it is preferable to evaluate the combined wing-body configurations it s preferable to evaluate the combined wing-body contribution using analytical methods.

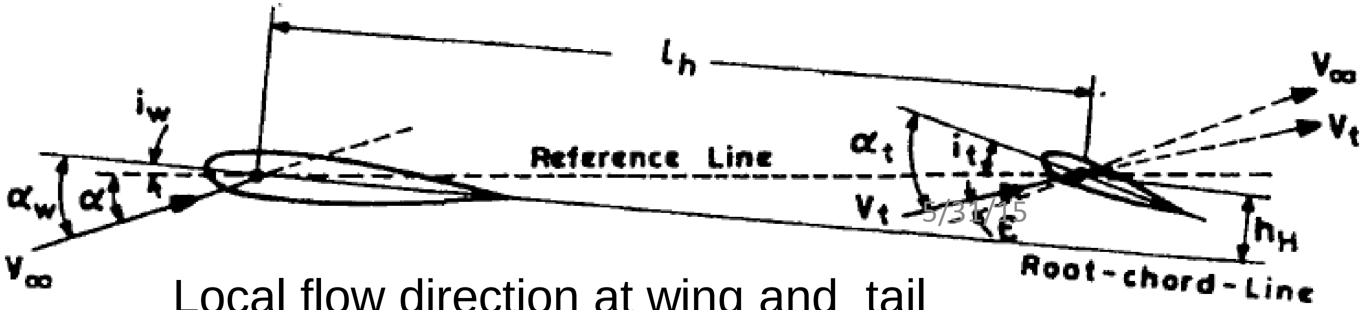
2. Static Longitudinal Stability

Tail contribution

➢ The local angle of attack of the horizontal tail is affected by the wing downwash.



Flow directions at wing and horizontal tail.



Local flow direction at wing and tail

➢ Let i_w and i_t be the incidences of wing and horizontal tail surfaces with respect to the zero-lift line (reference line) of the aircraft. The tail angle of attack is given by:

$$\alpha_t = \alpha_w - i_w + i_t - \varepsilon$$

➢ **ε** is the downwash angle at the horizontal tail aerodynamic center.

➢ The downwash is induced mainly because of wing-trailing vortices, and the magnitude of downwash depends on wing planform, aspect ratio, and the distance between the aerodynamic centers of wing and horizontal tail.

➢The downwash caused by the fuselage is generally small in comparison with that caused by the wing and can be ignored.

Effect of Power

- The effect of the propulsive power unit on longitudinal stability and trim can be both significant and difficult to evaluate. These effects also depend on the mode of propulsion such as turbo props or piston props, turbo fans, or turbo jets.
- Owing to these complexities, it is difficult to make a comprehensive evaluation of the power effects on longitudinal stability and trim. However, a qualitative analysis of the major effects can be made.
- For propeller aircraft, the effect consists of two parts:
  - direct effect caused by forces developed by propulsion unit.
  - indirect effect caused by propeller slipstream passing over wing or tail surfaces.
- The direct effect depends on the vertical location of the thrust line with respect to the center of gravity.

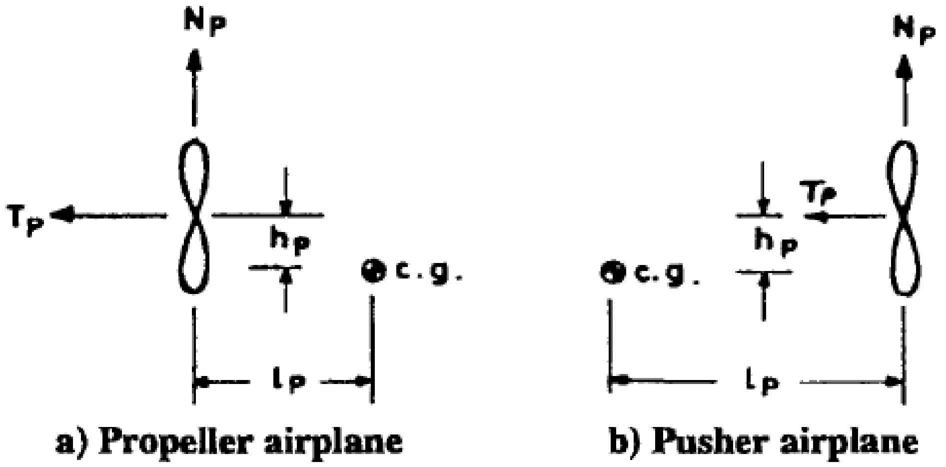


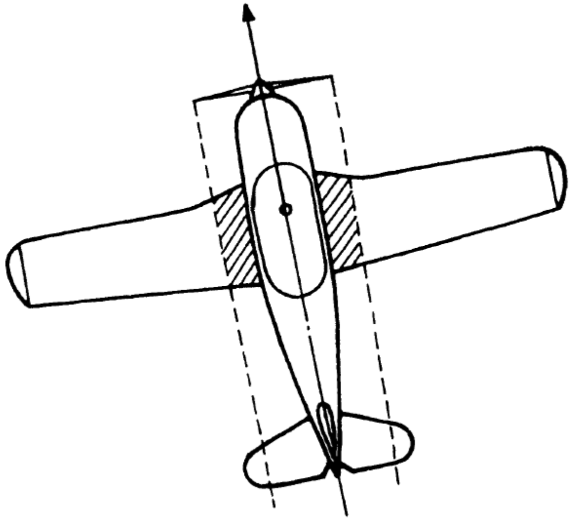
Fig. 3.26 Schematic illustration of power effects.

- A high thrust line is stabilizing, whereas a low thrust line is destabilizing.
- The direct effect also includes a normal force N_p acting on the propulsion unit, which for a propeller airplane is destabilizing and for a pusher airplane is stabilizing.

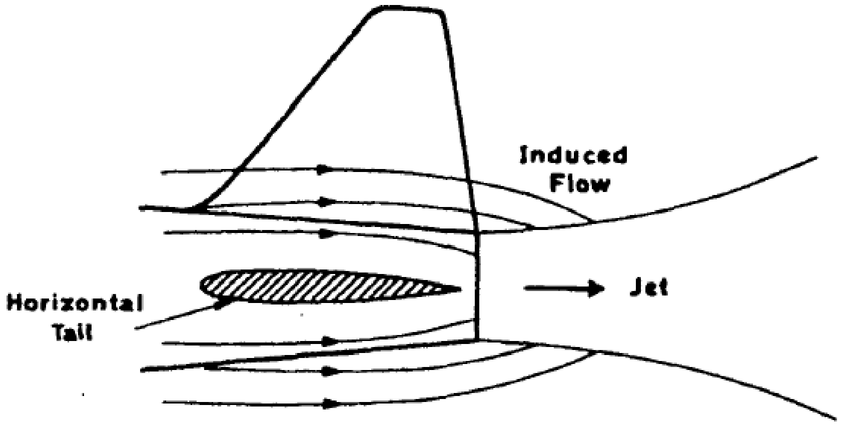
2. Static Longitudinal Stability

Effect of Power

- Indirect effects arise because of the influence of propeller slipstream passing over wing and tail surfaces.
- The wing sections exposed to the propeller slipstream experience a higher dynamic pressure and hence develop higher local lift and drag forces. The effect of this change in local lift and drag forces on pitching moment is usually small and can be ignored.



Schematic illustration of propeller slipstream effects.

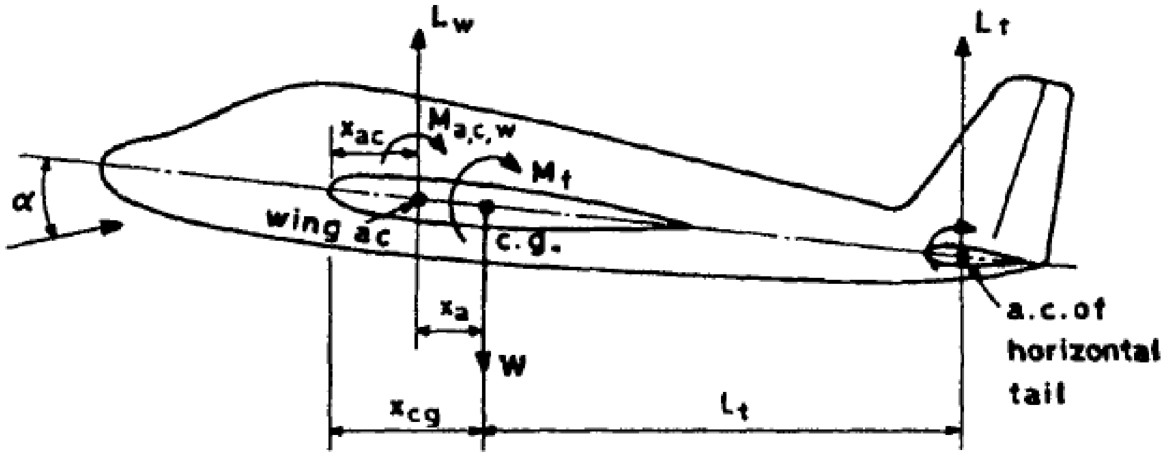


Jet-induced flow field at horizontal tail.

- For a jet aircraft, the direct effects caused by thrust and intake normal force are similar to those of propeller aircraft. The indirect effects due to the jet-induced flow field may affect the horizontal tail.

Total longitudinal stability

- For a general-aviation airplane (referred to as ‘conventional airplane’), the wing aerodynamic center is ahead of the center of gravity.



Aerodynamic forces and moments acting on an airplane in steady level flight.

- Assuming the thrust vector passes through the center of gravity,

$$C_{mcg} = C_{mw} + C_{mf} + C_{mt} \quad = \quad C_{L,w}\bar{x}_a + C_{mac,w} + C_{mf} - C_{L,t}\eta_t \bar{V}_1$$

- The subscript ‘cg’ can be dropped under the premise that the moment is defined about the center of gravity. Assuming $C_L = C_{L,w}$,

$$\frac{dC_m}{dC_L} = \bar{x}_{cg} - \bar{x}_{ac} + \left(\frac{dC_m}{dC_L}\right)_f - \frac{\alpha_t}{\alpha_w}\left(1 - \frac{d\varepsilon}{d\alpha}\right)\eta_t \bar{V}_1$$

2. Static Longitudinal Stability

Total longitudinal stability

- The level of longitudinal static stability depends on the location of the center of gravity- it increases as the center of gravity moves forward and vice versa.
- Let N_o be the location of the CG when the above differential is zero, or when the airplane becomes neutrally stable. N_o is then called the **stick-free neutral point**.

$$N_o = \overline{x}_{ac} - \left(\frac{dC_m}{dC_L}\right)_f + \frac{\alpha_t}{\alpha_w}\left(1 - \frac{d\varepsilon}{d\alpha}\right)\eta_t \overline{V}_1$$

$$\frac{dC_m}{dC_L} = \overline{x}_{cg} - N_o$$

- The concept of neutral point has a close similarity with that of the aerodynamic center.
- At neutral point, $\mathbf{dC_m/dC_L = 0}$, which implies that the incremental lift (of the complete airplane) due to a change in angle of attack acts through the neutral point.
- Thus, **the neutral point is, in essence, the aerodynamic center of the whole aircraft.**

- **Static margin** is defined as,

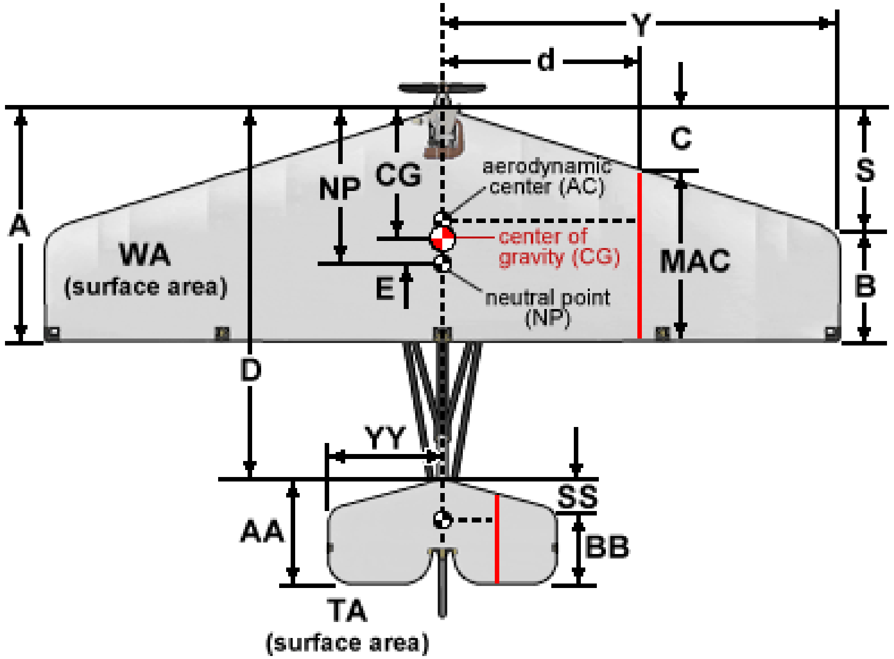
$$H_n = N_o - \overline{x}_{cg} = -\left(\frac{dC_m}{dC_L}\right)_{fix}$$

- It defines the level of **stick-fixed** longitudinal static stability of the airplane. **For a stable airplane, static margin is positive**.

2. Static Longitudinal Stability

Permissible center of gravity travel

- For an airplane to be statically stable in pitch, the center of gravity must lie ahead of the stick-free neutral point.
- From a stability point of view, it is desirable that the center of gravity be located as much forward of the neutral point N_o and possible.
- On the other hand, from the longitudinal control point of view, it is preferable that the center of gravity be located as much aft of $x_{cg,f}$ as possible.
- Therefore, to satisfy both these requirements, the center of gravity must always lie within these two limits.



$$\Delta \bar{x} = N_o - \bar{x}_{cg,f}$$

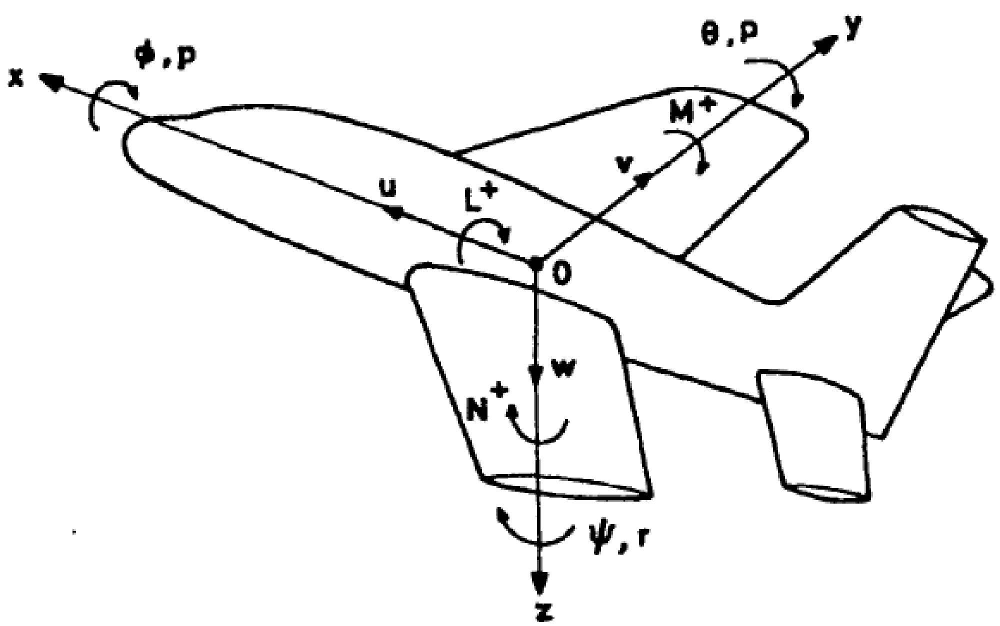
3. Stability in Maneuvering Flights

- The class of flight paths when the load factor exceeds unity is called **maneuvers**.
- During the pull-up maneuver, the aircraft experiences a steady rate of rotation in vertical plane, which is equivalent to a pitch rate about the 'y' body axis.
- On account of this pitch rate, the aircraft will experience higher levels of static stability compared to that in steady level flight and this apparent increase in stability demands additional elevator deflection.
- Because of this increased stability level during the maneuver, the magnitude of the elevator deflection required for trim also increases.
- 'Stick-free' maneuver stability is higher than the stick-free stability in level flight and the stick-free maneuver point is aft of the stick-free neutral point.

4. Static Directional Stability

- Directional stability considers the airplane stability with respect to a disturbance in sideslip, which is contained in the horizontal plane.
- It is assumed that the response of the airplane is sufficiently slow so that the yaw rate and roll rate can be ignored.
- The following nomenclature are used:
  - **u** - forward velocity, **w** - vertical velocity, **θ** - pitch angle, **q** - pitch rate.
  - for directional motion, **v** - sideslip velocity, **ψ** – yaw angle, **r** – yaw rate, and for lateral motion, **ϕ** – bank angle and **p** – roll rate.
- The lateral and directional degrees of freedom are always coupled because a sideslip induces both rolling and yawing motions. Similarly, a yawing motion indices both rolling motion and sideslip.
- For purpose of simplicity, the aircraft behavior in sideslip can be studies first and the lateral stability problem is added later.

4. Static Directional Stability



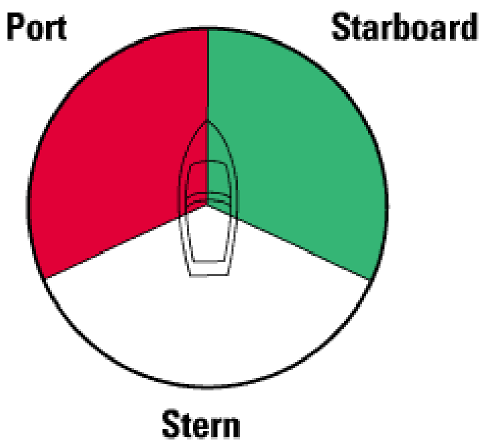
Axis system and nomenclature used in static stability analysis.

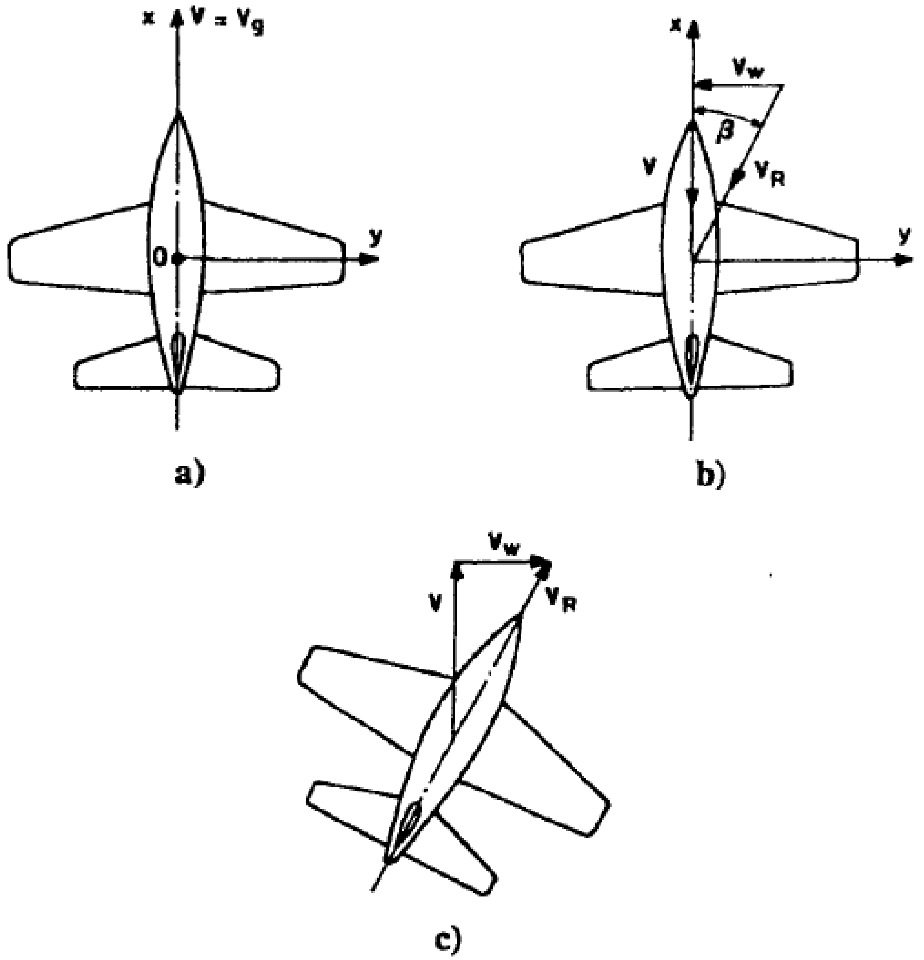
$$\phi = bank\ angle$$
$$\text{p} = \text{roll rate}$$
$$\theta = pitch\ angle$$
$$q = pitching\ rate$$
$$M^+ = pitching\ moment$$
$$\psi = yaw\ angle$$
$$r = yaw\ rate$$
$$N^+ = yawing\ moment$$
$$L^+ = rolling\ moment$$
$$\text{v} = \text{slideslip velocity}$$

- Static directional stability is a measure of the aircraft's ability to realign itself along the direction of the resultant wind so that the disturbance in sideslip is effectively eliminated.
- A disturbance in sideslip could be by horizontal gust, wind turbulence, or momentary (small) rudder deflection. Therefore, on encountering a disturbance in the horizontal plane, the aircraft orientation in space changes **but its heading remains the same as before with respect to earth**.

4. Static Directional Stability

- An aircraft in a steady (undisturbed) level flight subjected to a horizontal gust $\mathbf{V_w}$ blowing from the ***starboard*** side faces a resulting sideslip and realigns itself with the resultant velocity $\mathbf{V_R}$.
- Now, the sideslip is zero but the aircraft orientation in space has changed. The aircraft is still moving with the same velocity V with respect to earth as before. If the disturbances vanishes, the aircraft orientation with also be restored.





Aircraft orientation in horizontal plane.

4. Static Directional Stability

- The angle of sideslip is an aerodynamic angle defined as the angle between the velocity vector and the airplane's plane of symmetry, i.e.,

$$\sin \beta = \frac{v}{V}$$

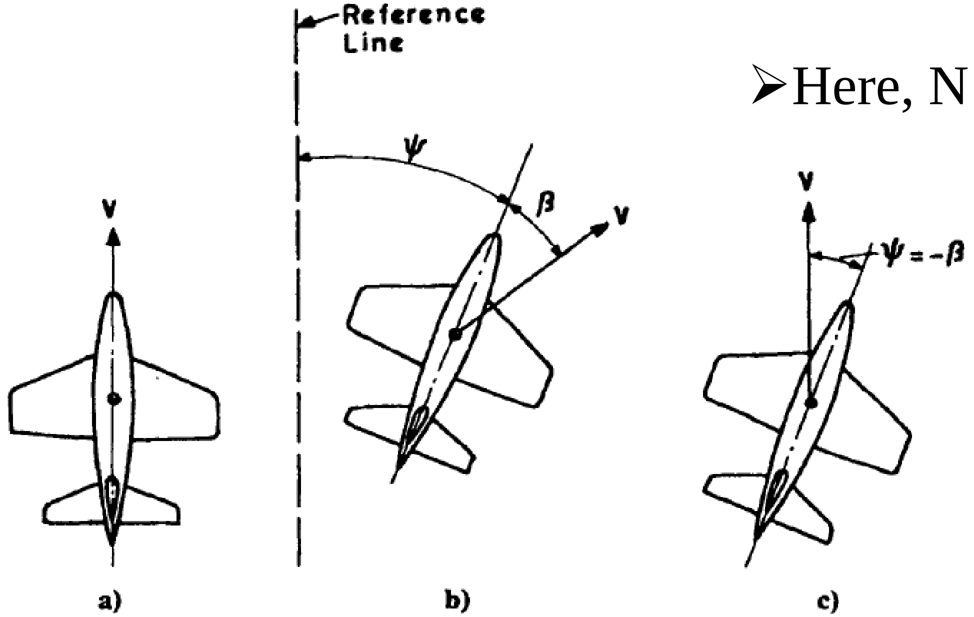
- The sideslip angle is considered positive if the airplane sideslip to starboard (right wing leading to sideslip) and negative if the airplane sideslips towards port side (left wing leading into sideslip).
- The angle of yaw, usually denoted by $\boldsymbol{\psi}$, is a kinematic angle and is a measure of the change in the heading or orientation of the aircraft relative to the earth.
- It is the angle between the airplane's plane of symmetry and a reference plane fixed in space. Usually, this reference plane is assumed to coincide with the airplane's plane of symmetry when the airplane is in steady level flight before it encounters the disturbance.
- However, in the special case when the equation of motion remains unchanged but the airplane is yawed, the sideslip and yaw are related by the relation $\boldsymbol{\psi = -\beta}$.
- Because the angle of yaw is a kinematic angle, the aerodynamic forces and moments do not depend on $\boldsymbol{\psi}$ except for this special case, which is usually encountered in wind-tunnel testing. On account of this, wind-tunnel test data are sometimes presented as a function of $\boldsymbol{\psi}$.

4. Static Directional Stability

Criterion of directional stability

➢ An airplane is said to be directionally stable if it has an inherent capability to realign itself into the resultant wind whenever disturbed from steady level flight.

➢ The criterion can be expressed mathematically as: $N_\beta > 0$ ‖ $C_{n\beta} > 0$

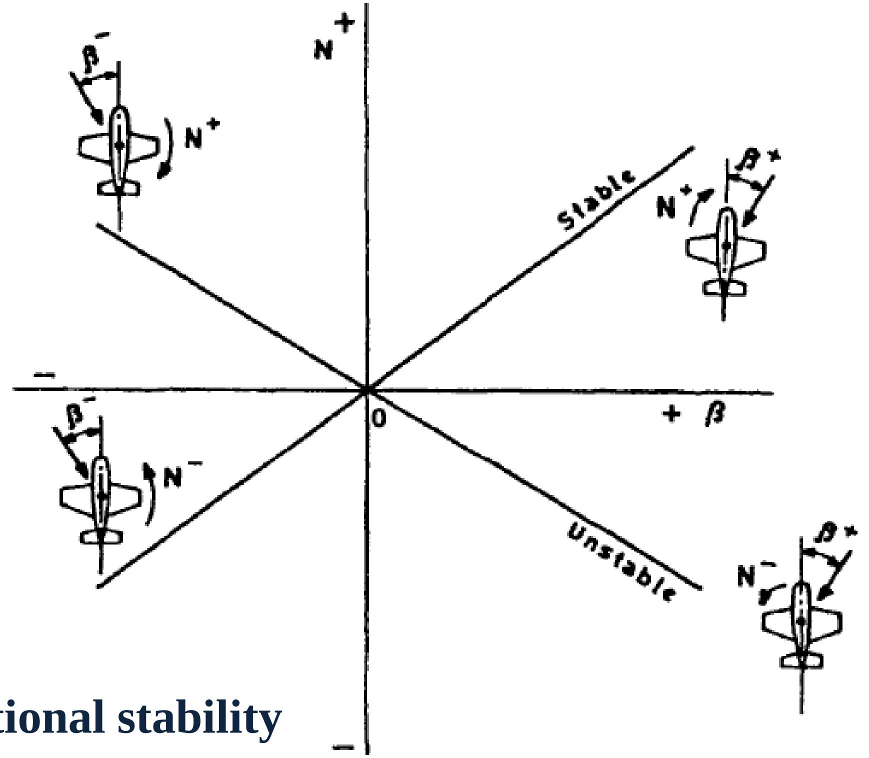


Definitions of angles of yaw and sideslip

➢Here, N is the yawing moment and,

$$C_n = \frac{N}{qSb}$$

$$C_{n\beta} = \frac{\partial C_n}{\partial \beta}$$



Concept of static directional stability

4. Static Directional Stability

Evaluation of static directional stability

➢ As assumed for longitudinal stability, the directional moment coefficient $C_{n\beta}$ of the airplane is the sum of individual contributions caused by fuselage, wing, and tail surfaces.

➢ **Wing contribution**: the wing contribution to directional stability mainly depends on its dihedral and leading-edge sweep. Generally, the magnitude of wing contribution to static directional stability is small. If the **wing has no dihedral and not much sweep, its contribution to directional stability can be ignored**.

- ➢ For a positive sideslip, the local dynamic pressure on both wings is approximately equal to the free stream dynamic pressure. The leading (starboard) wing experiences an increase in angle of attack and, therefore, an increase in lift and drag coefficients.

4. Static Directional Stability

Evaluation of static directional stability

- …
  - The port wing experiences opposite effects.
  - As a result of this imbalance in spanwise lift distribution, the wing develops a rolling moment.
  - However, the imbalance in drag forces gives rise to a yawing moment.
  - Thus, **the wing sweep can has a stabilizing effect on static directional stability**.

- **Fuselage contribution**: the fuselage contribution to static directional stability is generally destabilizing and is influenced by wing geometry and wing placement with respect to the fuselage.
- **Tail contribution**: the contribution of the horizontal tail, similar to that of the wing depends on dihedral and sweep.

4. Static Directional Stability

Evaluation of static directional stability

- …
  - The horizontal tail is usually much smaller in size than the wing. The contribution of the horizontal tail to static directional stability can be safely ignored.
  - The vertical tail is perhaps the single largest contributor to static directional stability. Its contribution depends on its moment arm from the center of gravity, surface area, aspect ratio, sweep and aft fuselage geometry.
  - The aft fuselage and the horizontal tail provide the beneficial endplate effect, which increases its effect aspect ratio, hence the lift-curve slope.
  - The contribution of the vertical tail is also affected by the fuselage sidewash.

4. Static Directional Stability

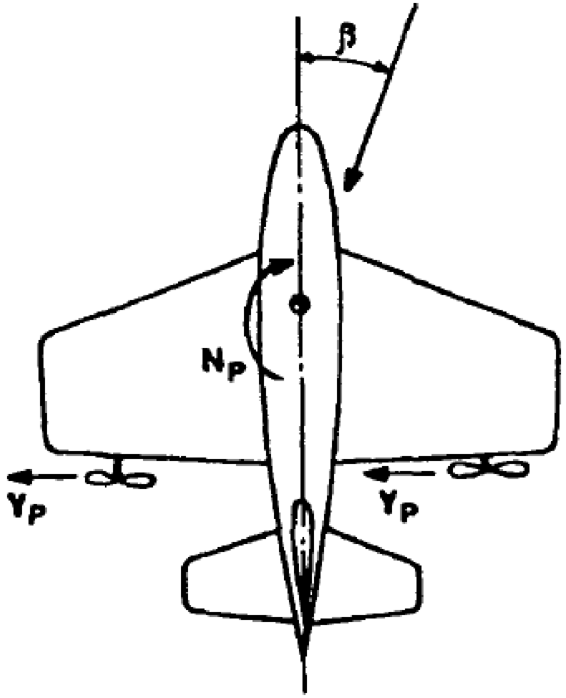
Effect of power

- For a propeller-driven aircraft, the effect of power on static directional stability consists of two parts:
    - the direct effect due to forces developed by or acting on the propulsion unit.
    - indirect effect caused by propeller slipstream passing over the wing or tail surface.
- The direct effect includes thrust developed by the propulsion unit and the side force (drag) acting on the propulsion unit because of sideslip.
- Because the resultant thrust vector is usually contained in the plane of symmetry, the contribution of the thrust to directional stability can be ignored. However, in case of an engine failure the direct thrust effect is significant.

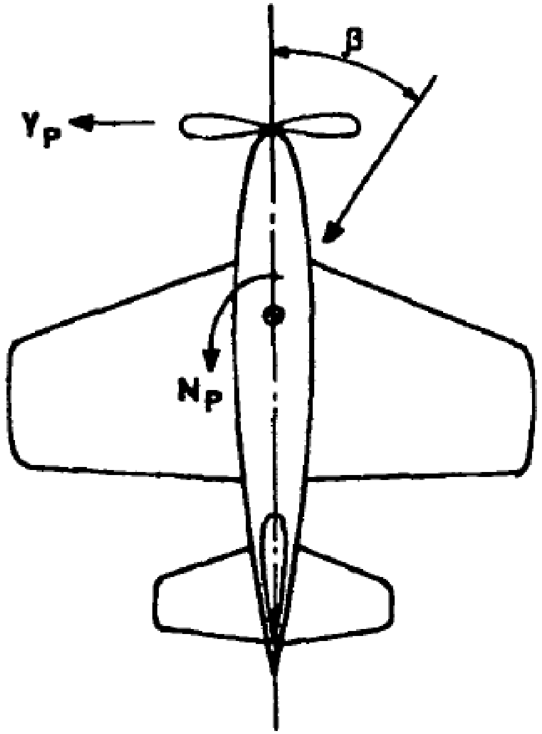
4. Static Directional Stability

Effect of power

➢ The effect of sideslip includes a side force created by the propeller, which depends on the location of the propulsion unit. The effect is destabilizing for a propeller airplane and stabilizing for a pusher airplane.



Power effects: pusher airplane



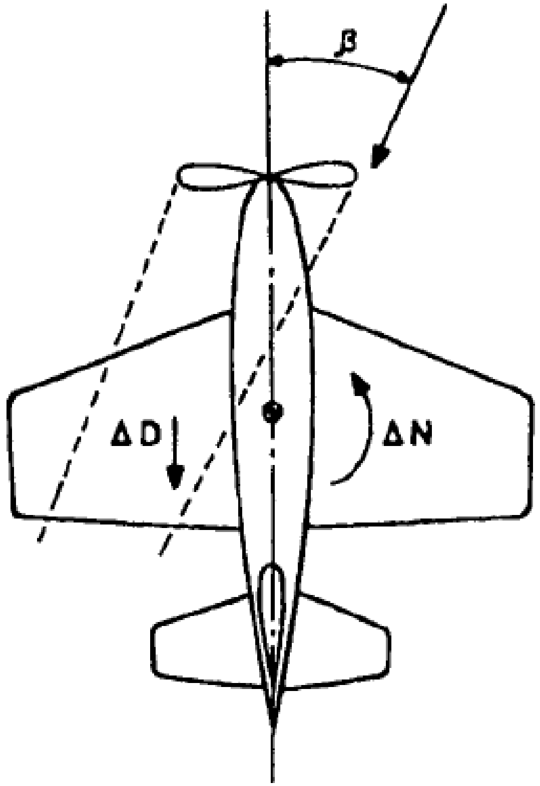
Power effects: propeller airplane

4. Static Directional Stability

Effect of power

- The indirect effects arise mainly because of the slipstream effect on the wing. The section of the wing coming under the influence of propeller slip stream experiences higher local lift and drag forces. **The asymmetry in drag produces a yawing destabilizing moment**.

- For a jet aircraft, the direct effects due to side forces on the intake are similar to that of the propeller airplane. The indirect effects caused by the jet-induced flow field affect the vertical tails in a manner similar to that for horizontal tails.



Propeller slipstream effects.

Propeller slipstream effects.

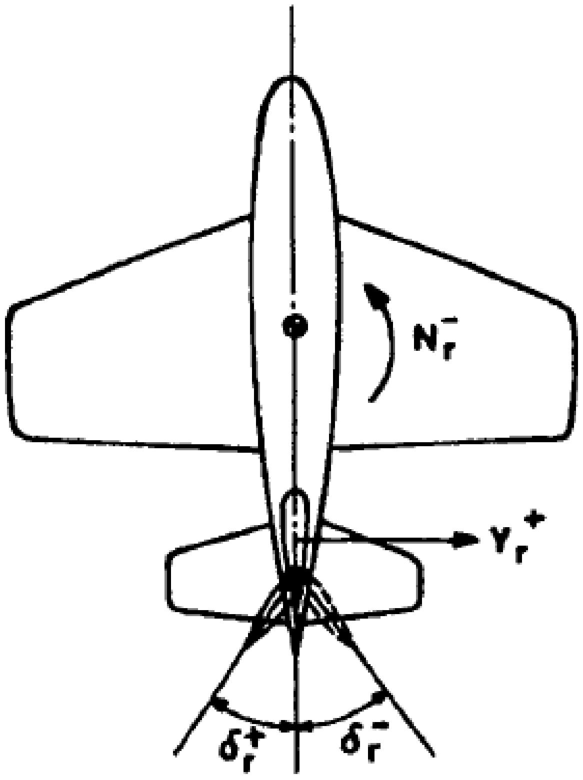
4. Static Directional Stability

Rudder-fixed directional stability

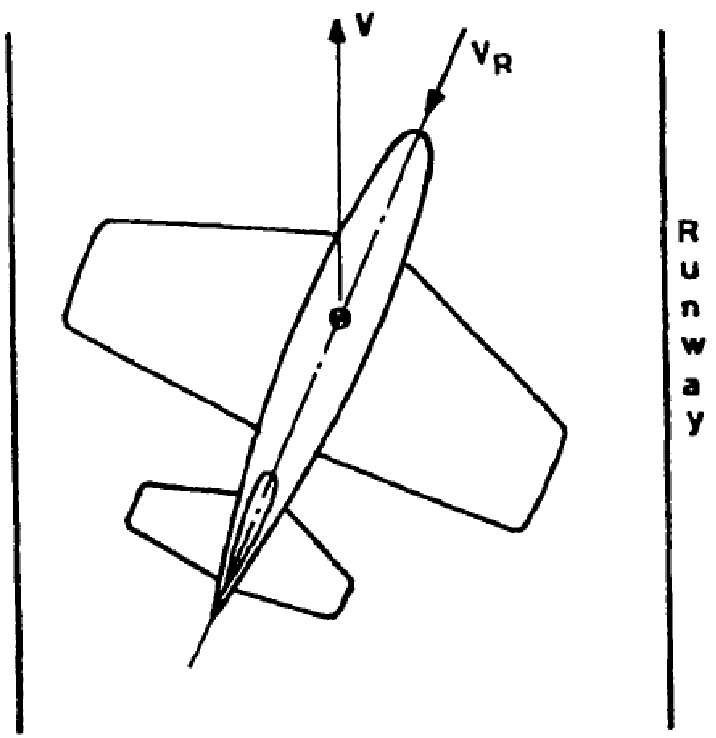
- ***Rudder requirement***: an airplane having an adequate level of static directional stability and symmetric power generally tends to maintain zero sideslip condition and, as such, the deflection of the rudder may not be usually warranted. However, under some critical conditions, it is possible that the static directional stability alone may not be sufficient to maintain zero sideslip, and the operation of the rudder becomes absolutely essential.
- ***Crosswind takeoff and landing***: An airplane with positive directional stability will tend to realign itself with the directional of the resultant wind so that the sideslip is eliminated. Takeoff with this kind of aircraft orientation during the run can pose safety problems. To prevent this, the rudder should be capable of generating a yawing moment to counter due to directional stability so that the aircraft sideslips but is properly oriented with respect to the runway.

4. Static Directional Stability

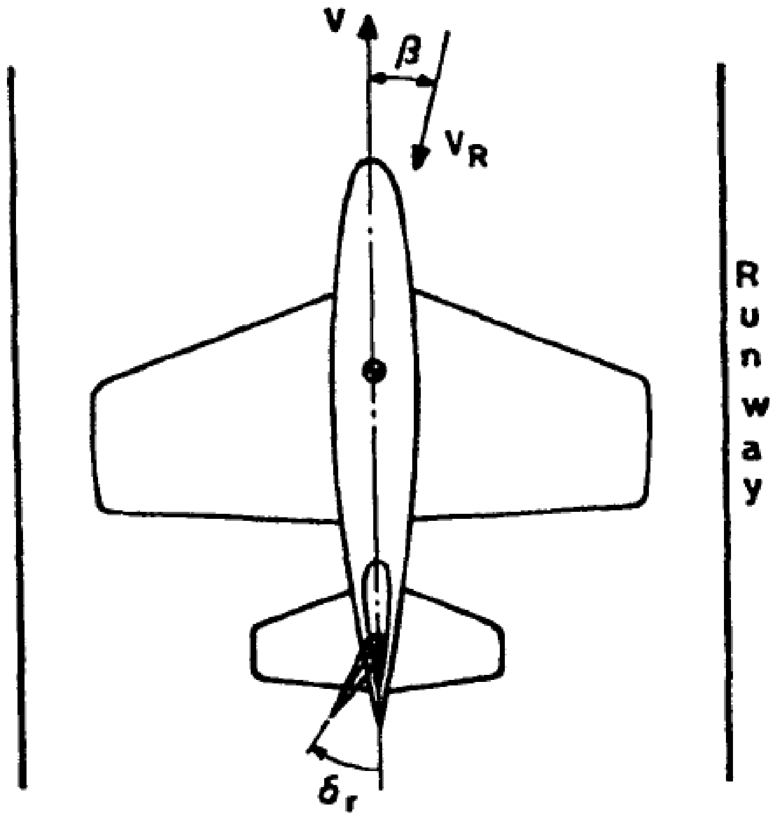
Rudder-fixed directional stability



Sign Convention of rudder deflection



Zero rudder deflection



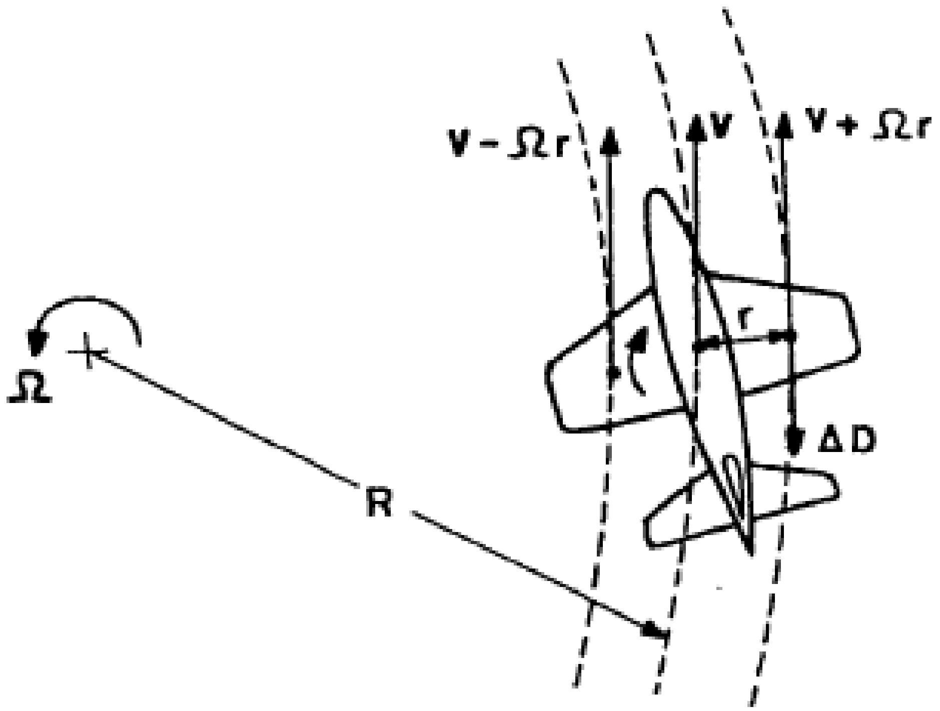
With rudder deflection

Crosswind landing/takeoff

4. Static Directional Stability

Rudder-fixed directional stability

- ***Adverse yaw***: for an airplane turning in a horizontal plane, the outer wing is moving with a higher velocity compared to inner wing.
- As a result, the outer wing experiences a relatively higher drag, and this imbalance in drag induces a yawing moment that tends to turn the nose of the aircraft away from the center of the turn.
- The phenomena is known as adverse yaw.
- Because of this adverse yaw a rolling motion may also be induced that tends to bank the aircraft away from the direction in which the aircraft is turning.
- The rudder should have sufficient control power to prevent the development of adverse yaw during a turn.



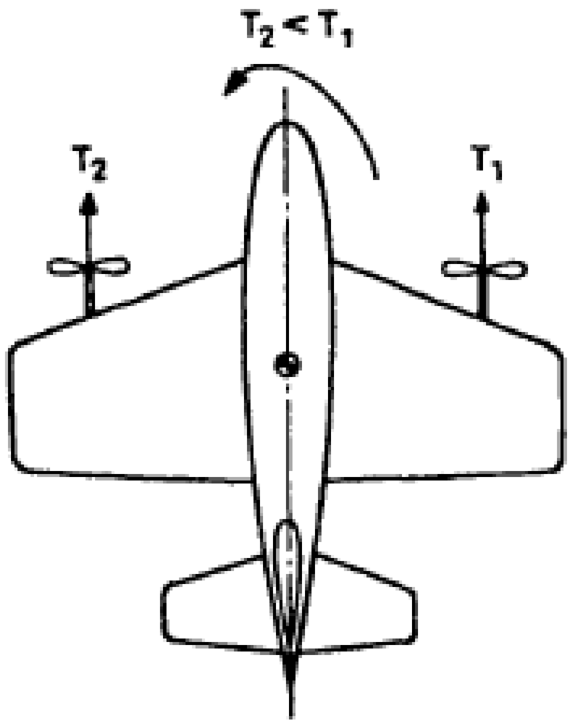
Adverse yaw during coordinated turn.

4. Static Directional Stability

Rudder-fixed directional stability

- ***Asymmetric power***: on multiengine aircraft, either partial or total failure of one or more engines gives rise to an asymmetric power situation that can generate a significant yawing moment. The rudder must be designed to

- ***Spin recovery***: generally, in spin, the airplane is operating at high angles of attack with wings horizontal tail surfaces more or less completely stalled. Quite often, the rudder may be the only control that has some effectiveness under these conditions. It must be capable of producing sufficient yawing moment to slow the spin rate and initiate a successful recovery.

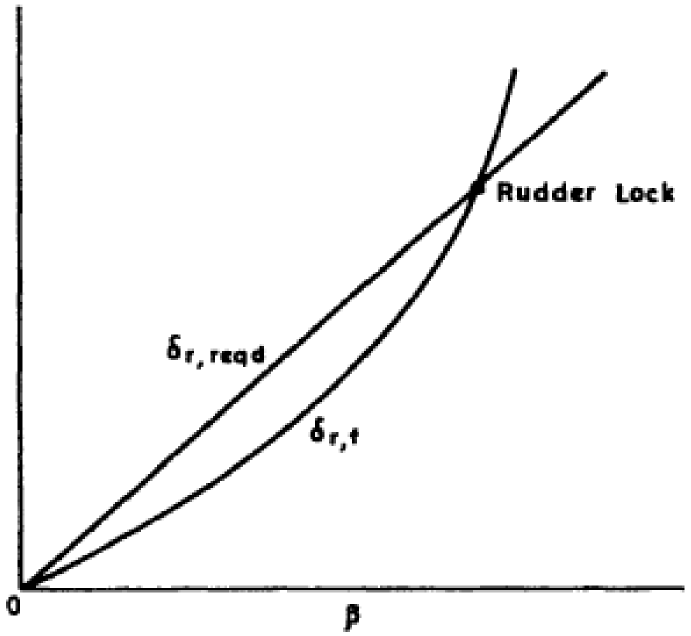


Asymmetric power effect.

4. Static Directional Stability

Rudder lock

- The floating angle of a rudder increases with sideslip.
- At high sideslip, the floating angle of the stick-free rudder increases beyond the linear rate because the center of pressure moves aft because of flow separation and stall.
- This accentuates the floating tendency of the rudder. At one point, the floating angle may catch up with the required rudder deflection. This condition is usually known as **rudder lock**.
- Beyond this point, the floating angle may overshoot and opposite pedal forces are required to operate the rudder.
- Such a situation is undesirable because it may take considerable effort for the pilot to break the rudder lock.



Concept of rudder lock.

4. Static Directional Stability

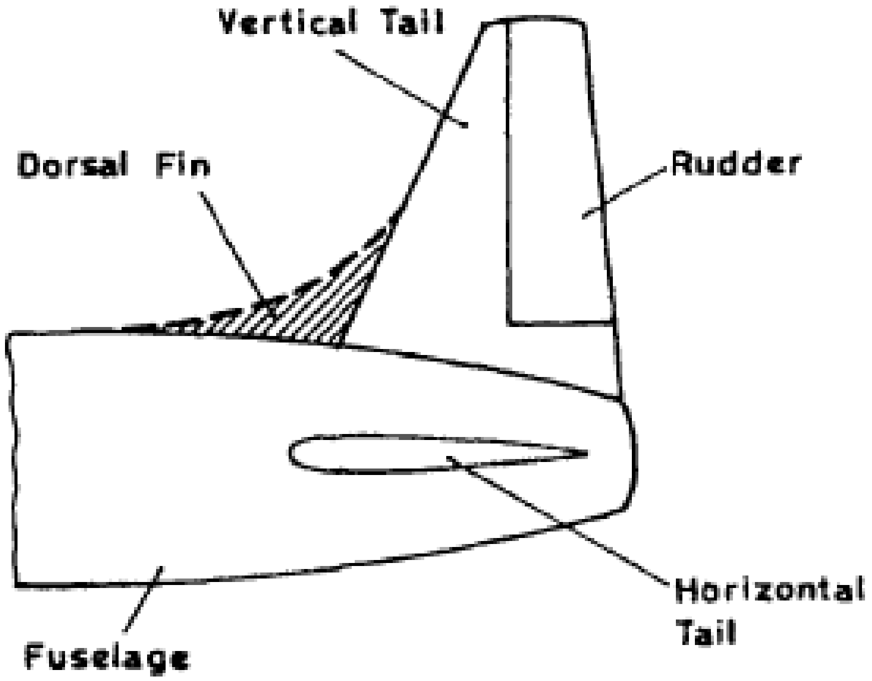
Rudder lock

- A method of preventing rudder lock is the use of a device called a ***dorsal fin***.

- The stall angle of a given lifting surface increases as the aspect ratio is reduced. Extending the chord of inboard sections adds area without extending the span so that the aspect ratio decreases.

- Addition of a suitably sized dorsal fin helps to delay the vertical tail stall to higher sideslip and minimizes the possibility of rudder lock.

- Also, the dorsal fin makes the pedal forces vary monotonically with side slip.

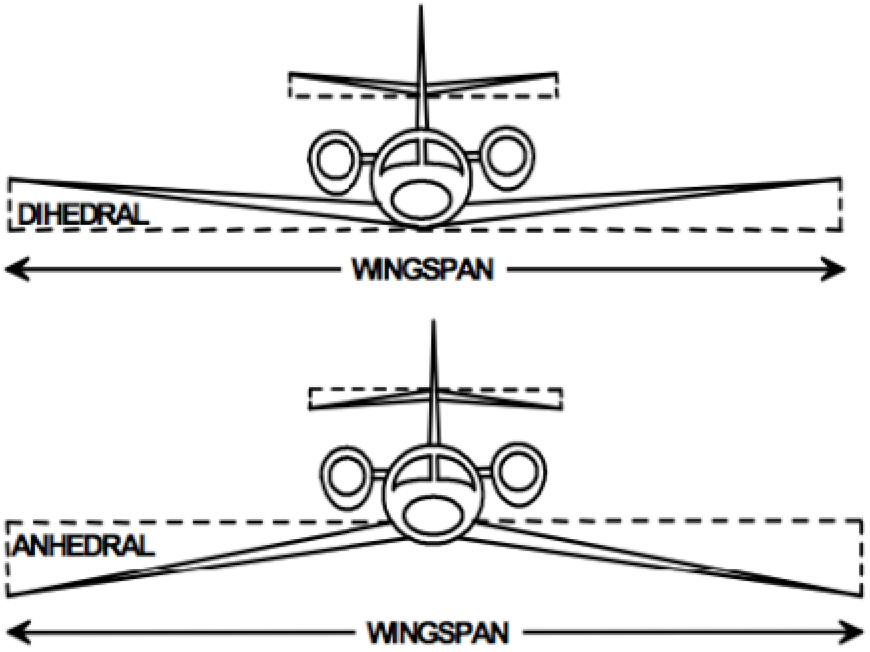


Dorsal fin

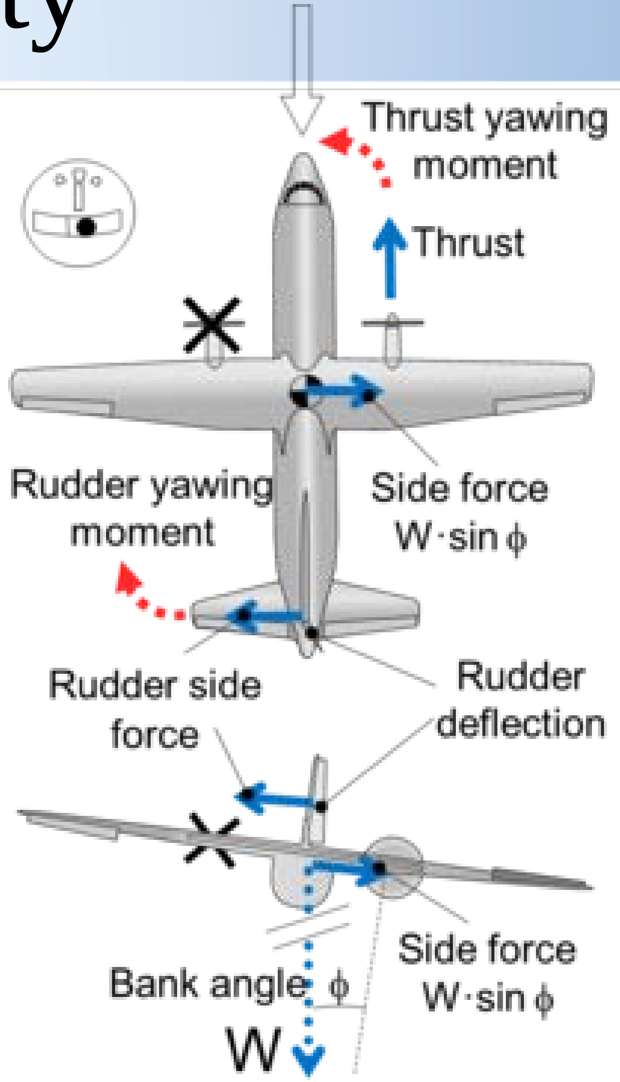
5. Lateral Stability

- Lateral stability is the inherent capability of the airplane to counter a disturbance in bank.
- In level flight, both wings are in a horizontal plane and the bank angle is zero. However, because of some disturbance, if the airplane banks but very slowly so that the roll rate is negligibly small, then there is no aerodynamic mechanism to generate a restoring a rolling moment unless sideslip develops.
- Therefore, **the airplane is neutrally stable with respect to a disturbance in bank without sideslip**.
- Fortunately, once banked, the airplane develops a sideslip in the direction of the bank because of a spanwise component of the weight.
- As a result of the sideslip, if a restoring rolling moment is induced, then the airplane is said to be laterally stable. Once the wings are back in level condition, the disturbances in bank angle and sideslip are eliminated, and the airplane returns to it’s original, steady level flight.

5. Lateral Stability



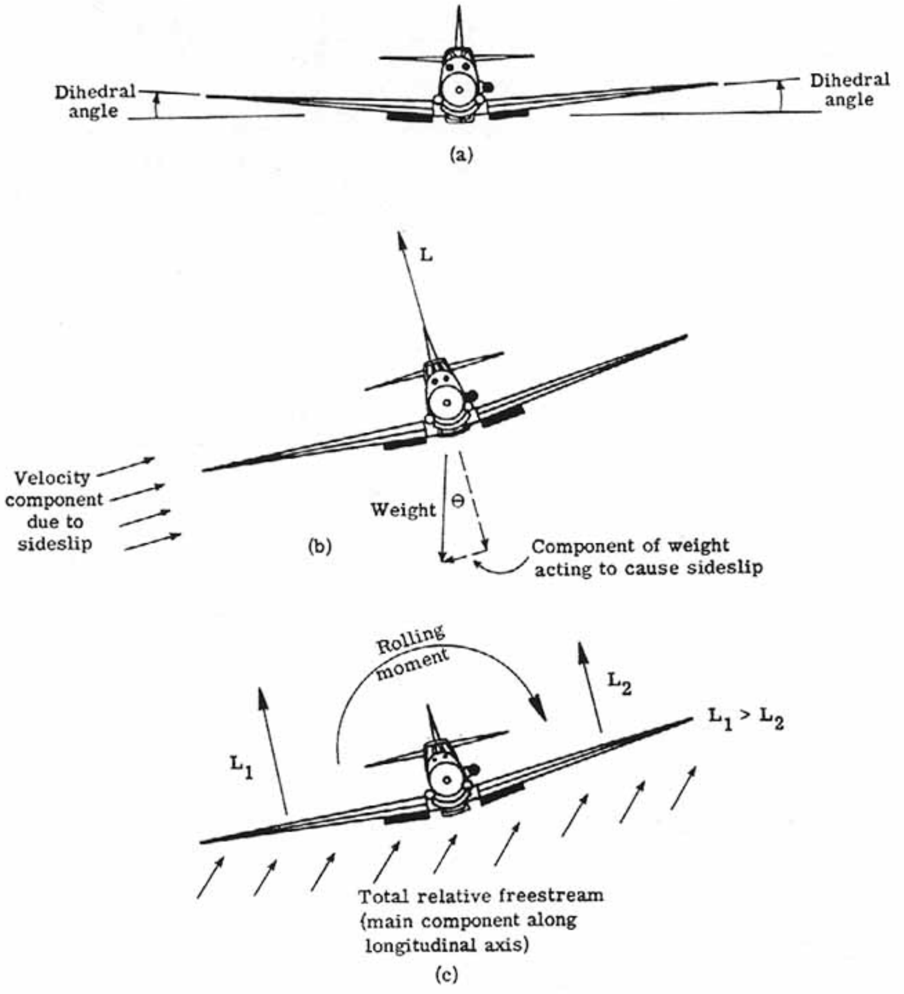
Definition of wing dihedral.



Sideslip due to bank angle and other lateral-directional effects.

5. Lateral Stability

- However, if the induced rolling moment causes the bank angle to increase further, generating more and more sideslip, the aircraft is said to be **laterally unstable**.
- If the induced rolling moment is zero and the airplane remains constantly banked and keeps on sideslipping, then it is said to be **neutrally stable**.
- The generation of a rolling moment due to sideslip is also called **dihedral effect**, and an airplane that develops a restoring moment because of sideslip is said to have a positive or stable dihedral effect.
- Therefore, a laterally stable airplane has a positive dihedral effect and vice versa.
- The dihedral effect (not the same as dihedral angle) is the rolling moment developed by the airplane because of sideslip and depends on many factors, including dihedral angle.



Dihedral effect, and the effect of dihedral angle.

5. Lateral Stability

Criterion of lateral stability

- For a laterally stable airplane, a positive (starboard) sideslip induces a restoring rolling moment, which according to the usual sign convention, is negative. While, if a stable airplane sideslip to port, the restoring rolling moment is positive.
- The criterion can be expressed mathematically as:

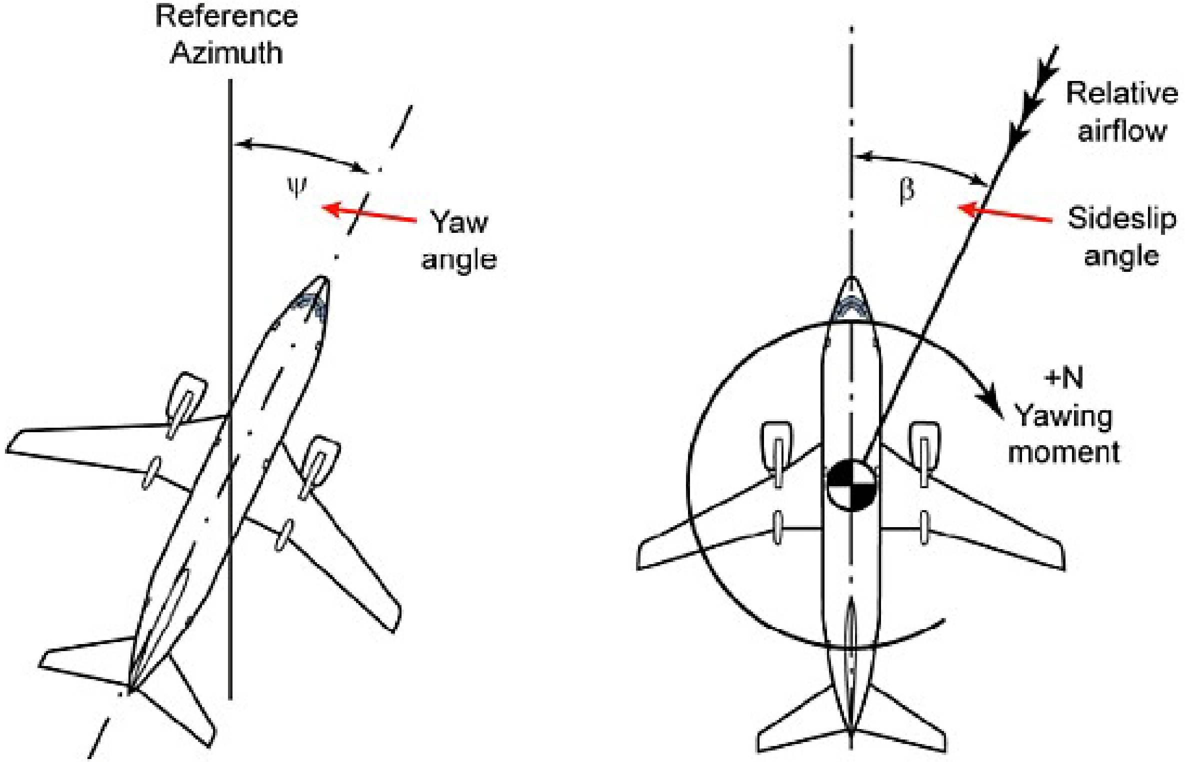
$$L_\beta < 0 \qquad \Bigg\| \qquad C_{l\beta} < 0$$

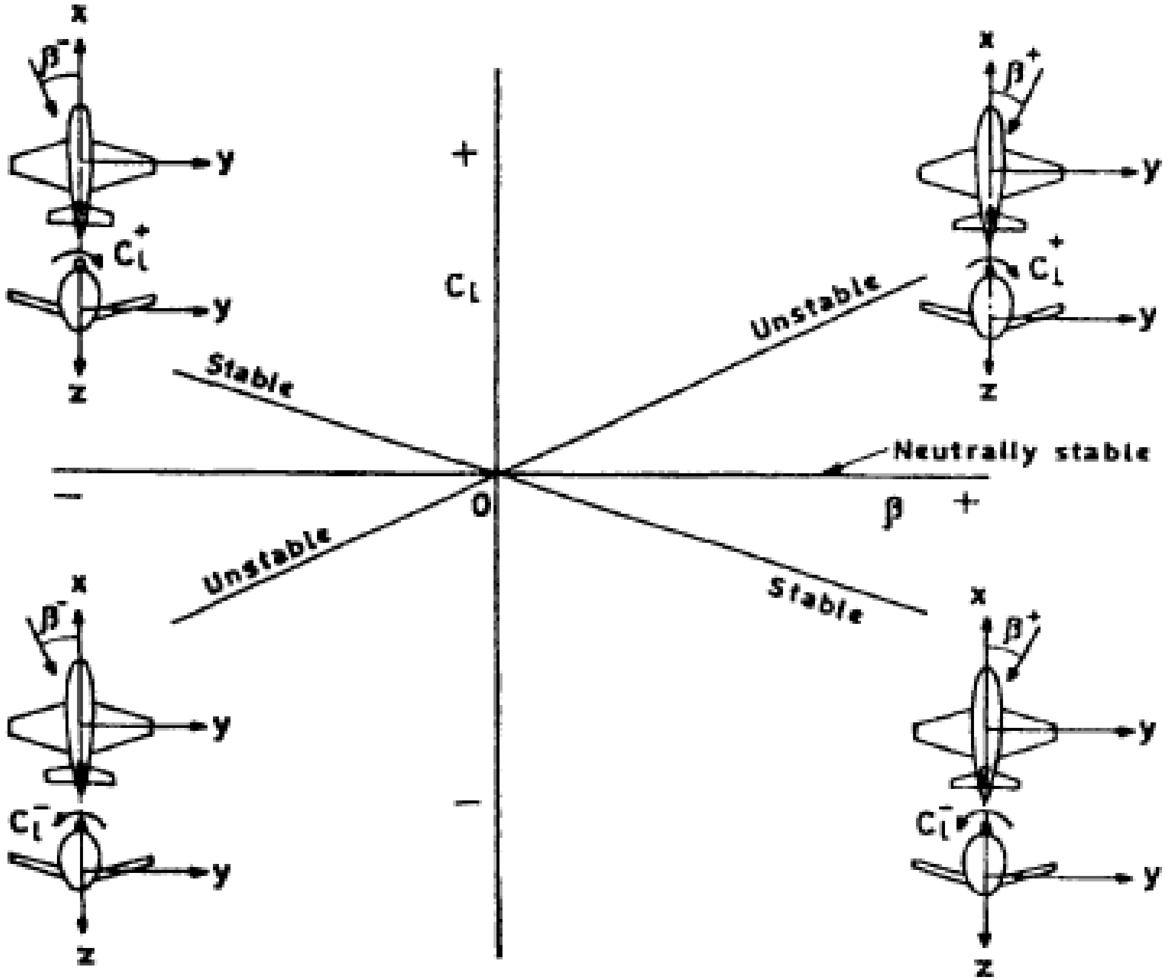
- Where, L is the rolling moment, and

$$L_\beta = \frac{\partial L}{\partial \beta} \qquad \Bigg\| \qquad C_{l\beta} = \frac{\partial C_l}{\partial \beta} \qquad \Bigg\| \qquad C_L = \frac{L}{qSb}$$

- An airplane that is neutrally stable in roll can still be flown needs constant intervention from pilot to counter roll-disturbances.

5. Lateral Stability



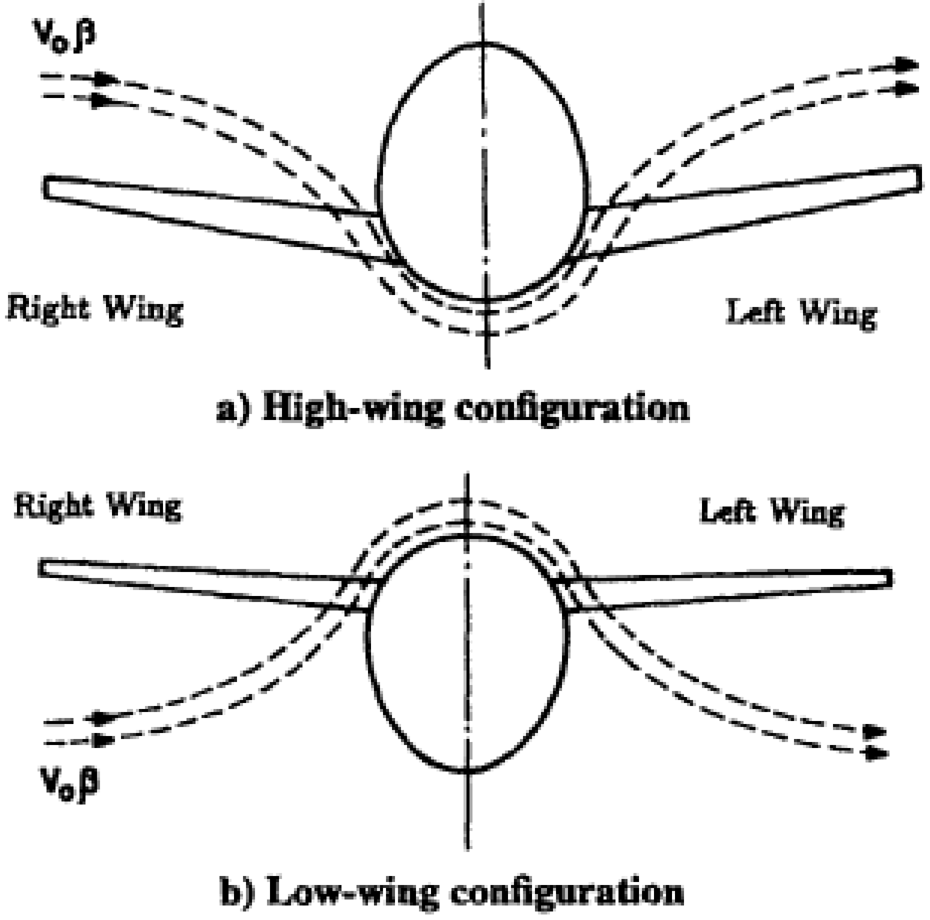


Concept of static lateral stability.

Evaluation of lateral stability

- **Fuselage contribution**: the direction contribution of fuselage to lateral stability is negligible.

- **Wing contribution**: the wing contribution to lateral stability mainly depends on
  1) wing-fuselage interference,
  2) wing dihedral angle, and
  3) wing leading-edge sweep.

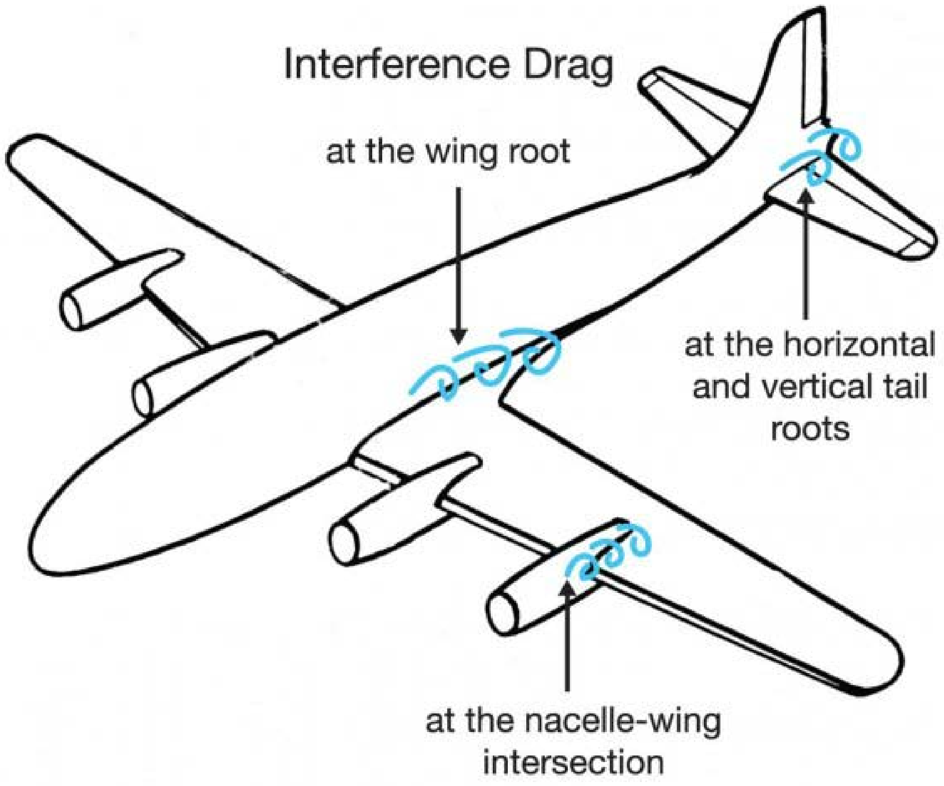


Schematic illustration of wing-fuselage interference in sideslip.

5. Lateral Stability

➢**Wing-fuselage interference**: the interference effect depends on the location of the wing. A high wing produces a stable contribution, while a low-wing produces an unstable or destabilizing contribution.
➢In positive sideslip for a high wing airplane, the inboard sections of the right wing experiences a local upwash and an increase in AOA, whereas the inboard sections of the port wing experiences a downwash and a decrease in AOA.
➢As a result, the lift on the right wing is higher compared to that on the left wing.
➢The imbalance gives rise to a stable or restoring moment for high-wing configuration

➢Similarly for a low wing configuration, the induced rolling moment is destabilizing.

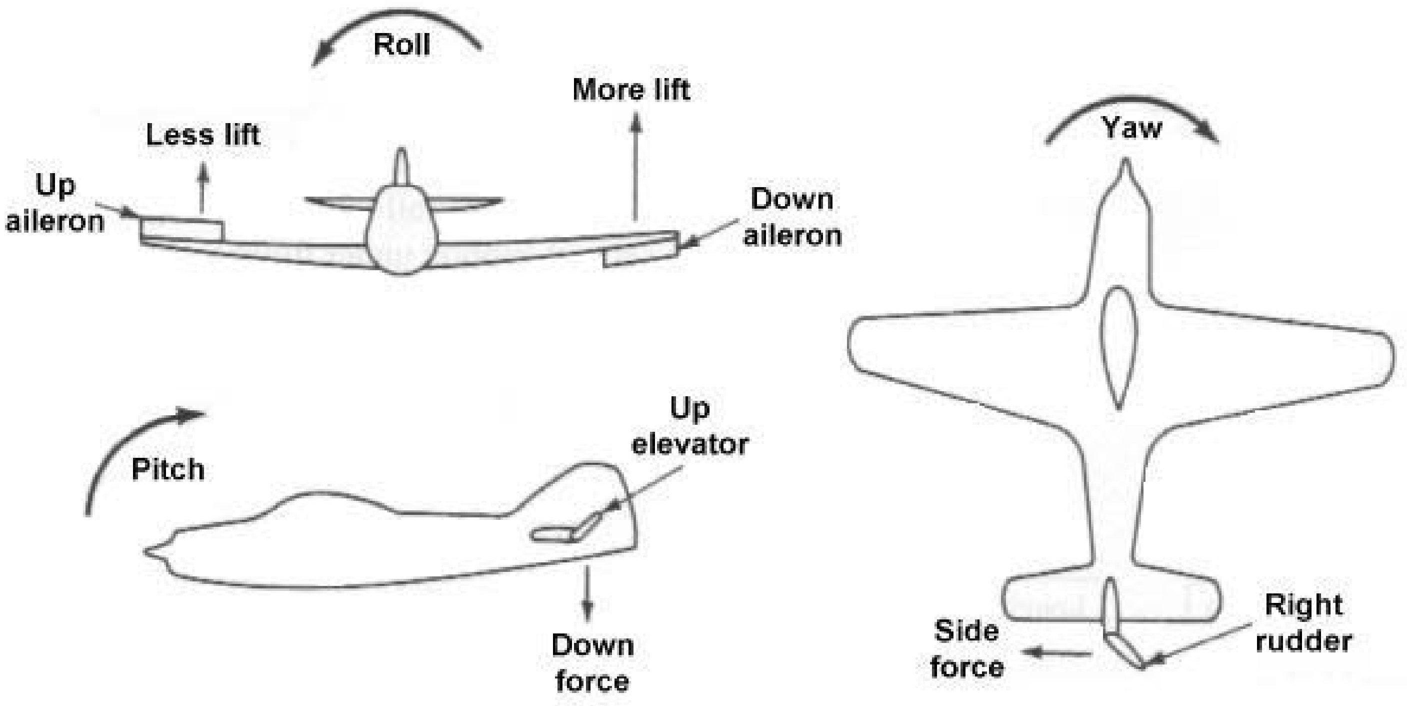


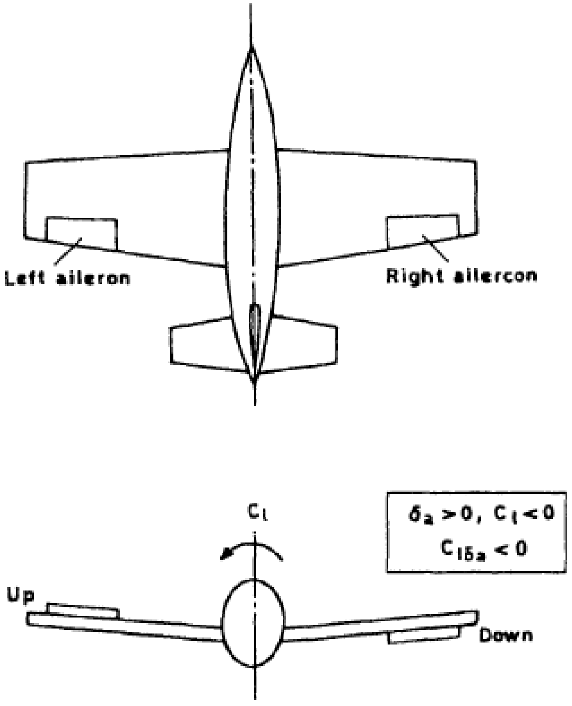
Schematic illustration of wing-fuselage interference in sideslip.

5. Lateral Stability

Evaluation of lateral stability

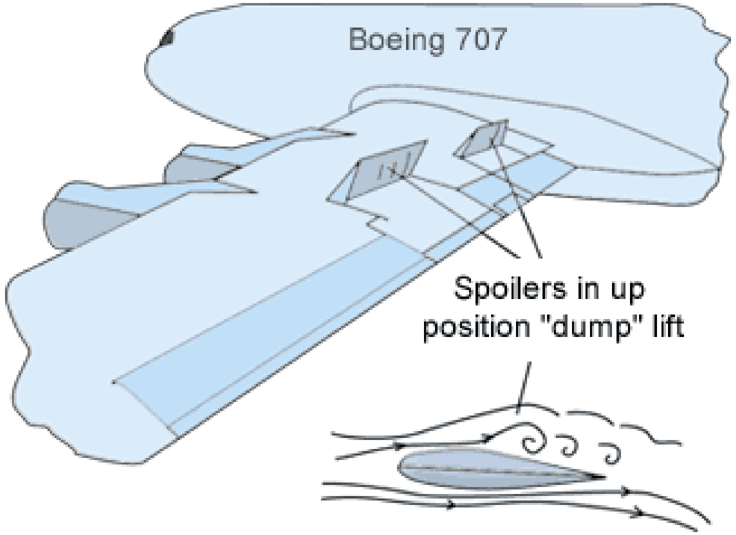
- **Wing dihedral**: in general, wing dihedral has a stabilizing effect on lateral stability.
- **Effect of sweep**: in general, the sweep-back has a stabilizing effect, and a sweep-forward has the opposite or destabilizing effect.

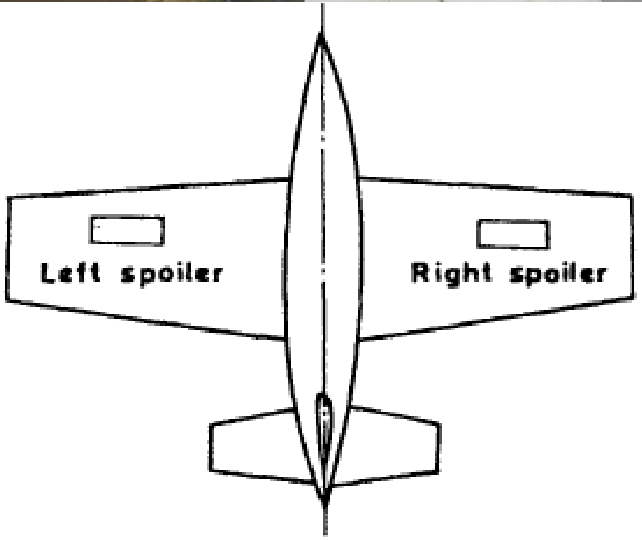


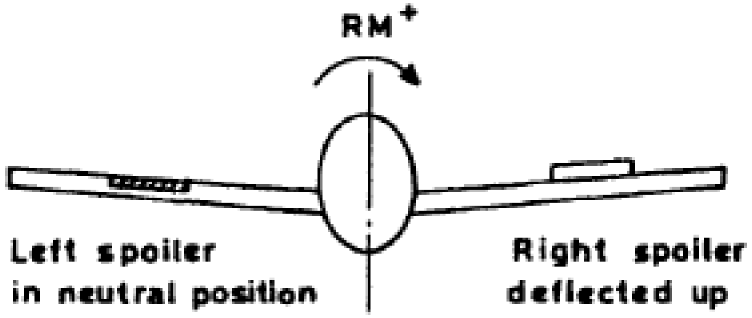


Sign convention for aileron deflection.

5. Lateral Stability







Roll control by spoilers.

6. Stick-Free Stability

Each control surface on an aircraft is mounted through a hinge. A deflection of control surface results in modified aerodynamic moment about the hinge line. The pilot (or some mechanism) must supply adequate force/ moment to counter this hinge moment.

Moment acting at hinge line of an elevator is to be overcome by pilot exerting a force on the control stick.

Reversible Controls

In reversible control system, the pilot controls are connected to the control surfaces. This is generally done by using pulleys, cables and push rods.

Therefore, if pilot moves the control stick then the corresponding control surface also sets deflected. Similarly, if control surface is deflected then the control stick also gets deflected.

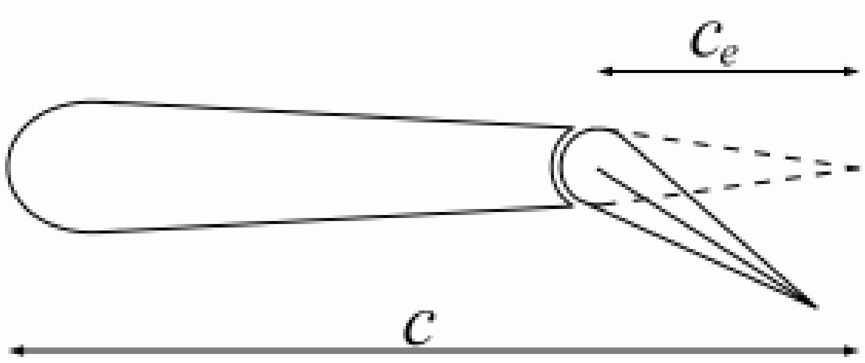


Figure 1: Hinge moment

6. Stick-Free Stability

Irreversible Control

- In irreversible control system, despite the controls are directly connected to surfaces; there is additional boost system that requisite force, moment to the controls.
- As a consequence, when pilot moves the stick then the control surface moves. However, movement of control surface will not move the stick.
- The boost system is supposed to hold the control surface in a fixed position once it is set at that position.
- For a reversible system in ‘hands off’ condition (pilot let go off the stick!) the control surface will float to the position where there is no hinge moment (force or moment applied to the control surface disappear).
- The condition where the hinge moment is equal to zero is called “stick free” condition. It is important to note that under this condition, the aerodynamic characteristics including the neutral point change.

7. Dynamic Stability

Positive Dynamic Stability

An aircraft is called dynamically stable if once ended the disturbance (which has moved it away from its trajectory), it returns in its original position.

That one can be reached after some damped oscillations, or in the best case, following a very damped trajectory.

Negative Dynamic Stability

If during the returning phase, the aircraft overpass its initial position and starts an oscillatory motion about the initial trajectory with growing amplitudes, there is a dynamically unstable (negative) situation.

Neutral Dynamic Stability

An aircraft is called dynamically neutral when starts a series of oscillations about the point of equilibrium, with constant amplitude, without damp.