Lift and Drag

The four forces acting on an aircraft in flight are **lift, weight, thrust and drag.** Weight always acts vertically toward the center of the earth. Lift acts perpendicular to the relative wind (not always vertically). Thrust and drag act opposite each other and parallel to the relative wind.

Lift is produced by air flowing over the curved wing surfaces. The air flowing over the upper surface of the wing is deflected further than that flowing across the lower surface and therefore is accelerated. **Bernoulli's Principle** states that when a gas is accelerated, its pressure decreases. Thus the pressure on the upper wing surface is lower than that on the lower surface and lift is produced.

Angle of attack is the angle between the relative wind and chord line of wing. At zero angle of attack, the pressure on the upper surface of the wing is still less than atmospheric, but the wing is producing minimum lift. As the angle of attack is increased, the lift developed by the wing increases proportionately. This is true until the angle of attack exceeds a critical value, when the air flowing over the top of the wing breaks up into a turbulent flow and the wing stalls.

Angle of attack and indicated airspeed determine the total lift. An increase in either indicated airspeed or angle of attack increases total lift (up to the stalling angle of attack) and a decrease in either decreases total lift. To maintain the same total lift (i.e., maintain level flight), a pilot has to change the angle of attack anytime indicated airspeed is changed. For example, as indicated airspeed is decreased, the angle of attack must be increased to compensate for the loss of lift. The relationship between indicated airspeed and lift for a given angle of attack involves the law of squares. If the angle of attack does not change, total lift varies with the square of the indicated airspeed. For example, if the airspeed doubles, the lift will increase by four times.

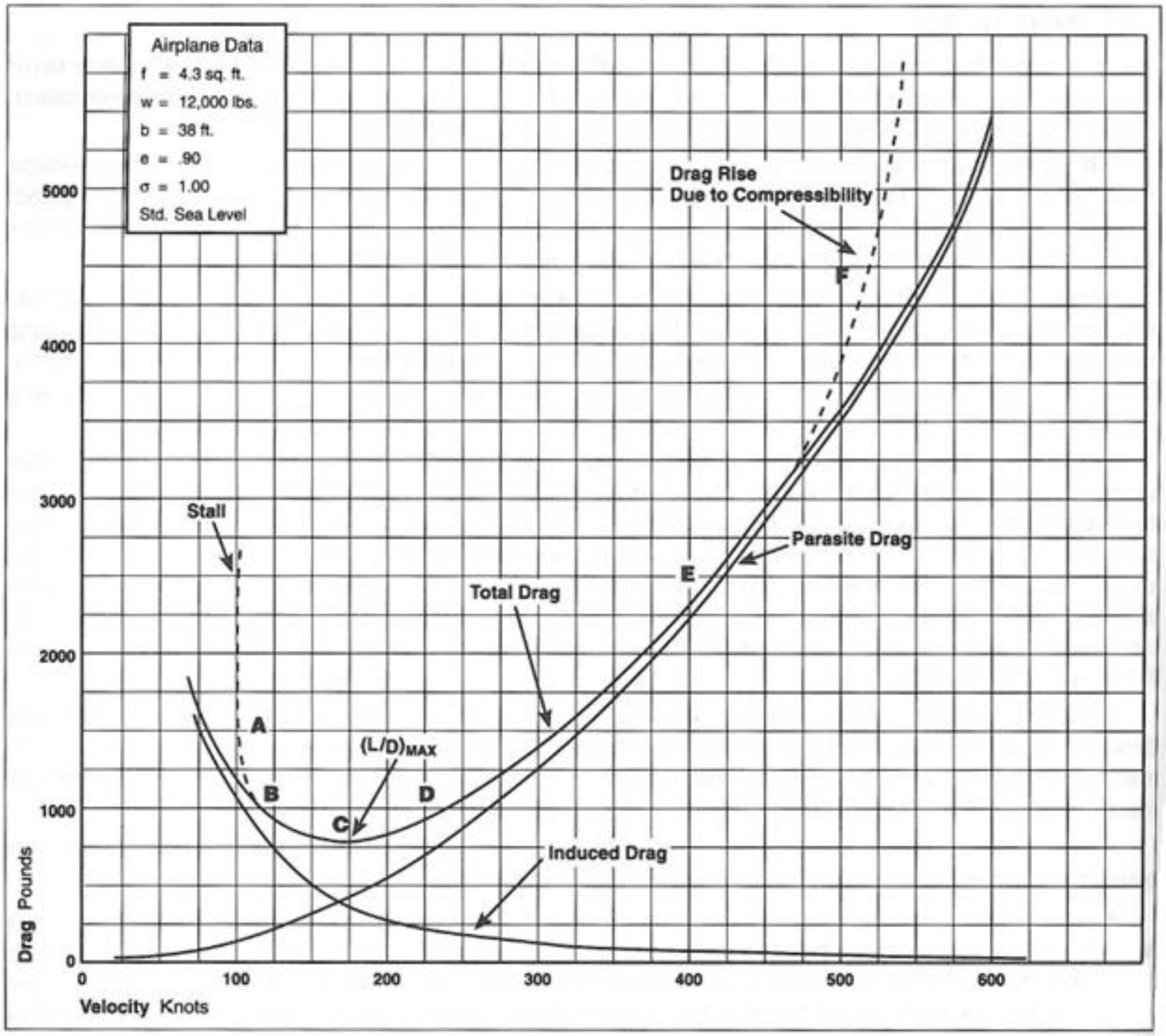
Indicated airspeed can be thought of as having two elements—the actual speed of the airplane through the air (true airspeed) and the density of the air. As altitude increases, air density decreases. To maintain the same indicated airspeed at altitude an aircraft must fly at a higher true airspeed. To produce the same amount of lift at altitude, a higher true airspeed is required for a given angle of attack.

A wing will always stall at the same angle of attack. The load factor, weight and density altitude will cause the stalling true airspeed to vary, but the stall angle of attack will always be the same.

A curve comparing total drag to parasite and induced drag reveals an airspeed at which drag is at a minimum value. At higher airspeeds, total drag increases because of increasing parasite drag. At lower airspeeds, induced drag increases which increases the total drag. Since the lift stays constant (equal to weight), the low point on the curve is the airspeed that produces the best lift to drag (L/D) ratio. This point is referred to as **L/D_{MAX}**. *See* Figure 3-1.

A change in weight changes the L/D curve. The amount of parasite drag is mainly a function of indicated airspeed. The amount of induced drag is a function of angle of attack. When an aircraft's weight is increased, any indicated airspeed will require a higher angle of attack to produce the required lift. This means that induced drag will increase with increases in weight while there will be little change in parasite drag.

When an airplane is within about one wingspan of the ground, the flow of air around the wingtips is inhibited by the close proximity of the ground. This **ground effect** reduces induced drag (and therefore total drag) and increases lift. As an airplane flies out of ground effect on takeoff, the increased induced drag will require a higher angle of attack.

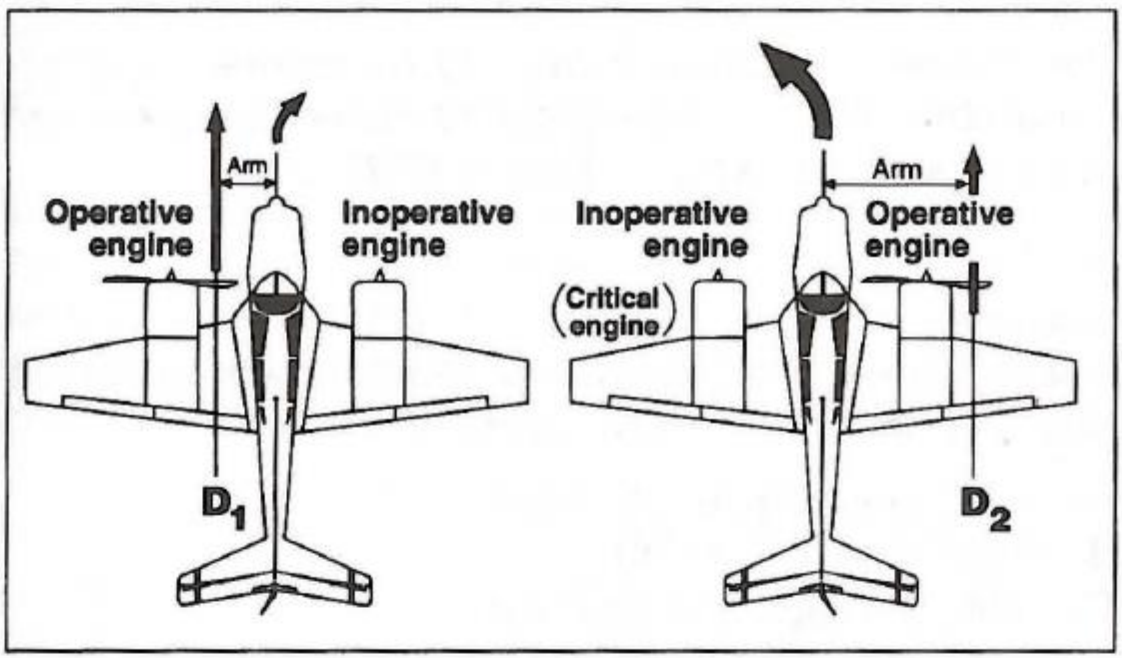

Airplane Data
f = 4.3 sq. ft.
w = 12,000 lbs.
b = 38 ft.
e = .90
σ = 1.00
Std. Sea Level
Drag Rise
Due to Compressibility
F
Stall
Parasite Drag
E
Total Drag
A
(L/D)MAX
B
D
C
Induced Drag
Drag Pounds
0
1000
2000
3000
4000
5000
0
100
200
300
400
500
600
Velocity Knots

Critical Engine and V_{MC}

Because of "P-Factor" on most propeller-driven airplanes, the loss of one particular engine at high angles of attack would be more detrimental to performance than the loss of the other. One of the engines has its thrust line closer to the aircraft centerline (*see* Figure 3-2). The loss of this engine would more adversely affect the performance and handling of the aircraft; therefore this is the "critical engine."

For unsupercharged engines, V_{MC} decreases as altitude is increased. Stalls should never be practiced with one engine inoperative because of the potential for loss of control. Engine out approaches and landings should be made the same as normal approaches and landings.

Banking at least 5° into the good engine ensures the airplane will be controllable at any speed above the certificated V_{MC}, that the airplane will be in a minimum drag configuration for best climb performance, and that the stall characteristics will not be degraded. Engine out flight with the ball centered is never correct.



Maneuvering Flight

In a turn, centrifugal force is counterbalanced by a portion of the lift of the wing. The horizontal component of lift turns the airplane and the vertical component of lift opposes gravity. When the pilot rolls the airplane into a turn he must increase the total lift of the wing so that the vertical component is equal to the airplane's weight. This is done by increasing the angle of attack. If no compensation is made for the loss of vertical component of lift in a turn, the aircraft will develop a sink rate.

Load factor is the ratio of the weight supported by the wings to the actual weight of the aircraft. For example, if an aircraft with a gross weight of 2,000 pounds were subjected to a total load of 6,000 pounds in flight, the load factor would be 3 Gs. On the ground or in unaccelerated flight the load factor is one. Conditions which can increase the load factor are vertical gusts (turbulence) and level turns. In a **level turn**, the load factor is dependent only on the angle of bank. Airspeed, turn rate or aircraft weight have no effect on load factor.

Rate of turn is the number of degrees per second at which the aircraft turns. The rate of turn is dependent on both the aircraft's airspeed and its angle of bank. To increase the rate of turn, the pilot must increase the angle of bank or decrease the airspeed or both. The rate of turn will decrease if the bank angle is decreased or if the airspeed is increased. The **radius of turn** is also dependent on both the bank angle and the airspeed. If angle of bank is increased or airspeed is decreased, the radius of turn will decrease. If bank angle is shallowed or if airspeed is increased, the radius of turn will increase.

Stability

Static stability describes the initial reaction of an aircraft after it has been disturbed from equilibrium in one or more of its axes of rotation. If the aircraft has an initial tendency to return to its original attitude of equilibrium, it has **positive static stability**. When it continues to diverge, it exhibits **negative static stability**. If an aircraft tends to remain in its new, disturbed state, it has **neutral static stability**. Most airplanes have positive static stability in pitch and yaw, and are close to neutrally stable in roll.

When an aircraft exhibits positive static stability in one of its axes, the term "dynamic stability" describes the long term tendency of the aircraft. When an aircraft is disturbed from equilibrium and then tries to return, it will invariably overshoot the original attitude and then pitch back. This results in a series of oscillations. If the oscillations become smaller with time, the aircraft has positive dynamic stability. If the aircraft diverges further away from its original attitude with each oscillation, it has negative dynamic stability.

The entire design of an aircraft contributes to its **stability** (or lack of it) in each of its axes of rotation. However, the vertical tail is the primary source of direction stability (yaw), and the horizontal tail is the primary source of pitch stability. The **center of gravity (CG)** location also affects stability. If the CG is toward its rearward limit, the aircraft will be less stable in both roll and pitch. As the CG is moved forward, the stability improves. Even though an airplane will be less stable with a rearward CG, it will have some desirable aerodynamic characteristics due to reduced aerodynamic loading of horizontal tail surface. This type of an airplane will have a slightly lower stall speed and will cruise faster for a given power setting.

High Speed Flight

Mach number is the ratio of the true airspeed to the speed of sound (TAS ÷ Speed of Sound). For example, an aircraft cruising at Mach .80 is flying at 80% of the speed of sound. The speed of sound is Mach 1.0.

A large increase in drag occurs when the air flow around the aircraft exceeds the speed of sound (Mach 1.0). Because lift is generated by accelerating air across the upper surface of the wing, local air flow velocities will reach sonic speeds while the aircraft Mach number is still considerably below the speed of sound. With respect to **Mach cruise control,** flight speeds can be divided into three regimes—subsonic, transonic and supersonic. The **subsonic regime** can be considered to occur at aircraft Mach numbers where all the local air flow is less than the speed of sound. The **transonic range** is where some but not all the local air flow velocities are Mach 1.0 or above. In **supersonic** flight, all the air flow around the aircraft exceeds Mach 1.0. The exact Mach numbers will vary with each aircraft type but as a very rough rule of thumb the subsonic regime occurs below Mach .75, the transonic regime between Mach .75 and Mach 1.20, and the supersonic regime over Mach 1.20.

A limiting speed for a subsonic transport aircraft is its critical Mach number (M_{CRIT}). That is the speed at which airflow over the wing first reaches, but does not exceed, the speed of sound. At M_{CRIT} there may be sonic but no supersonic flow.

When an airplane exceeds its critical Mach number, a shock wave forms on the wing surface that can cause a phenomenon known as shock stall. If this shock stall occurs symmetrically at the wing roots, the loss of lift and loss of downwash on the tail will cause the aircraft to pitch down or "tuck under." This tendency is further aggravated in sweptwing aircraft because the center of pressure moves aft as the wing roots shock stall. If the wing tips of a sweptwing airplane shock stall first, the wing's center of pressure would move inward and forward causing a pitch up motion. See Figure 3-3.

The less airflow is accelerated across the wing, the higher the critical Mach number (i.e., the maximum flow velocity is closer to the aircraft's Mach number). Two ways of increasing M_{CRIT} in jet transport designs are to give the wing a lower camber and increase wing sweep. A thin airfoil section (lower camber) causes less airflow acceleration. The sweptwing design has the effect of creating a thin airfoil section by inducing a spanwise flow, thus increasing the effective chord length. See Figure 3-4.

Although a sweptwing design gives an airplane a higher critical Mach number (and therefore a higher maximum cruise speed), it results in some undesirable flight characteristics. One of these is a reduced maximum coefficient of lift. This requires that sweptwing airplanes extensively employ high lift devices, such as slats and slotted flaps, to get acceptably low takeoff and landing speeds. The purpose of high lift devices such as flaps, slats and slots is to increase lift at low airspeeds and to delay stall to a higher angle of attack.

Another disadvantage of the sweptwing design is the tendency, at low airspeeds, for the wing tips to stall first. This results in loss of aileron control early in the stall, and in very little aerodynamic buffet on the tail surfaces.

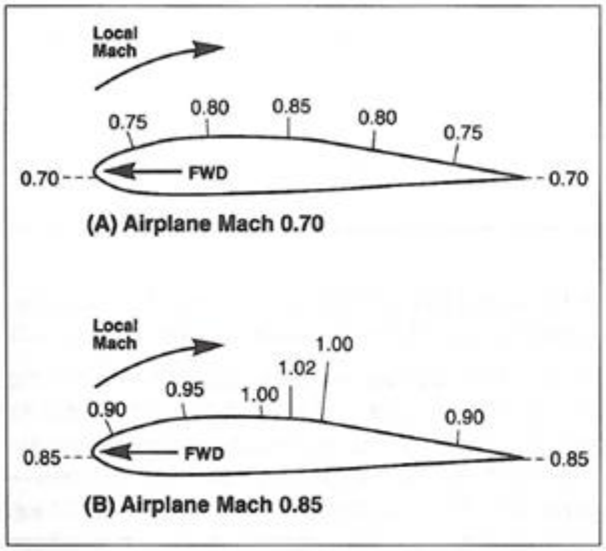


Figure 3-3. Local airstream Mach numbers

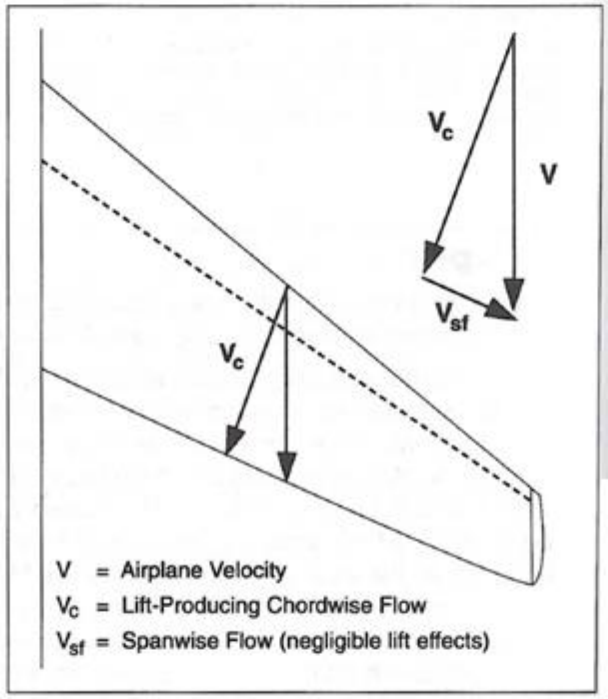


Figure 3-4. Effect of wing sweep on M_{CRIT}

Primary Flight Controls

Because of the high air loads, it is very difficult to move the flight control surfaces of jet aircraft with just mechanical and aerodynamic forces. So flight controls are usually moved by hydraulic actuators. Flight controls are divided into **primary flight controls** and **secondary** or **auxiliary flight controls**. The primary flight controls are those that maneuver the aircraft in roll, pitch and yaw. These include the ailerons, elevator and rudder. Secondary (or auxiliary) flight controls include tabs, trailing-edge flaps, leading-edge flaps, spoilers and slats. *See* Figure 3-5.

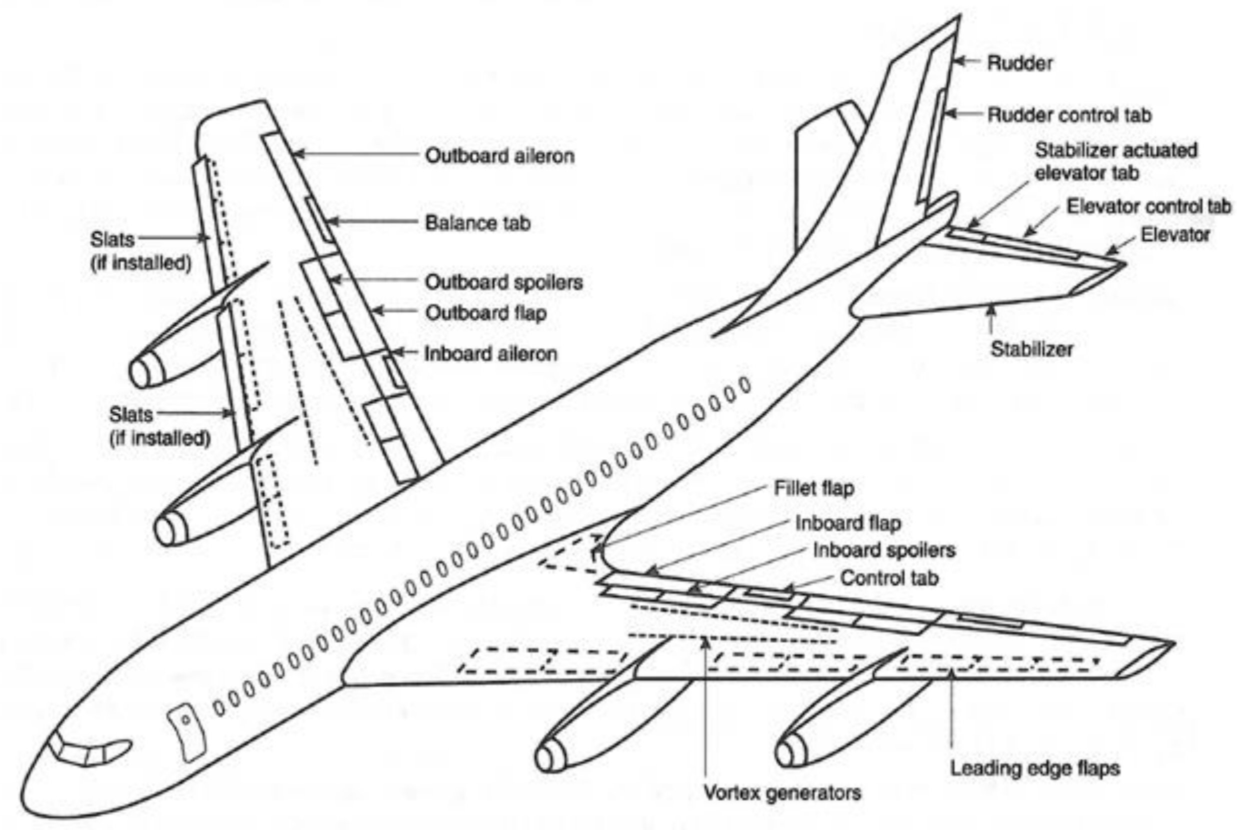
Roll control of most jet aircraft is accomplished by ailerons and flight spoilers. The exact mix of controls is determined by the aircraft's flight regime. In low speed flight all control surfaces operate to provide the desired roll control. As the aircraft moves into higher speed operations, control surface movement is reduced to provide approximately the same roll response to a given input through a wide range of speeds.

Many aircraft have two sets of ailerons-inboard and outboard. The inboard ailerons operate in all flight regimes. The outboard ailerons work only when the wing flaps are extended and are automatically locked out when flaps are retracted. This allows good roll response in low speed flight with the flaps extended and prevents excessive roll and wing bending at high speeds when the flaps are retracted.

Spoilers increase drag and reduce lift on the wing. If raised on only one wing, they aid roll control by causing that wing to drop. If the spoilers raise symmetrically in flight, the aircraft can either be slowed in level flight or can descend rapidly without an increase in airspeed. When the spoilers rise on the ground at high speeds, they destroy the wing's lift which puts more of the aircraft's weight on its wheels which in turn makes the brakes more effective.

Often aircraft have both flight and ground spoilers. The flight spoilers are available both in flight and on the ground. However, the ground spoilers can only be raised when the weight of the aircraft is on the landing gear. When the spoilers deploy on the ground, they decrease lift and make the brakes more effective. In flight, a ground-sensing switch on the landing gear prevents deployment of the ground spoilers.

Vortex generators are small (an inch or so high) aerodynamic surfaces located in different places on different airplanes. They prevent undesirable airflow separation from the surface by mixing the boundary airflow with the high energy airflow just above the surface. When located on the upper surface of a wing, the vortex generators prevent shock-induced separation from the wing as the aircraft approaches its critical Mach number. This increases aileron effectiveness at high speeds.


Rudder
Rudder control tab
Stabilizer actuated elevator tab
Elevator control tab
Elevator
Stabilizer
Outboard aileron
Balance tab
Slats (if installed)
Outboard spoilers
Outboard flap
Inboard aileron
Slats (if installed)
Fillet flap
Inboard flap
Inboard spoilers
Control tab
Leading edge flaps
Vortex generators

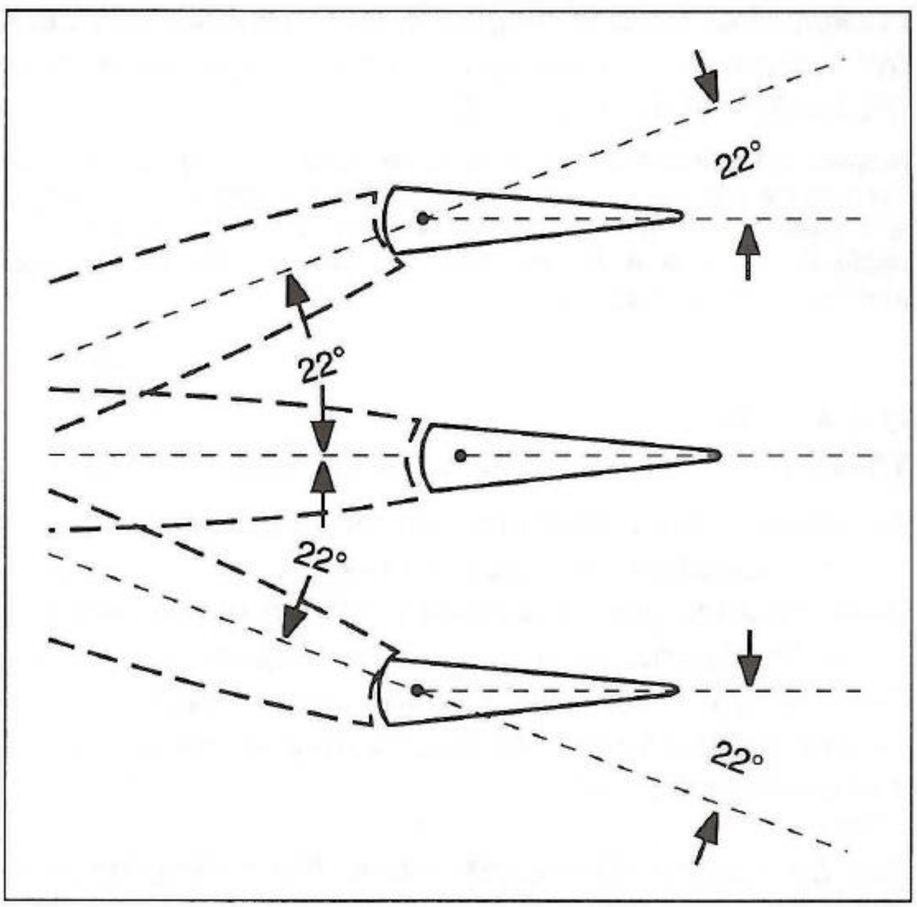
Tabs

Flight control surfaces are sometimes equipped with servo tabs. These tabs are on the trailing edge of the control surface and are mechanically linked to move opposite the direction of the surface. If the tab moves up, the surface moves down. This "servo" movement moves the control surface. See Figure 3-6.

One method of modifying the downward tail load through changes in airspeed and configuration is by using trim tabs. Trim tabs are moved by a separate trim control from the cockpit. Movement of the trim tab (like the servo tab) is opposite that of the primary control surface.

Anti-servo tabs move in the same direction as the primary control surface. This means that as the control surface deflects, the aerodynamic load is increased by movement of the anti-servo tab. This helps to prevent the control surface from moving to a full deflection. It also makes a hydraulically-boosted flight control more aerodynamically effective than it would otherwise be.

Some jet aircraft have control tabs for use in the event of loss of all hydraulic pressure. Movement of the control wheel moves the control tab which causes the aerodynamic movement of the control surface. The control tab is used only during manual reversion; that is, with the loss of hydraulic pressure. They work the same as a servo tab but only in the manual mode.



High-Lift Devices

Sweptwing jet aircraft are equipped with a number of high-lift devices. These include leading edge flaps, slots or slats, and trailing edge flaps. The primary purpose of high-lift devices (flaps, slots, slats, etc.) is to increase the **maximum coefficient of lift** (CL_{MAX}) of the airplane and reduce the stall speed. The takeoff and landing speeds are consequently reduced.

The two most common types of **leading-edge devices** are **slats** and **Krueger flaps**. The Krueger flap extends from the leading edge of the wing, increasing its camber. The slat also extends from the wing's leading edge but it creates a gap or slot. This slot allows high energy from under the wing to flow over the top of the wing that delays stall to a higher angle of attack than would otherwise occur. It is common to find Krueger flaps and slats on the same wing.