TURBINE AEROPLANE AERODYNAMICS, STRUCTURES AND SYSTEMS

THEORY OF FLIGHT

SUB-MODULE 01

PART-66 SYLLABUS LEVELS

CERTIFICATION CATEGORY →	A	B1
Sub-Module 01 THEORY OF FLIGHT Knowledge Requirements		
11.1 Theory of Flight		
11.1.1 - Aeroplane Aerodynamics and Flight Controls Operation and effect of: — roll control: ailerons and spoilers; — pitch control: elevators, stabilator's, variable incidence stabilizers and canards; — yaw control, rudder limiters; Control using elevons, ruddervators; High lift devices, slots, slats, flaps, flaperons; Drag inducing devices, spoilers, lift dumpers, speed brakes; Effects of wing fences, saw tooth leading edges; Boundary layer control using, vortex generators, stall wedges or leading edge devices; Operation and effect of trim tabs, balance and antibalance (leading) tabs, servo tabs, spring tabs, mass balance, control surface bias, aerodynamic balance panels.	1	2
11.1.2 - High Speed Flight Speed of sound, subsonic flight, transonic flight, supersonic flight; Mach number, critical Mach number, compressibility buffet, shock wave, aerodynamic heating, area rule; Factors affecting airflow in engine intakes of high speed aircraft; Effects of sweepback on critical Mach number.	1	2

Level 1
A familiarization with the principal elements of the subject.

Objectives:
(a) The applicant should be familiar with the basic elements of the subject.
(b) The applicant should be able to give a simple description of the whole subject, using common words and examples.
(c) The applicant should be able to use typical terms.

Level 2
A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical fundamentals of the subject.
(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

The directional control of a fixed wing aircraft takes place around the lateral, longitudinal, and vertical axes by means of flight control surfaces designed to create movement about these axes. These control devices are hinged or movable surfaces through which the attitude of an aircraft is controlled during takeoff, flight, and landing. They are usually divided into two major groups: 1) primary or main flight control surfaces and 2) secondary or auxiliary control surfaces.

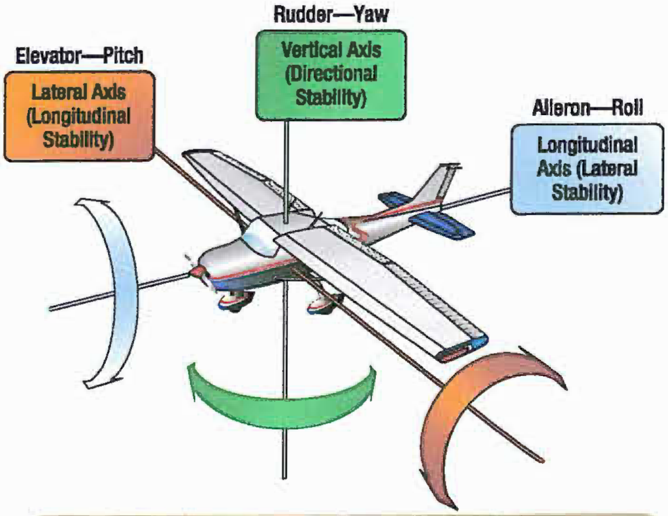
PRIMARY FLIGHT CONTROL SURFACES

The primary flight control surfaces on a fixed wing aircraft include: ailerons, elevators, and the rudder. The ailerons are attached to the trailing edge of both wings and when moved, rotate the aircraft around the longitudinal axis. The elevator is attached to the trailing edge of the horizontal stabilizer. When it is moved, it alters aircraft pitch, which is the attitude about the horizontal or lateral axis. The rudder is hinged to the trailing edge of the vertical stabilizer. When the rudder changes position, the aircraft rotates about the vertical axis (yaw). ***Figure 1-1*** shows the primary flight controls of a light aircraft and the movement they create relative to the three axes of flight.

Primary control surfaces are usually similar in construction to one another and vary only in size, shape, and methods of attachment. On aluminum light aircraft, their structure is often similar to an all metal wing. This is appropriate because the primary control surfaces are simply smaller aerodynamic devices. They are typically made from an aluminum alloy structure built around a single spar member or torque tube to which ribs are fitted and a skin is attached. The lightweight ribs are, in many cases, stamped out from flat aluminum sheet stock. Holes in the ribs lighten the assembly. An aluminum skin is attached with rivets. ***Figure 1-2*** illustrates this type of structure, which can be found on the primary control surfaces of light aircraft as well as on medium and heavy aircraft.

Primary control surfaces constructed from composite materials are also commonly used. These are found on many heavy and high performance aircraft, as well as gliders, homebuilt, and light sport aircraft. The weight and strength advantages over traditional construction can be significant. A wide variety of materials and construction techniques are employed. ***Figure 1-3*** shows examples of aircraft that use composite technology on primary flight control surfaces. Note that the control surfaces of fabric covered aircraft often have fabric covered surfaces just as aluminum skinned (light) aircraft typically have all aluminum control surfaces. There is a critical need for primary control surfaces to be balanced so they do not vibrate or flutter in the wind.

Performed to manufacturer's instructions, balancing usually consists of assuring that the center of gravity of



Primary Control Surface	Airplane Movement	Axes of Rotation	Type of Stability
Aileron	Roll	Longitudinal	Lateral
Elevator/ Stabilator	Pitch	Lateral	Longitudinal
Rudder	Yaw	Vertical	Directional

Figure 1-1. Flight control surfaces move the aircraft around the three axes of flight.

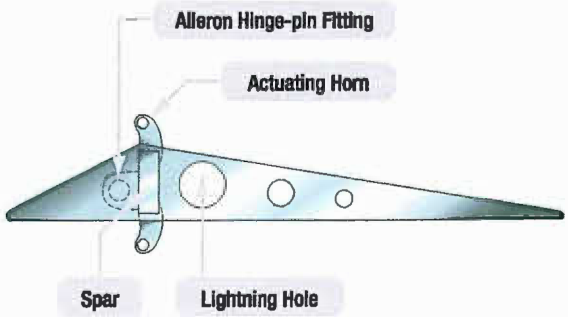


Figure 1-2. Typical structure of an aluminum flight control surface.

a particular device is at or forward of the hinge point. Failure to properly balance a control surface could lead to catastrophic failure. ***Figure 1-4*** illustrates several aileron configurations with their hinge points well aft of the leading edge. This is a common design feature used to prevent flutter.

OPERATION AND EFFECT OF ROLL CONTROL DEVICES

AILERONS

Ailerons are the primary flight control surfaces that move the aircraft about the longitudinal axis. In other words, movement of the ailerons in flight causes the aircraft to roll. Ailerons are usually located on the outboard trailing edge of each of the wings. They are built into the wing and are calculated as part of the wing's surface area. ***Figure 1-5*** shows aileron locations on various wing tip designs.

Ailerons are controlled by a side to side motion of the control stick in the cockpit or a rotation of the control yoke. When the aileron on one wing deflects down, the aileron on the opposite wing deflects upward. This amplifies the movement of the aircraft around the longitudinal axis. On the wing on which the aileron trailing edge moves downward, camber is increased and lift is increased. Conversely, on the other wing, the raised aileron decreases lift. (***Figure 1-6***) The result is a sensitive response to the control input to roll the aircraft.

The pilot's request for aileron movement and roll are transmitted from the cockpit to the actual control surface in a variety of ways depending on the aircraft. A system of control cables and pulleys, push pull tubes, hydraulics, electric, or a combination of these can be employed. (***Figure 1-7***)

Figure 1-3. Composite control surfaces and some of the many aircraft that utilize them.

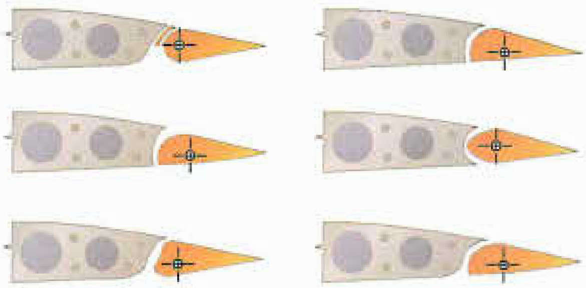


Figure 1-4. Aileron hinge locations are very close to but aft of the center of gravity to prevent flutter.

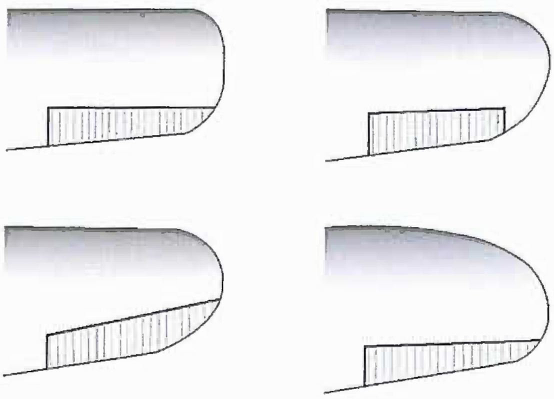


Figure 1-5. Aileron location on various wings.

Simple, light aircraft usually do not have hydraulic or electric fly by wire aileron control. These are found on heavy and high performance aircraft. Large aircraft and some high performance aircraft may also have a second set of ailerons located inboard on the trailing edge of the wings. These are part of a complex system of primary and secondary control surfaces used to provide lateral control and stability in flight. At low speeds, the ailerons may be augmented by the use of flaps and spoilers. At high speeds, only inboard aileron deflection is required to roll the aircraft while the other control surfaces are locked out or remain stationary. ***Figure 1-8*** illustrates the location of the typical flight control surfaces found on a transport category aircraft.

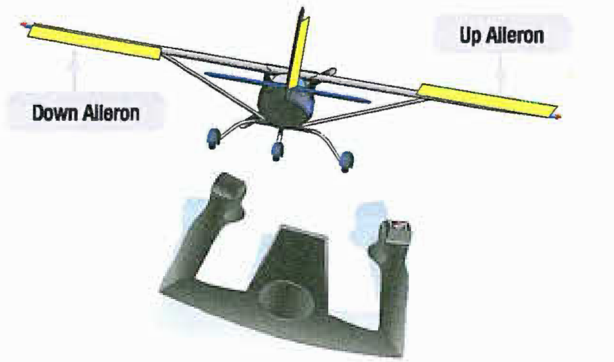


Figure 1-6. Differential aileron control movement. When one aileron is moved down, the aileron on the opposite wing is deflected upward.

SPOILERS

A spoiler is a device found on the upper surface of many heavy and high performance aircraft. It is stowed flush to the wing's upper surface. When deployed, it raises up into the airstream and disrupts the laminar airflow of the wing, thus reducing lift.

Spoilers are made with similar construction materials and techniques as the other flight control surfaces on the aircraft. Often, they are honeycomb core flat panels. At low speeds, spoilers are rigged to operate when the ailerons operate to assist with the lateral movement and

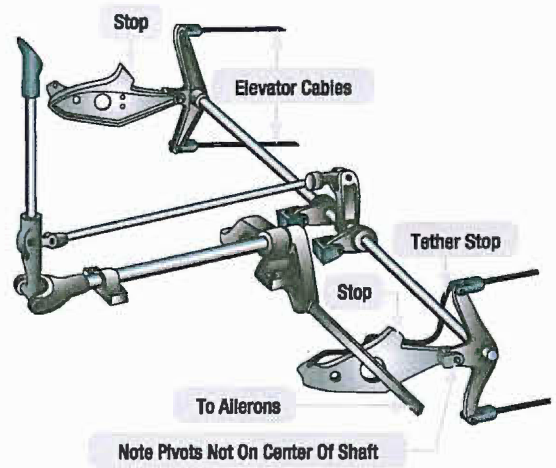


Figure 1-7. Transferring control surface inputs from the cockpit.

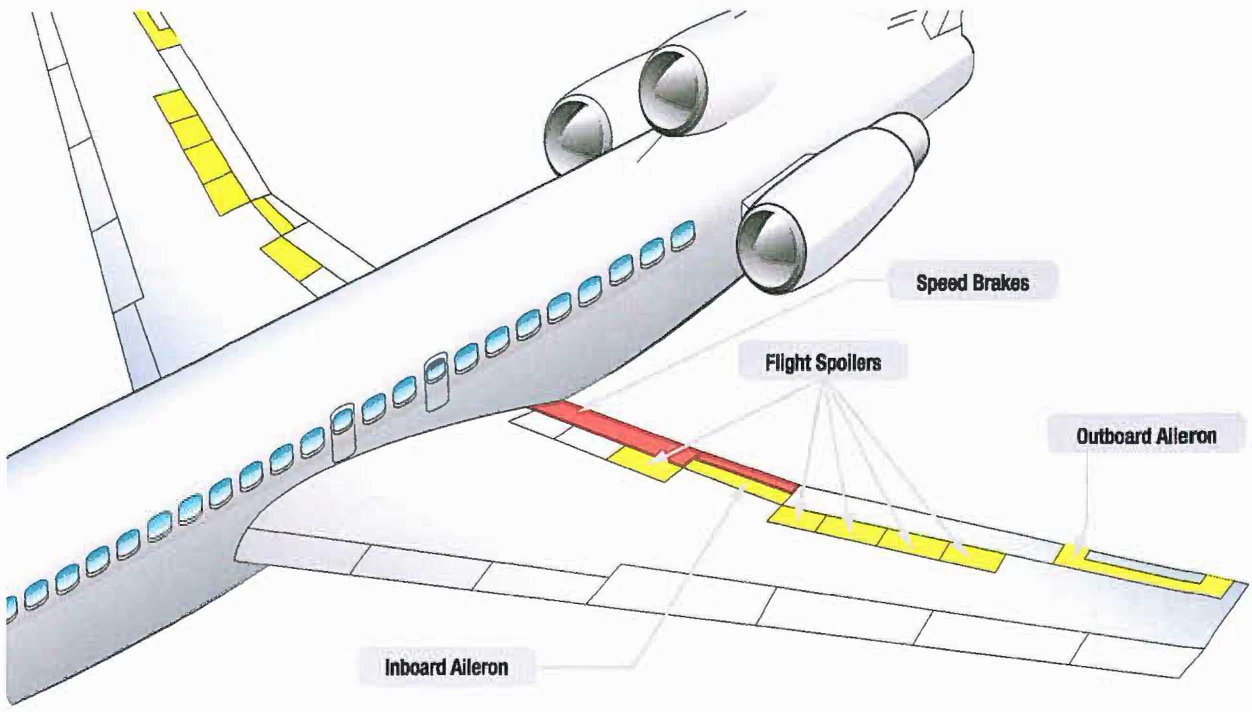


Figure 1-8. Typical flight control surfaces on a transport category aircraft.

stability of the aircraft. On the wing where the aileron is moved up, the spoilers also raise thus amplifying the reduction of lift on that wing. (*Figure 1-9*)

On the wing with downward aileron deflection, the spoilers remain stowed. As the speed of the aircraft increases, the ailerons become more effective and the spoiler interconnect disengages. Note that spoilers are also used in as drag inducing devices.

Figure 1-9. Spoilers deployed upon landing a transport category aircraft.

OPERATION AND EFFECT OF PITCH CONTROL DEVICES

ELEVATORS

The elevator is the primary flight control surface that moves the aircraft around the horizontal or lateral axis. This causes the nose of the aircraft to pitch up or down. The elevator is hinged to the trailing edge of the horizontal stabilizer and typically spans most or all of its width. It is controlled in the cockpit by pushing or pulling the control yoke forward or aft.

Light aircraft use a system of control cables and pulleys or push pull tubes to transfer cockpit inputs to the movement of the elevator. High performance and large aircraft typically employ more complex systems. Hydraulic power is commonly used to move the elevator on these aircraft. On aircraft equipped with fly by wire controls, a combination of electrical and hydraulic power is used.

STABILATORS

A movable horizontal tail section, called a stabilator, is a control surface that combines the action of both the horizontal stabilizer and the elevator. (*Figure 1-10*) Basically, a stabilator is a horizontal stabilizer that can also be rotated about the horizontal axis to affect the pitch of the aircraft.

Figure 1-10. A stabilizer and index marks on a transport category aircraft.

VARIABLE INCIDENCE STABILIZERS

A variable incidence stabilizer refers to any horizontal stabilizer in which the angle of incidence of the horizontal stabilizer is adjustable. Thus, a stabilator is a variable incidence horizontal stabilizer. Various mechanisms and operating rigging are available. Most large aircraft use a motorized jackscrew to alter the position of the stabilizer often energized by the trim tab switch on the control yoke. The reason for a stabilator or any horizontal stabilizer variable incidence device is to minimize drag when trimming the aircraft in flight. Deflection of the elevator via the use of a trim tab causes drag and requires a relatively large elevator on large aircraft to achieve all desired trim settings. By varying the angle of the horizontal stabilizer to adjust pitch, less drag is created and elevator size and deflection may be reduced. (*Figure 1-11*)

CANARDS

A canard utilizes the concept of two lifting surfaces. It functions as a horizontal stabilizer located in front of the main wings. In effect, the canard is an airfoil similar to the horizontal surface on a conventional aft tail design.

The difference is that the canard actually creates lift and holds the nose up, as opposed to the aft tail design which exerts downward force on the tail to prevent the nose from rotating downward. (***Figure 1-12***)

The canard design dates back to the pioneer days of aviation, most notably used on the Wright Flyer. Recently, the canard configuration has regained popularity and is appearing on newer aircraft. Canard designs include two types, one with a horizontal surface of about the same size as a normal aft tail design, and the other with a surface of the same approximate size and airfoil shape of the aft mounted wing known as a tandem wing configuration. Theoretically, the canard is considered more efficient because using the horizontal surface to help lift the weight of the aircraft should result in less drag for a given amount of lift.

OPERATION AND EFFECT OF YAW CONTROL DEVICES

RUDDERS

The rudder is the primary control surface that causes an aircraft to yaw or move about the vertical axis. This provides directional control and thus points the nose of the aircraft in the direction desired. Most aircraft have a single rudder hinged to the trailing edge of the vertical stabilizer. It is controlled by a pair of foot operated rudder pedals in the cockpit. When the right pedal is pushed forward, it deflects the rudder to the right which moves the nose of the aircraft to the right. The left pedal is rigged to simultaneously move aft. When the left pedal is pushed forward, the nose of the aircraft moves to the left.

As with the other primary flight controls, the transfer of the movement of the cockpit controls to the rudder varies with the complexity of the aircraft. Many aircraft incorporate the directional movement of the nose or tail wheel into the rudder control system for ground operation. This allows the operator to steer the aircraft with the rudder pedals during taxi when the airspeed is not high enough for the control surfaces to be effective. Some large aircraft have a split rudder arrangement. This is actually two rudders, one above the other. At low speeds, both rudders deflect in the same direction when the pedals are pushed. At higher speeds, one of the rudders becomes inoperative as the deflection of a single rudder is aerodynamically sufficient to maneuver the aircraft.

RUDDER LIMITERS

In flight, most large aircraft oscillate slightly from side to side. Yaw dampener units automatically detect this movement and send signals to the hydraulic power control unit (PCU) that moves the rudder so that it can correct for these yaw oscillations. Similarly, rudders are known to deflect without being commanded to do so by the flight crew. Again, the yaw dampener is designed to correct the fluctuations by signaling the PCU. However, too large of an involuntary deflection to a rudder can cause a loss of control of the aircraft.

A ruder limiter is fitted to many aircraft to prevent any more than a few degrees of involuntary motion of the rudder. Essentially, it limits the movement unless it is commanded from the flight deck.

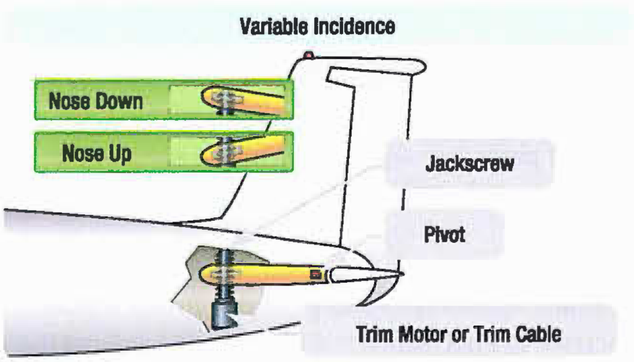


Figure 1-11. Some airplanes, including most jet transports, use an variable stabilizer to provide the required pitch trim forces.

Figure 1-12. The Piaggio P180 includes a variable-sweep canard design, which provides longitudinal stability about the lateral axis.

SECONDARY OR AUXILIARY CONTROL SURFACES

There are several secondary or auxiliary flight control surfaces. Their names, locations, and functions of those for most large aircraft are listed in ***Figure 1-13***.

OPERATION AND EFFECT OF TABS

TRIM TABS

The force of the air against a control surface during the high speed of flight can make it difficult to move and hold that control surface in the deflected position. A control surface might also be too sensitive for similar reasons. Several different tabs are used to aid with these types of problems. The table in ***Figure 1-14*** summarizes the various tabs and their uses. While in flight, it is desirable for the pilot to be able to take his or her hands and feet off of the controls and have the aircraft maintain its flight condition.

Trims tabs are designed to allow this. Most trim tabs are small movable surfaces located on the trailing edge of a primary flight control surface. A small movement of the tab in the direction opposite of the direction the flight control surface is deflected, causing air to strike the tab, in turn producing a force that aids in maintaining the flight control surface in the desired position. Through linkage set from the cockpit, the tab can be positioned so that it is actually holding the control surface in position rather than the pilot. Therefore, elevator tabs are used to maintain the speed of the aircraft since they assist in maintaining the selected pitch. Rudder tabs can be set to hold yaw in check and maintain heading. Aileron tabs can help keep the wings level.

Occasionally, a simple light aircraft may have a stationary metal plate attached to the trailing edge of a primary flight control, usually the rudder. This is also a trim tab as shown in ***Figure 1-15***. It can be bent slightly on the ground to trim the aircraft in flight to a hands off condition when flying straight and level. The correct amount of bend can be determined only by flying the aircraft after an adjustment. Note that a small amount of bending is usually sufficient.

BALANCE TABS

The aerodynamic phenomenon of moving a trim tab in one direction to cause the control surface to experience a force moving in the opposite direction is exactly what occurs with the use of balance tabs. (***Figure 1-16***) Often, it is difficult to move a primary control surface due to

Secondary/Auxiliary Flight Control Surfaces		
Name	**Location**	**Function**
Flaps	Inboard trailing edge of wings	Extends the camber of the wing for greater lift and slower flight. Allows control at low speeds for short field takeoffs and landings.
Trim Tabs	Trailing edge of primary flight control surfaces	Reduces the force needed to move a primary control surface.
Balance Tabs	Trailing edge of primary flight control surfaces	Reduces the force needed to move a primary control surface.
Anti-balance Tabs	Trailing edge of primary flight control surfaces	Increases feel and effectiveness of primary control surface.
Servo Tabs	Trailing edge of primary flight control surfaces	Assists or provides the force for moving a primary flight control.
Spoilers	Upper and/or trailing edge of wing	Decreases (spoils) lift. Can augment aileron function.
Slats	Mid to outboard leading edge of wing	Extends the camber of the wing for greater lift and slower flight. Allows control at low speeds for short field takeoffs and landings.
Slots	Outer leading edge of wing forward of ailerons	Directs air over upper surface of wing during high angle of attack. Lowers stall speed and provides control during slow flight.
Leading Edge Flap	Inboard leading edge of wing	Extends the camber of the wing for greater lift and slower flight. Allows control at low speeds for short field takeoffs and landings.

NOTE: An aircraft may possess none, one, or a combination of the above control surfaces.

Figure 1-13. Secondary or auxiliary control surfaces and respective locations for larger aircraft.

Flight Control Tabs			
Type	Direction of Motion (In relation to control surface)	Activation	Effect
Trim	Opposite	Set by pilot from cockpit. Uses independent linkage.	Statically balances the aircraft in flight. Allows "hands off" maintenance of flight condition.
Balance	Opposite	Moves when pilot moves control surface. Coupled to control surface linkage.	Aids pilot in overcoming the force needed to move the control surface.
Servo	Opposite	Directly linked to flight control input device. Can be primary or back-up means of control.	Aerodynamically positions control surfaces that require too much force to move manually.
Anti-balance or Anti-servo	Same	Directly linked to flight control input device.	Increases force needed by pilot to change flight control position. De-sensitizes flight controls.
Spring	Opposite	Located in line of direct linkage to servo tab. Spring assists when control forces become too high in high-speed flight.	Enables moving control surface when forces are high. Inactive during slow flight.

Figure 1-14. Various tabs and their uses.

its surface area and the speed of the air rushing over it. Deflecting a balance tab hinged at the trailing edge of the control surface in the opposite direction of the desired control surface movement causes a force to position the surface in the proper direction with reduced force to do so. Balance tabs are usually linked directly to the control surface linkage so that they move automatically when there is an input for control surface movement. They also can double as trim tabs, if adjustable on the flight deck.

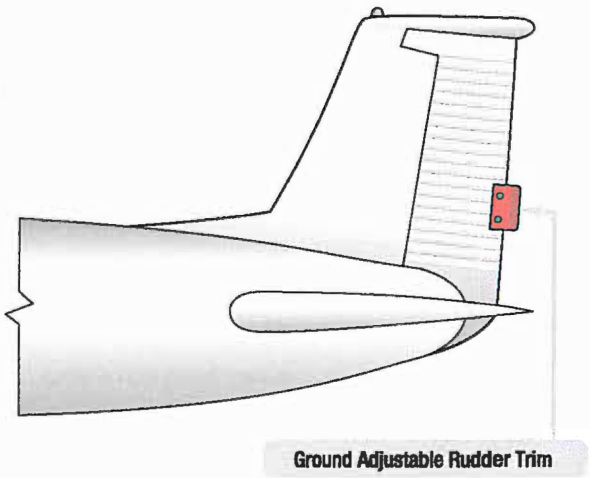


Figure 1-15. Example of a trim tab.

SERVO TABS

A servo tab is similar to a balance tab in location and effect, but it is designed to operate the primary flight control surface, not just reduce the force needed to do so. It is usually used as a means to back up the primary control of the flight control surfaces. (***Figure 1-17***)

On heavy aircraft, large control surfaces require too much force to be moved manually and are usually deflected out of the neutral position by hydraulic actuators. These power control units are signaled via a system of hydraulic valves connected to the yoke and rudder pedals.

On fly by wire aircraft, the hydraulic actuators that move the flight control surfaces are signaled by electric input. In the case of hydraulic system failure(s), manual linkage to a servo tab can be used to deflect it. This, in turn, provides an aerodynamic force that moves the primary control surface.

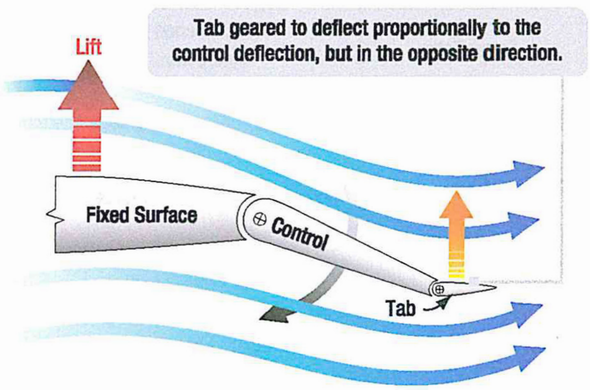


Figure 1-16. Balance tabs assist with forces needed to position control surfaces.

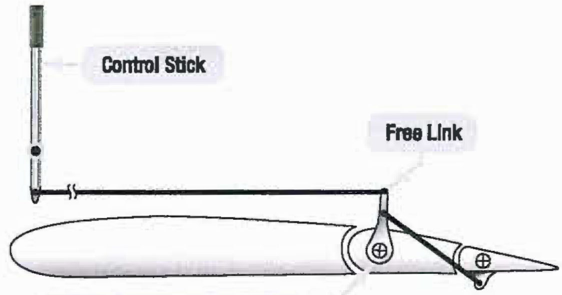


Figure 1-17. Servo tabs can be used to position flight control surfaces in case of hydraulic failure.

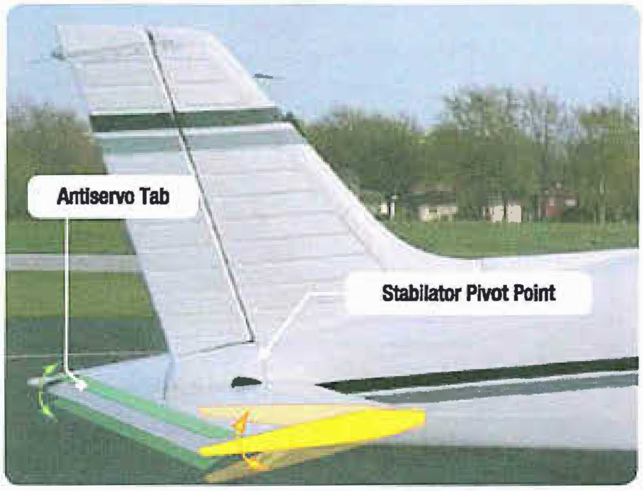


Figure 1-18. An Anti-servo tab moves in the same direction as the control tab. Shown here on a stabilator, it desensitizes the pitch control.

ANTI-SERVO/ANTI-BALANCE TABS

Anti-servo tabs, as the name suggests, are like servo tabs but move in the same direction as the primary control surface. On some aircraft, especially those with a movable horizontal stabilizer, the input to the control surface can be too sensitive. An Anti-servo tab tied through the control linkage creates an aerodynamic force that increases the effort needed to move the control surface. This makes flying the aircraft more stable for the pilot. ***Figure 1-18*** shows an Anti-servo tab in the near neutral position. Deflected in the same direction as the desired stabilator movement, it increases the required control surface input. Anti servo tabs are also known as anti-balance tabs.

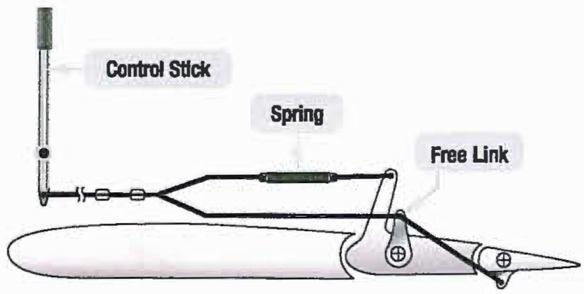


Figure 1-19. Many tab linkages have a spring tab that kicks in as the forces needed to deflect a control increase with speed and the angle of desired deflection.

SPRING TABS

A control surface may require excessive force to move only in the final stages of travel. When this is the case, a spring tab can be used. This is essentially a servo tab that does not activate until an effort is made to move the control surface beyond a certain point. When reached, a spring in line of the control linkage aids in moving the control surface through the remainder of its travel. (***Figure 1-19***)

AERODYNAMIC BALANCE PANELS

Figure 1-20 shows another way of assisting the movement of an aileron on a large aircraft. It is called an aileron balance panel. Not visible when approaching the aircraft, it is positioned in the linkage that hinges the aileron to the wing. Balance panels have been constructed typically of aluminum skin covered frame assemblies or aluminum honeycomb structures. The trailing edge of the wing just forward of the leading edge of the aileron is sealed to allow controlled airflow in and out of the hinge area where the balance panel is located.

MASS BALANCE

Flutter is an undesirable oscillation of an aircraft control surface which can have catastrophic effect on controllability of the aircraft. The center of lift on a control surface should be aft of the control surface center of gravity to prevent control surface flutter. Often, the addition of weight to the forward surface of an aileron, for example, is sufficient to move the CG of the airfoil forward and prevent flutter. Some aircraft designs, however, place the weight on a lever arm that extends forward of the control surface. This is known as a mass balance. Mass balances help prevent flutter and also reduce the required control stick pressure used to move a control surface. (***Figure 1-21***)

CONTROL SURFACE BIAS

When a control surface is in the neutral position, is faired with the wing rudder or horizontal stabilizer and no effect on the aircrafts aerodynamic surfaces. Some aircraft are designed with control surface bias. This means that a control surface is not naturally in the

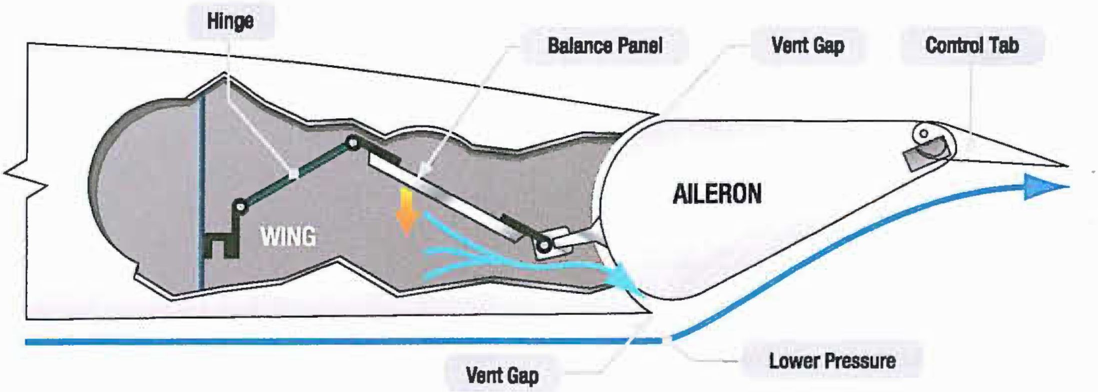


Figure 1-20. An aileron balance panel and linkage uses varying air pressure to assist in control surface positioning.

neutral position. It is designed to impart a force on the airfoil at all times. The force is generally used to counter balance a design imbalance and alter the aircraft's aerodynamics for easy hands off flight. This means that when the aircraft is flying straight and level, the control surface bias has effect but all trim position gauges on the flight deck indicate zero trim.


Figure 1-21. An aileron mass balance.

HIGH LIFT DEVICES

Aircraft wings contain devices that are designed to increase the lift produced by the wing with the devices deployed during certain phases of flight.

FLAPS

Flaps are one such high lift device found on most aircraft. They are usually inboard on the wings' trailing edges adjacent to the fuselage. Leading edge flaps are also common. They extend forward and down from the inboard wing leading edge. The flaps are lowered to increase the camber of the wings and provide greater lift and control at slow speeds. They enable landing at slower speeds and shorten the amount of runway required for takeoff and landing. The amount that the flaps extend and the angle they form with the wing can be selected from the cockpit. Typically, flaps can extend up to 45–50°. ***Figure 1-22*** shows various aircraft with flaps in the extended position.


Figure 1-22. An aileron balance panel and linkage uses varying air pressure to assist in control surface positioning.

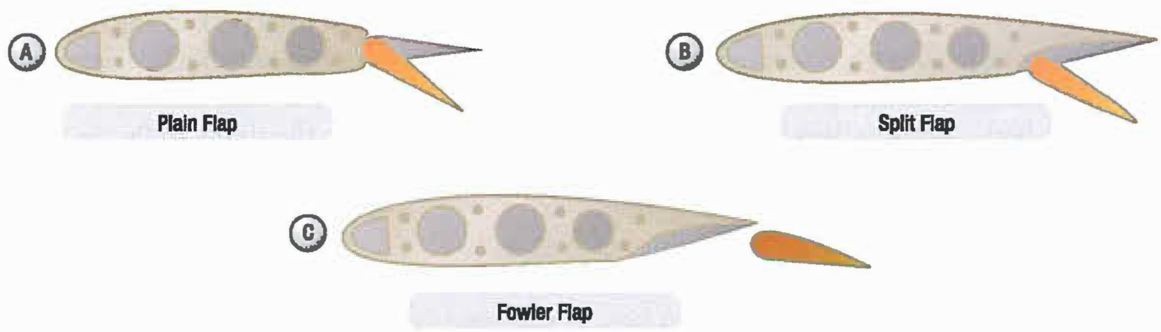


Figure 1-23. Various types of flaps.

Flaps are usually constructed of materials and with techniques used on the other airfoils and control surfaces of a particular aircraft. Aluminum skin and structure flaps are the norm on light aircraft. Heavy and high performance aircraft flaps may also be aluminum, but the use of composite structures is also common.

There are various kinds of flaps. Plain flaps form the trailing edge of the wing when the flap is in the retracted position. (***Figure 1-23A***) The airflow over the wing continues over the upper and lower surfaces of the flap, making the trailing edge of the flap essentially the trailing edge of the wing. The plain flap is hinged so that the trailing edge can be lowered. This increases wing camber and provides greater lift.

A split flap is normally housed under the trailing edge of the wing. (***Figure 1-23B***) It is usually just a braced flat metal plate hinged at several places along its leading edge. The upper surface of the wing extends to the trailing edge of the flap. When deployed, the split flap trailing edge lowers away from the trailing edge of the wing. Airflow over the top of the wing remains the same. Airflow under the wing now follows the camber created by the lowered split flap, increasing lift.

Fowler flaps not only lower the trailing edge of the wing when deployed but also slide aft, effectively increasing the area of the wing. (***Figure 1-23C***) This creates more lift via the increased surface area, as well as the wing camber. When stowed, the fowler flap typically retracts up under the wing trailing edge similar to a split flap. The sliding motion of a fowler flap can be accomplished with a worm drive and flap tracks.

An enhanced version of the fowler flap is a set of flaps that actually contains more than one aerodynamic

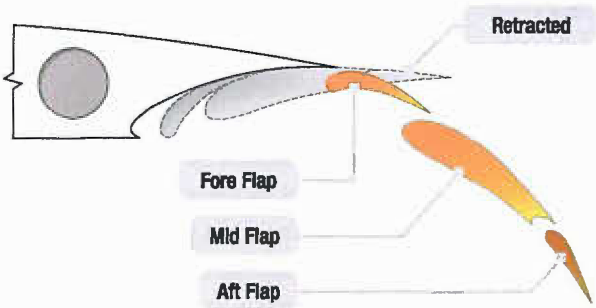


Figure 1-24. Triple slotted flap.

surface. ***Figure 1-24*** shows a triple slotted flap. In this configuration, the flap consists of a fore flap, a mid flap, and an aft flap. When deployed, each flap section slides aft on tracks as it lowers. The flap sections also separate leaving an open slot between the wing and the fore flap, as well as between each of the flap sections. Air from the underside of the wing flows through these slots. The result is that the laminar flow on the upper surfaces is enhanced. The greater camber and effective wing area increase overall lift.

Heavy aircraft often have leading edge flaps that are used in conjunction with the trailing edge flaps. (***Figure 1-25***) They can be made of machined magnesium or can have an aluminum or composite structure.

While they are not installed or operate independently, their use with trailing edge flaps can greatly increase wing camber and lift. When stowed, leading edge flaps retract into the leading edge of the wing.

The differing designs of leading edge flaps essentially provide the same effect. Activation of the trailing edge flaps automatically deploys the leading edge flaps, which are driven out of the leading edge and downward, extending the camber of the wing. ***Figure 1-26*** shows a Krueger flap, recognizable by its flat midsection.

FLAPERONS

Some aircraft are equipped with flaperons. (***Figure 1-27***) Flaperons are ailerons which can also act as flaps. Flaperons combine both aspects of flaps and ailerons. In addition to controlling the bank angle of an aircraft like conventional ailerons, flaperons can be lowered together to function much the same as a dedicated set of flaps. The pilot retains separate controls for ailerons and flaps. A mixer is used to combine the separate pilot inputs into this single set of control surfaces called flaperons. Many designs that incorporate flaperons mount the control surfaces away from the wing to provide undisturbed airflow at high angles of attack and/or low airspeeds.

SLATS

Another leading edge device which extends wing camber is a slat. Slats can be operated independently of the flaps with their own switch in the cockpit. Slats not only extend out of the leading edge of the wing increasing camber and lift, but most often, when fully deployed leave a slot between their trailing edges and the leading edge of the wing. (***Figure 1-28***) This increases the angle of attack at which the wing will maintain its laminar airflow, resulting in the ability to fly the aircraft slower and still maintain control.

SLOTS

A fixed device mounted to extend the leading edge of the wing forward and downward is known as a slot or cuff. (***Figure 1-29***) It essentially increases the camber of the wing and allows the aircraft to fly at slower speeds and higher angles of attack. Moreover, slots reduce the stall speed of the aircraft by mixing high speed air flow exiting the slot with boundary layer air. The result is a delay in boundary layer separation. However, slots increase drag. The benefits of good low speed handling characteristics when weighed against the increased drag that a slot causes at higher speeds limits the use of slots. Full span slots span the full wing from root to tip. They are commonly used on STOL (short takeoff and

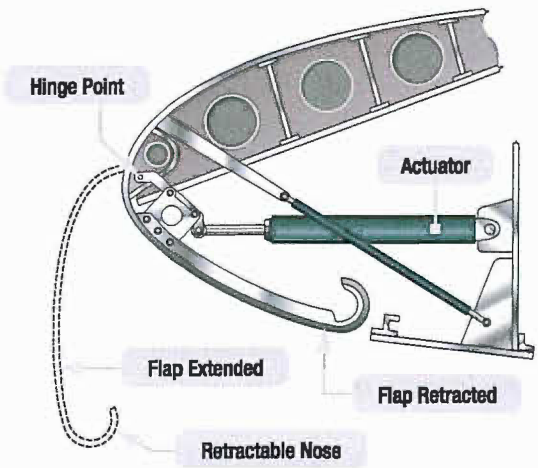


Figure 1-25. Leading edge flaps.

Figure 1-27. Flaperons on a Skystar Kitfox MK 7.

Figure 1-26. Side view (left) and front view (right) of a Krueger flap on a Boeing 737.

landing) aircraft. Partial span slots are positioned on the outboard section of the wing leading edge. This increases the angle of attack at which the outboard wing stalls and ensures that the wing root stalls first. When the wing root stalls first, stall characteristics are docile. Recovery is easier because the partial span slots maintain air flow over the ailerons during the stall.

ELEVONS AND RUDDERVATORS

Elevons perform the combined functions of the ailerons and the elevator. (***Figure 1-30***) They are typically used on aircraft that have no true separate empennage such as a delta wing or flying wing aircraft.

They are installed on the trailing edge of the wing. When moved in the same direction, the elevons cause a pitch adjustment. When moved in opposite directions, the aircraft rolls. Elevons may also move differentially in the same direction causing adjustments to roll and pitch. The control yoke or stick activated elevon movement through a mechanical or electronic mixing device. A ruddervator combines the action of the rudder and elevator. (***Figure 1-31***)

This is possible on aircraft with V–tail empennages where the traditional horizontal and vertical stabilizers do not exist. Instead, two stabilizers angle upward and outward from the aft fuselage in a "V" configuration. Each contains a movable ruddervator built into the trailing edge. Movement of the ruddervators can alter the movement of the aircraft around the horizontal and/or vertical axis.

Figure 1-28. Air passing through the slot aft of the slat promotes boundary layer airflow on the upper surface at high angles of attack.

Figure 1-29. A leading edge slot on a STOL aircraft.

Figure 1-30. Elevons.

Figure 1-31. Ruddervator.

DRAG INDUCING DEVICES

SPOILERS

Spoilers are unique in that they may be fully deployed on both wings to act as speed brakes. The reduced lift and increased drag can quickly reduce the speed of the aircraft in flight. Spoilers are sometimes called lift dumpers.

SPEED BRAKES

Dedicated speed brake panels similar to flight spoilers in construction can be found on the upper surface of the wing trailing edge of heavy and high performance aircraft. They are designed specifically to increase drag and reduce the speed of the aircraft when deployed. These speed brake panels do not operate differentially with the ailerons at low speed like the spoilers.

A speed brake control lever in the cockpit can deploy all spoiler and speed brake surfaces fully when operated. Often, speed brakes surfaces are rigged to deploy on the ground automatically when engine thrust reversers are activated. The location of speed brake panels is visible in ***Figure 1-8***.

BOUNDARY LAYER CONTROLS

The boundary layer is a very thin layer of air lying over the surface of the wing and, for that matter, all other surfaces of the aeroplane. Because air has viscosity, this layer of air tends to adhere to the wing. As the wing moves forward through the air, the boundary layer at first flows smoothly over the streamlined shape of the airfoil. This flow is called the laminar layer. As the boundary layer approaches the center of the wing, it begins to lose speed due to skin friction and it becomes thicker and turbulent. Here it is called the turbulent layer.

The point at which the boundary layer changes from laminar to turbulent is called the transition point. Where the boundary layer becomes turbulent, drag due to skin friction is relatively high. As speed increases, the transition point tends to move forward. As the angle of attack increases, the transition point also tends to move forward. With higher angles of attack and further thickening of the boundary layer, the turbulence becomes so great the air breaks away from the surface of the wing. At this point, the lift of the wing is destroyed and a condition known as a stall has occurred.

In ***Figure 1-32***, view A shows a normal angle of attack and the airflow staying in contact with the wing. View B shows an extreme angle of attack and the airflow separating and becoming turbulent on the top of the wing. In view B, the wing is in a stall.

VORTEX GENERATORS

Vortex generators are small airfoil sections usually attached to the upper surface of a wing. (***Figure 1-33***) They are designed to promote positive laminar airflow over the wing and control surfaces.

Usually made of aluminum and installed in a spanwise line or lines, the vortices created by these devices swirl downward assisting maintenance of the boundary layer of air flowing over the wing. They can also be found on the fuselage and empennage. ***Figure 1-34*** shows the unique vortex generators on a Symphony SA-160 wing.

WING FENCE

A chordwise barrier on the upper surface of the wing, called a wing fence or stall fence, is used to halt the spanwise flow of air along the wing. During low speed flight, this can maintain proper chordwise airflow reducing the tendency for the wing to stall. Usually made of aluminum, the fence is a fixed structure most common on swept wings, which have a natural spanwise tending boundary air flow. (***Figure 1-35***)

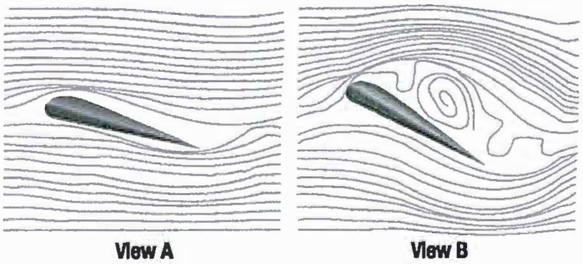


Figure 1-32. Wing boundary layer separation.

Figure 1-33. Vortex generators.

STALL WEDGES
A stall wedge or stall strip is a fixed wedge shaped strip attached spanwise to the wing leading edge. (*Figure 1-36*)

It is located on the inboard section of the wing at such a point that it causes the boundary airflow to become turbulent as the angle of attack increases to a certain point. This purposeful destruction of the boundary airflow as the angle of attack increases causes the root of the wing to stall first. Thus, airflow over the outboard wing section and over the ailerons is preserved during the stall making it easier to recover.

SAWTOOTH LEADING EDGE
A few aircraft have a sawtooth leading edge where, rather than being a smooth continuos surface, the leading edge juts out slightly at a point(s) determined to be beneficial by design engineers. The purpose of the sawtooth wing is to utilize the vortex created by an inboard section of the wing to improve boundary layer flow over an outboard section. This increases lift and resistance to stall. Sawtooth wing leading edges are most common on high performance military aircraft.

WINGTIP VORTICES
Wingtip vortices are caused by the air beneath the wing, which is at the higher pressure, flowing over the wingtip and up toward the top of the wing. The end result is a spiral or vortex that trails behind the wingtip anytime lift is being produced. This vortex is also referred to as wake turbulence, and is a significant factor in determining how closely one aeroplane can follow behind another on approach to land. The wake turbulence of a large aeroplane can cause a smaller aeroplane, if it is following too closely, to be thrown out of control. Vortices from the wingtip as well as the inboard edge of the ailerons and from the horizontal stabilizer are visible on the MD-11 shown in ***Figure 1-37***.

Upwash and downwash refer to the effect an airfoil has on the free airstream. Upwash is the deflection of the oncoming airstream, causing it to flow up and over the wing.

Downwash is the downward deflection of the airstream after it has passed over the wing and is leaving the trailing edge. This downward deflection is what creates the action and reaction described under lift and Newton's third law.

Figure 1-34. The Symphony SA-160 has two unique vortex generators on its wing to ensure aileron effectiveness through the stall.

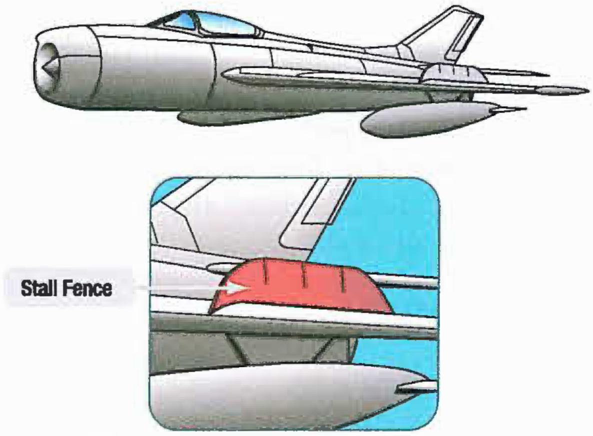


Figure 1-35. A stall fence aids in maintaining chordwise airflow over the wing.

Figure 1-36. A stall wedge causes the wing root to stall before the outboard wing. This preserves airflow over the ailerons for controlled recovery from the stall.

Figure 1-38. A winglet reduces aerodynamic drag caused by air spilling off of the wing tip.

Figure 1-37. Vortices on an MD-11.

WINGLET

A winglet is an obvious vertical upturn of the wing's tip resembling a vertical stabilizer. (*Figure 1-38*) It is an aerodynamic device designed to reduce the drag created by wing tip vortices in flight. Usually made from aluminum or composite materials, winglets can be designed to optimize performance at a desired speed. They use the flow of air from under the wing to create thrust thereby reducing induced drag. Significant fuel savings are also achieved.

HIGH SPEED FLIGHT

SPEED OF SOUND

Sound, in reference to aeroplanes and their movement through the air, is nothing more than pressure disturbances in the air. It is like dropping a rock in the water and watching the waves flow out from the center. As an aeroplane flies through the air, every point on the aeroplane that causes a disturbance creates sound energy in the form of pressure waves. These pressure waves flow away from the aeroplane at the speed of sound, which at standard day temperature of 59°F, is 761 mph.

The speed of sound in air changes with temperature, increasing as temperature increases. *Figure 1-39* shows how the speed of sound changes with altitude.

MACH NUMBER, SUBSONIC, TRANSONIC AND SUPERSONIC FLIGHT

In high speed flight and/or high altitude flight, the measurement of speed is expressed in terms of a "Mach number"—the ratio of the true airspeed of the aircraft to the speed of sound in the same atmospheric conditions. An aircraft traveling at the speed of sound is traveling at Mach 1.0. Aircraft speed regimes are defined approximately as follows:

- Subsonic—Mach numbers below 0.75
- Transonic—Mach numbers from 0.75 to 1.20
- Supersonic—Mach numbers from 1.20 to 5.00
- Hypersonic—Mach numbers above 5.00

When an aeroplane is flying at subsonic speed, all of the air flowing around the aeroplane is at a velocity of less than the speed of sound (known as Mach 1). Keep in mind that the air accelerates when it flows over certain parts of the aeroplane, like the top of the wing, so an aeroplane flying at 500 mph could have air over the top of the wing reach a speed of 600 mph. How fast an aeroplane can fly and still be considered in subsonic flight varies with the design of the wing, but as a Mach number, it will typically be just over Mach 0.8.

When an aeroplane is flying at transonic speed, part of the aeroplane is experiencing subsonic airflow and part is experiencing supersonic airflow. Over the top of the wing the velocity of the air will reach Mach 1 and a shock wave will form. The shock wave forms 90 degrees to the airflow approximately halfway between the leading and trailing edge of the wing. It is known as a normal shock wave. Stability problems can be encountered during transonic flight, because the shock wave can cause the airflow to separate from the wing. The shock wave also causes the center of lift to shift aft, causing the nose to pitch down. The speed at which the shock wave forms is known as the critical Mach number.

When an aeroplane is flying at supersonic speed, the entire aeroplane is experiencing supersonic airflow. At this speed, the shock wave which formed on top of the wing during transonic flight has moved all the way aft and has attached itself to the wing trailing edge. Supersonic speed is from Mach 1.20 to 5.0. If an aeroplane flies faster than Mach 5, it is said to be in hypersonic flight.

SHOCK WAVE

Sound coming from an aeroplane is the result of the air being disturbed as the aeroplane moves through it, and the resulting pressure waves that radiate out from the source of the disturbance. For a slow moving aeroplane, the pressure waves travel out ahead of the aeroplane, traveling at the speed of sound. When the speed of the aeroplane reaches the speed of sound, however, the pressure waves (sound energy) cannot get away from the aeroplane. At this point the sound energy starts to pile up, initially on the top of the wing, and eventually attaching itself to the wing leading and trailing edges. This piling up of sound energy is called a shock wave. If the shock waves reach the ground, and cross the path of a person, they will be heard as a sonic boom. ***Figure 1-40A*** shows a wing in slow speed flight, with many disturbances on the wing generating sound pressure waves that are radiating outward. ***Figure 1-40B*** is the wing of an aeroplane in supersonic flight, with the sound pressure waves piling up toward the wing leading edge.

Altitude In Feet	Temperature (°F)	Speed of Sound (mph)
0	59.00	761
1 000	55.43	758
2 000	51.87	756
3 000	48.30	753
4 000	44.74	750
5 000	41.17	748
6 000	37.60	745
7 000	34.04	742
8 000	30.47	740
9 000	26.90	737
10 000	23.34	734
15 000	5.51	721
20 000	−12.32	707
25 000	−30.15	692
30 000	−47.98	678
35 000	−65.82	663
*36 089	−69.70	660
40 000	−69.70	660
45 000	−69.70	660
50 000	−69.70	660
55 000	−69.70	660
60 000	−69.70	660
65 000	−69.70	660
70 000	−69.70	660
75 000	−69.70	660
80 000	−69.70	660
85 000	−64.80	664
90 000	−56.57	671
95 000	−48.34	678
100 000	−40.11	684

*Altitude at which temperature stops decreasing

Figure 1-39. Altitude and temperature versus speed of sound.

Normal Shock Wave

When an aeroplane is in transonic flight, the shock wave that forms on top of the wing, and eventually on the bottom of the wing, is called a normal shock wave. If the leading edge of the wing is blunted, instead of being rounded or sharp, a normal shock wave will also form in front of the wing during supersonic flight. Normal shock waves form perpendicular to the airstream. The velocity of the air behind a normal shock wave is subsonic, and the static pressure and density of the air are higher. ***Figure 1-41*** shows a normal shock wave forming on the top of a wing.

Oblique Shock Wave

An aeroplane that is designed to fly supersonic will have very sharp edged surfaces, in order to have the least amount of drag. When the aeroplane is in supersonic flight, the sharp leading edge and trailing edge of the

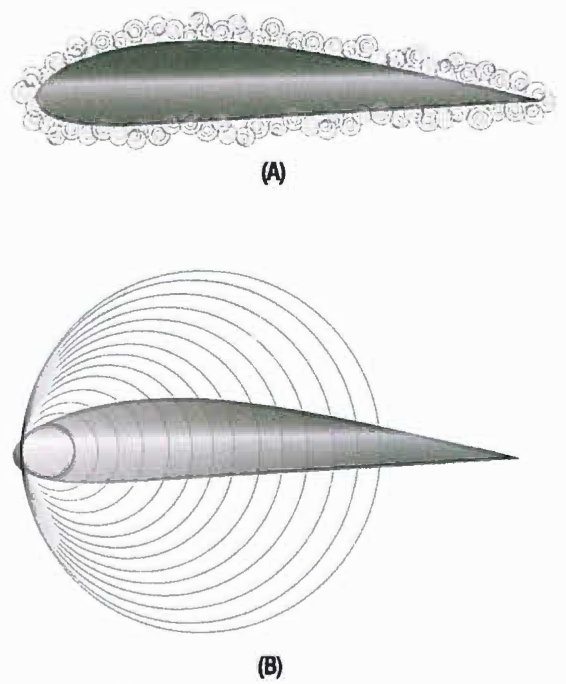


Figure 1-40. Sound energy in subsonic and supersonic flight.

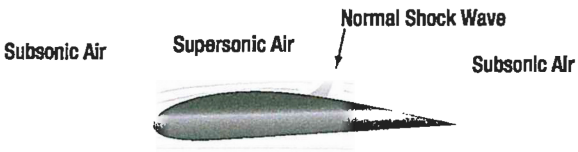


Figure 1-41. Normal shock wave.

wing will have shock waves attach to them. These shock waves are known as oblique shock waves. Behind an oblique shock wave the velocity of the air is lower, but still supersonic, and the static pressure and density are higher. ***Figure 1-42*** shows an oblique shock wave on the leading and trailing edges of a supersonic airfoil.

Expansion Wave

Earlier in the discussion of high speed aerodynamics, it was stated that air at supersonic speed acts like a compressible fluid. For this reason, supersonic air, when given the opportunity, wants to expand outward. When supersonic air is flowing over the top of a wing, and the wing surface turns away from the direction of flow, the air will expand and follow the new direction.

At the point where the direction of flow changes, an expansion wave will occur. Behind the expansion wave the velocity increases, and the static pressure and density decrease. An expansion wave is not a shock wave. ***Figure 1-42*** shows an expansion wave on a supersonic airfoil.

CRITICAL MACH NUMBER

While flights in the transonic and supersonic ranges are common occurrences for military aircraft, civilian jet aircraft normally operate in a cruise speed range of Mach 0.7 to Mach 0.90.

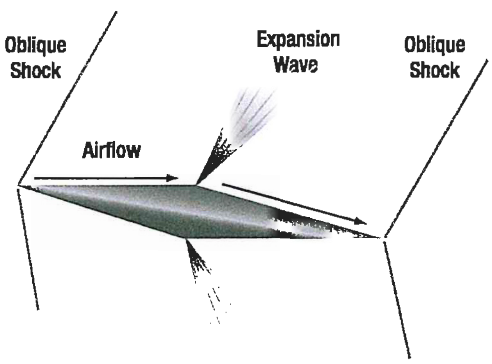


Figure 1-42. Supersonic airfoil with oblique shock waves and expansion waves.

The speed of an aircraft in which airflow over any part of the aircraft or structure under consideration first reaches (but does not exceed) Mach 1.0 is termed "critical Mach number" or "Mach Crit." Thus, critical Mach number is the boundary between subsonic and transonic flight and is largely dependent on the wing and airfoil design. Critical Mach number is an important point in transonic flight. When shock waves form on the aircraft, airflow separation followed by buffet and aircraft control difficulties can occur. Shock waves, buffet, and airflow separation take place above critical Mach number. A jet aircraft typically is most efficient when cruising at or near its critical Mach number.

At speeds 5-10 percent above the critical Mach number, compressibility effects begin. Drag begins to rise sharply. Associated with the "drag rise" are buffet, trim and stability changes, and a decrease in control surface effectiveness. This is the point of "drag divergence." (***Figure 1-43***)

AFFECTS OF SWEEPBACK ON CRITICAL MACH NUMBER

Most of the difficulties of transonic flight are associated with shock wave induced flow separation. Therefore, any means of delaying or alleviating the shock induced separation improves aerodynamic performance. One method is wing sweepback. Sweepback theory is based upon the concept that it is only the component of the airflow perpendicular to the leading edge of the wing that affects pressure distribution and formation of shock waves. (***Figure 1-44***)

On a straight wing aircraft, the airflow strikes the wing leading edge at 90°, and its full impact produces pressure and lift. A wing with sweepback is struck by

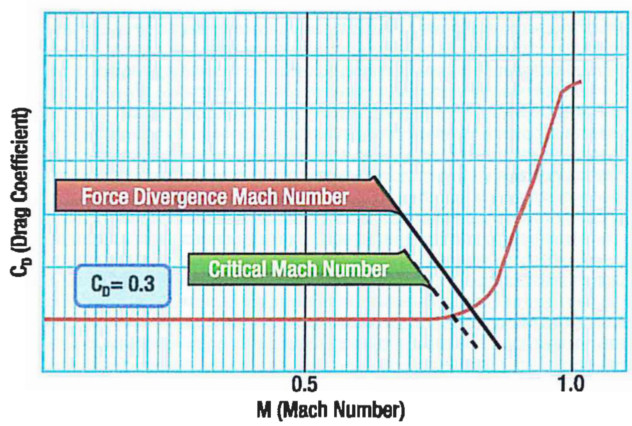


Figure 1-43. Critical Mach.

the same airflow at an angle smaller than 90°. This airflow on the swept wing has the effect of persuading the wing into believing that it is flying slower than it really is; thus the formation of shock waves is delayed.

Advantages of wing sweep include an increase in critical Mach number, force divergence Mach number, and the Mach number at which drag rises peaks. In other words, sweep delays the onset of compressibility effects.

The Mach number, which produces a sharp change in drag coefficient, is termed the "force divergence" Mach number and, for most airfoils, usually exceeds the critical Mach number by 5 to 10 percent. At this speed, the airflow separation induced by shock wave formation can create significant variations in the drag, lift, or pitching moment coefficients.

In addition to the delay of the onset of compressibility effects, sweepback reduces the magnitude in the changes of drag, lift or moment coefficients. In other words, the use of sweepback "softens" the force divergence.

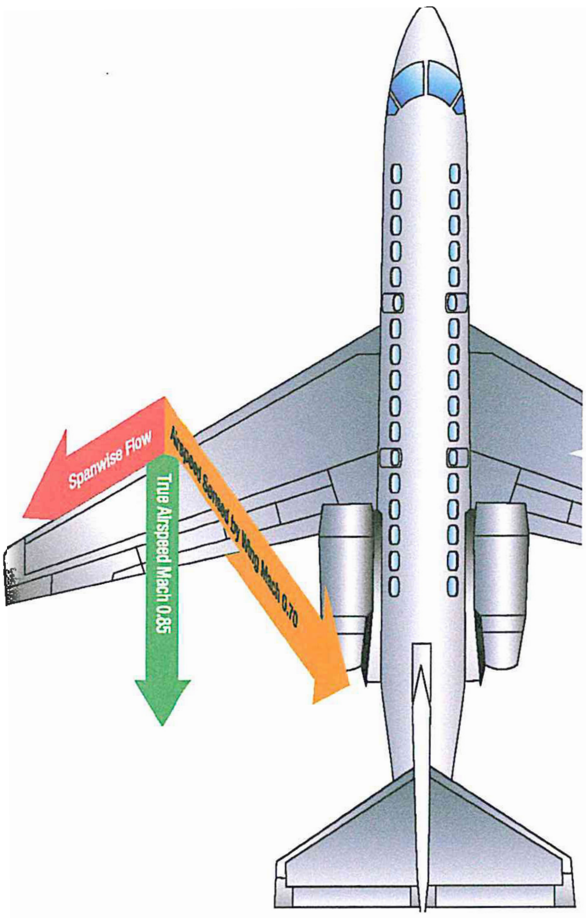


Figure 1-44. Sweepback effect.

COMPRESSIBILITY BUFFET

When air is flowing at subsonic speed, it acts like an incompressible fluid. When air at subsonic speed flows through a diverging shaped passage, the velocity decreases and the static pressure rises, but the density of the air does not change. In a converging shaped passage, subsonic air speeds up and its static pressure decreases. When supersonic air flows through a converging passage, its velocity decreases and its pressure and density both increase. (***Figure 1-45***) At supersonic flow, air acts like a compressible fluid. Because air behaves differently when flowing at supersonic velocity, aeroplanes that fly supersonic must have wings with a different shape.

As stated previously, a pressure wave builds up in front of the aircraft as it approaches Mach 1. However, some localized airflow over the wings reaches Mach 1 before the aircraft reaches this speed. Compressibility buffeting is experience as the airflow is no longer smooth over these areas. Violent vibration can occur causing possible damage to the aircraft and control surfaces as well as a loss of control of the aircraft.

AERODYNAMIC HEATING

One of the problems with aeroplanes and high speed flight is the heat that builds up on the aeroplane's surface because of air friction. When the SR-71 Blackbird aeroplane is cruising at Mach 3.5, skin temperatures on its surface range from 450°F to over 1 000°F. To withstand this high temperature, the aeroplane was constructed of titanium alloy, instead of the traditional aluminum alloy. The supersonic transport Concorde was originally designed to cruise at Mach 2.2, but its cruise speed was reduced to Mach 2.0 because of structural problems that started to occur because of aerodynamic heating. If aeroplanes capable of hypersonic flight are going to be built in the future, one of the obstacles that will have to be overcome is the stress on the aeroplane's structure caused by heat.

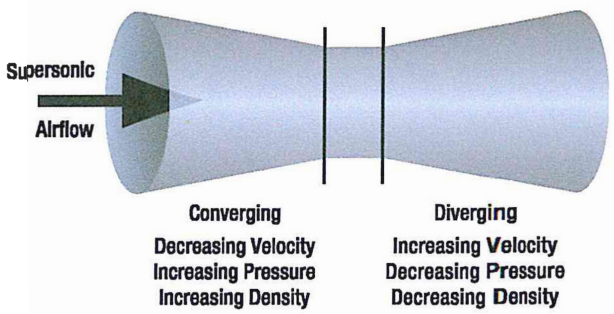


Figure 1-45. Supersonic airflow through a venturi.

AREA RULE

When designing an aircraft for transonic flight, it must be streamlined to keep drag to a minimum. Area rule is technique for doing so. Using area rule, design engineers consider the area of successive cross section slices of the entire aircraft (not just the fuselage) and shape the total cross sectional area of each slice so that together, they produce an streamlined shape. Use of area rule reduces drag, especially where the wings and fuselage come together.

ENGINE INTAKE AIRFLOW OF HIGH SPEED AIRCRAFT

Engine intake airflow on subsonic aircraft must be kept below the critical Mach number. The shape of the engine intake is designed so that air arrives at the first stage of compression at a designed speed for maximum efficiency. This is typically around .5 Mach. A divergent duct cross section slows airflow to the intake on subsonic aircraft. A convergent duct increases intake airflow speed. On supersonic aircraft, the opposite is true. Regardless, engine intake airflow is controlled through the shape of the intake duct and duct air valves operated at particular speeds to result in the proper intake air speed.