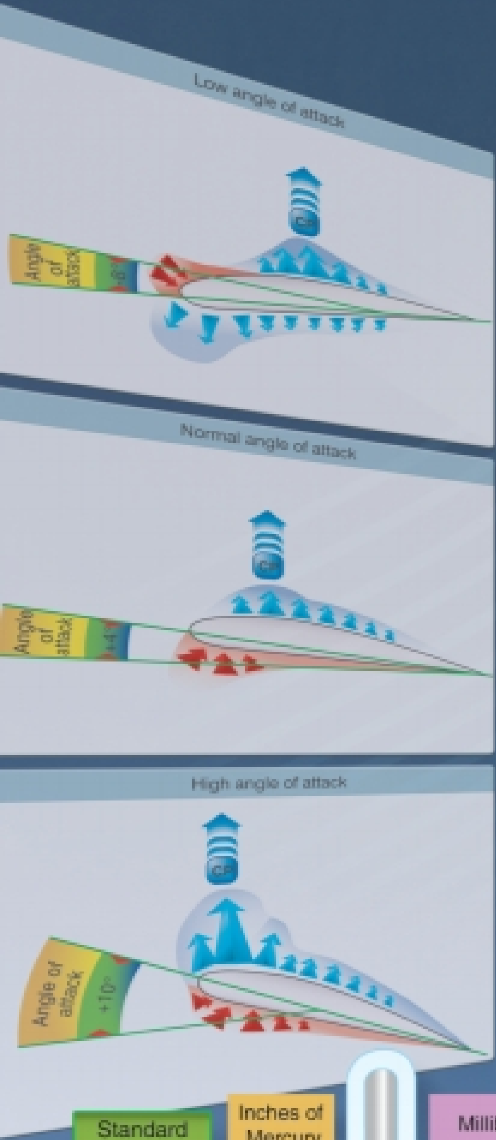
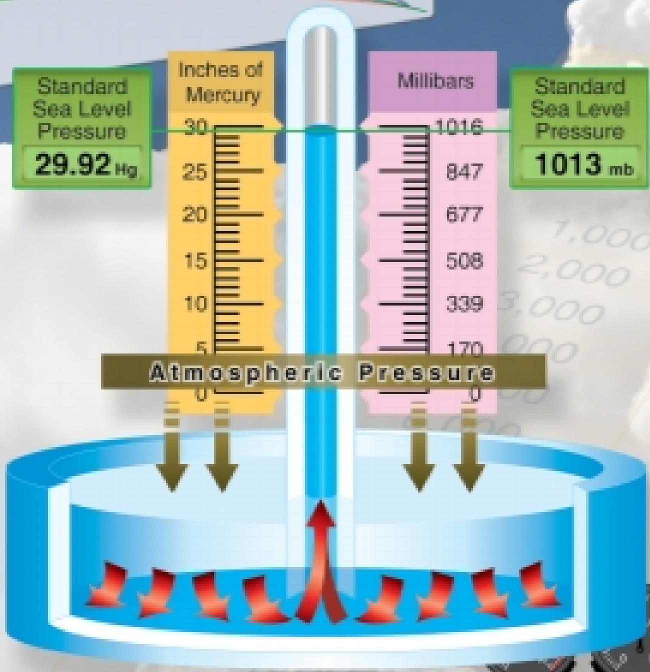
Principles of Flight





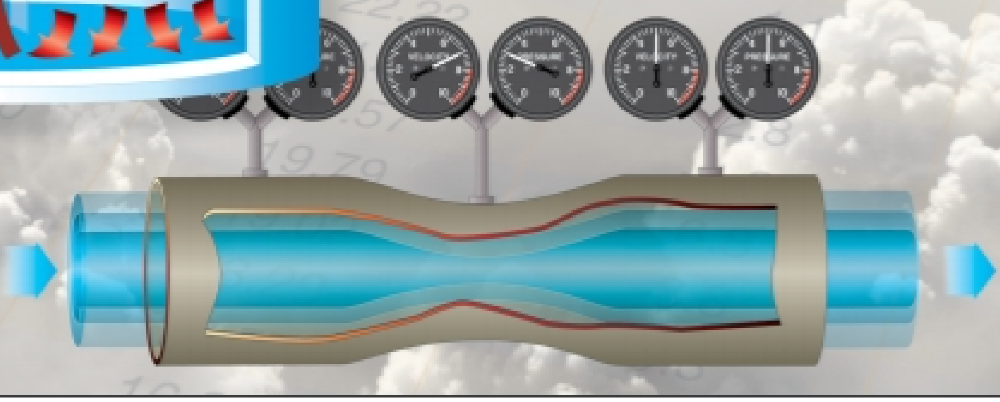
Introduction

This chapter examines the fundamental physical laws governing the forces acting on an aircraft in flight, and what effect these natural laws and forces have on the performance characteristics of aircraft. To control an aircraft, be it an airplane, helicopter, glider, or balloon, the pilot must understand the principles involved and learn to use or counteract these natural forces.

Structure of the Atmosphere

The atmosphere is an envelope of air that surrounds the Earth and rests upon its surface. It is as much a part of the Earth as the seas or the land, but air differs from land and water as it is a mixture of gases. It has mass, weight, and indefinite shape.

The atmosphere is composed of 78 percent nitrogen, 21 percent oxygen, and 1 percent other gases, such as argon or helium. Some of these elements are heavier than others. The heavier elements, such as oxygen, settle to the surface of the Earth, while the lighter elements are lifted up to the region of higher altitude. Most of the atmosphere's oxygen is contained below 35,000 feet altitude.



PRINCIPLES OF FLIGHT

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3. Air, like fluid, is able to flow and change shape when subjected to even minute pressures because it lacks strong molecular cohesion. For example, air completely fills any container into which it is placed, expanding or contracting to adjust its shape to the limits of the container

Atmospheric Pressure

4. Although there are various kinds of pressure, pilots are mainly concerned with atmospheric pressure. It is one of the basic factors in weather changes, helps to lift an aircraft, and actuates some of the important flight instruments. These instruments are the altimeter, airspeed indicator, vertical speed indicator, and manifold pressure gauge.

5. Air is very light, but it has mass and is affected by the attraction of gravity. Therefore, like any other substance, it has weight, and because of its weight, it has force. Since it is a fluid substance, this force is exerted equally in all directions, and its effect on bodies within the air is called pressure. Under standard conditions at sea level, the average pressure exerted by the weight of the atmosphere is approximately 14.70 pounds per square inch (psi) of surface, or 1,013.2 hectopascals (hPa). Its thickness is limited; therefore, the higher the altitude, the less air there is above. For this reason, the weight of the atmosphere at 18,000 feet is one-half what it is at sea level.

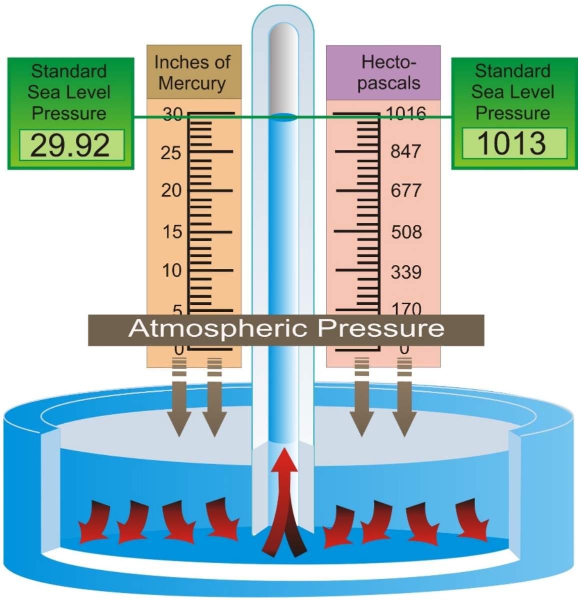


Figure 1.1 Standard Sea Level Pressure

6. The pressure of the atmosphere varies with time and location. Due to the changing atmospheric pressure, a standard reference was developed. The standard atmosphere at sea level is a surface temperature of 15°C and a surface pressure of 1013,25 hectopascals (hPa), or 29.92 inches of

mercury ("Hg) [Figure 1-1]

7. The standard temperature lapse rate is one in which the temperature decreases at the rate of approximately 2°C (1.98°C) per thousand feet up to 36,090 feet which is -56.5°C. Above this point, the temperature is considered constant up to 80,000 feet. The standard pressure lapse rate is a pressure decrease at a rate of approximately 1 hPa per 30 feet of altitude gain to 8,000 feet. [Figure 1-2] The International Civil Aviation Organization (ICAO) has established this as a worldwide standard, and it is often referred to as International Standard Atmosphere (ISA) or ICAO Standard Atmosphere. Any temperature or pressure that differs from the standard lapse rates is considered non-standard temperature and pressure.

Standard Atmosphere		
Altitude (ft)	Pressure (hPa)	Temperature (°C)
0	1013.25	15.0
1 000	977.2	13.02
2 000	942.1	11.04
3 000	908.1	9.06
4 000	875.1	7.08
5 000	843.1	5.09
6 000	812.0	3.11
7 000	781.9	1.13
8 000	752.6	-0.85
9 000	724.3	-2.83
10 000	696.8	-4.81
11 000	670.2	-6.79
12 000	644.4	-8.77
13 000	619.4	-10.76
14 000	595.2	-12.74
15 000	571.8	-14.72
16 000	549.2	-16.70
17 000	527.2	-18.68
18 000	506.0	-20.66
19 000	485.5	-22.64
20 000	465.6	-24.62

Figure 1.2 Standard Atmosphere Characteristics

8. Since aircraft performance is compared and evaluated with respect to the standard atmosphere, all aircraft instruments are calibrated for the standard atmosphere. In order to account properly for the nonstandard atmosphere, certain related terms must be defined.

Pressure Altitude

9. Pressure altitude is the height above a standard datum plane (SDP), which is a theoretical level where the weight of the atmosphere is 1,013.25hPa (29.92"Hg) as measured by a barometer. An altimeter is essentially a sensitive barom eter calibrated to indicate altitude in the standard atmosphere. If the altimeter is set for 1013,25 hPa, the altitude indicated is the pressure altitude. As atmospheric pressure changes, the SDP may be below, at, or above sea level. Pressure altitude is important as a basis for determining aeroplane performance, as well as for assigning flight levels to aeroplanes operating above transition altitude.

10. The pressure altitude can be determined by either of two methods:

a. Setting the barometric scale of the altimeter to 1013,25 hPa and reading the indicated altitude.

b. Applying a correction factor to the indicated altitude according to the reported altimeter setting.

Density Altitude

11. SDP is a theoretical pressure altitude, but aircraft operate in a nonstandard atmosphere and the term density altitude is used for correlating aerodynamic performance in the nonstandard atmosphere. Density altitude is the vertical distance above sea level in the standard atmosphere at which a given density is to be found. The density of air has significant effects on the aircraft's perform ance because as air becomes less dense, it reduces:

- Power, because the engine takes in less air.
- Thrust, because a propeller is less efficient in thin air.
- Lift, because the thin air exerts less force on the aerofoils.

12. Density altitude is pressure altitude corrected for non-standard temperature. As the density of the air increases (lower density altitude), aircraft performance increases and conversely as air density decreases

(higher density altitude), aircraft perform ance decreases. A decrease in air density means a high density altitude; an increase in air density means a lower density altitude. Density altitude is used in calculating aircraft performance, because under standard atmospheric conditions, air at each level in the atmosphere not only has a specific density, its pressure altitude and density altitude identify the same level.

13. The computation of density altitude involves consideration of pressure (pressure altitude) and temperature. Since aircraft performance data at any level is based upon air density under standard day conditions, such performance data apply to air density levels that may not be identical with altim eter indications. Under conditions higher or lower than standard, these levels cannot be determined directly from the altimeter.

14. Density altitude is determined by first finding pressure altitude, and then correcting this altitude for nonstandard temperature variations. Since density varies directly with pressure, and inversely with temperature, a given pressure altitude may exist for a wide range of temperature by allowing the density to vary. However, a known density occurs for any one temperature and pressure altitude. The density of the air has a pronounced effect on aircraft and engine performance. Regardless of the actual altitude at which the aircraft is operating, it will perform as though it were operating at an altitude equal to the existing density altitude.

15. Air density is affected by changes in altitude, temperature, and humidity. High density altitude refers to thin air while low density altitude refers to dense air. The conditions that result in a high density altitude are high elevations, low atmospheric pressures, high temperatures, high humidity, or some combination of these factors. Lower elevations, high atm ospheric pressure, low temperatures, and low humidity are more indicative of low density altitude.

Effect of Pressure on Density

16. Since air is a gas, it can be compressed or expanded. W hen air is compressed, a greater amount of air can occupy a given volume. Conversely, when pressure on a given volume of air is decreased, the air expands and occupies a greater space. At a lower pressure, the original column of air contains a smaller mass of air. The density is decreased because density is directly proportional to pressure. If the pressure is doubled, the density is doubled; if the pressure is lowered, the density is lowered. This statement is true only at a constant temperature.

Effect of Temperature on Density

17. Increasing the temperature of a substance decreases its density. Conversely, decreasing the temperature increases the density. Thus, the density of air varies inversely with temperature. This statement is true only at a constant pressure. In the atmosphere, both temperature and pressure decrease with altitude, and have conflicting effects upon density. However, the fairly rapid drop in pressure as altitude is increased usually has the dominating effect. Hence, pilots can expect the density to decrease with altitude.

Effect of Humidity (Moisture) on Density

18. The preceding paragraphs refer to air that is perfectly dry. In reality, it is never completely dry. The small amount of water vapour suspended in the atmosphere may be almost negligible under certain conditions, but in other conditions humidity may become an important factor in the performance of an aircraft. W ater vapour is lighter than air; consequently, moist air is lighter than dry air. Therefore, as the water content of the air increases, the air becomes less dense, increasing density altitude and decreasing performance. It is lightest or least dense when, in a given set of conditions, it contains the maximum amount of water vapour.

19. Humidity, also called relative humidity, refers to the amount of water vapour contained in the atmosphere, and is expressed as a percentage of the maximum amount of water vapour the air can hold. This amount varies with temperature. W arm air holds more water vapour, while colder air holds less. Perfectly dry air that contains no water vapour has a relative humidity of zero percent, while saturated air, which cannot hold any more water vapour, has a relative humidity of 100 percent. Humidity alone is usually not considered an important factor in calculating density altitude and aircraft performance, but it does contribute.

21. As temperature increases, the air can hold greater amounts of water vapour. W hen comparing two separate air masses, the first warm and moist (both qualities tending to lighten the air) and the second cold and dry (both qualities making it heavier), the first must be less dense than the second. Pressure, temperature, and humidity have a great influence on aircraft performance because of their effect upon density.

Theories in the Production of Lift

Newton's Basic Laws of Motion

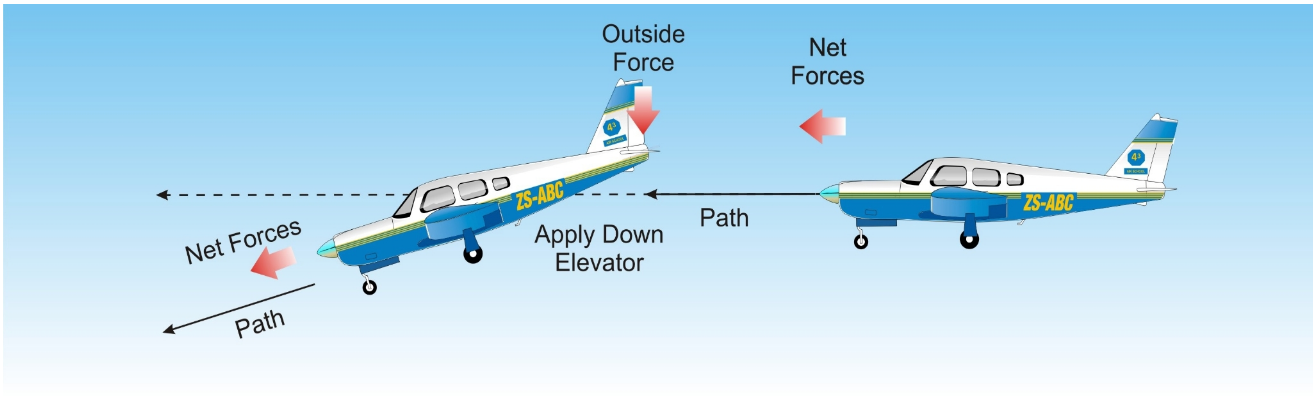


Figure 1.3 Newton's First Law of Motion : The Law of Inertia

22. The formulation of lift has historically been the adaptation over the past few centuries of basic physical laws. These laws, although seem ingly applicable to all aspects of lift, do not answer how lift is formulated. In fact, one must consider the many aerofoils that are symmetrical, yet produce significant lift.

23. The fundamental physical laws governing the forces acting upon an aircraft in flight were adopted from postulated theories developed before any human successfully flew an aircraft. The use of these physical laws grew out of the Scientific Revolution, which began in Europe in the 1600s. Driven by the belief the universe operated in a predictable manner open to hum an understanding, m any p h ilo s o p h e r s , mathematicians, natural scientists, and inventors spent their lives unlocking the secrets of the universe. One of the best known was Sir Isaac Newton, who not only formulated the law of universal gravitation, but also described the three basic laws of motion.

24. Newton's First Law: "Every object persists in its state of rest or uniform motion in a straight line unless it is compelled to change that state by forces impressed on it."

25 This means that nothing starts or stops moving until some outside force causes it to do so. An aircraft at rest on the ramp remains at rest unless a force strong enough to overcome its inertia is applied. Once it is moving, its inertia keeps it moving, subject to the various other forces acting on it. These forces may add to its motion, slow it down, or change its direction.

26. Newton's Second Law: "Force is equal to the change in momentum per change in time. For a constant mass, force = mass x acceleration."

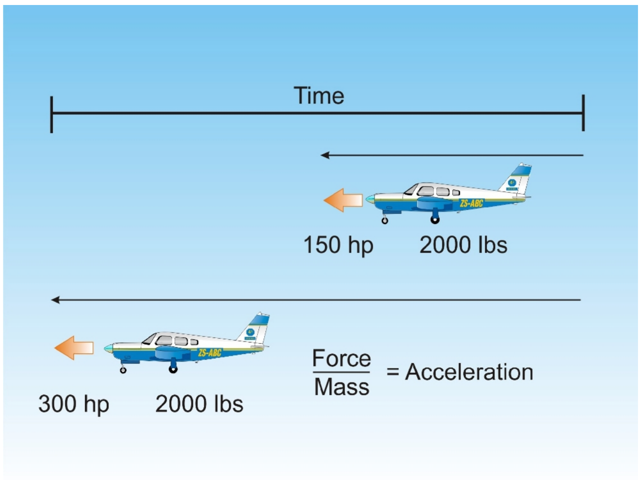


Figure 1.4 Newton's Second Law of Motion

27. When a body is acted upon by a constant force, its resulting acceleration is inversely proportional to the mass of the body and is directly proportional to the applied force. This takes into account the factors involved in overcoming Newton's First Law. It covers both changes in direction and speed, including starting up from rest (positive acceleration) and coming to a stop (negative acceleration or deceleration).

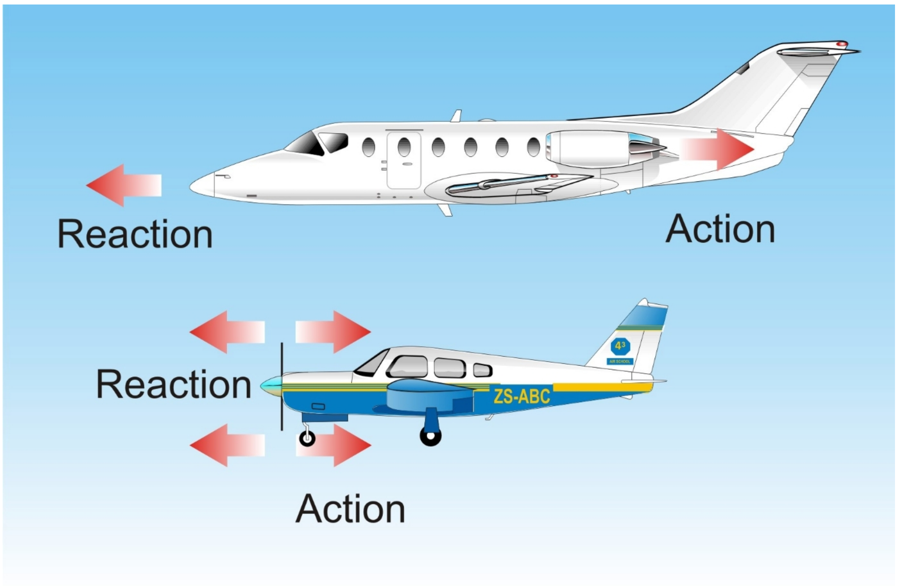


Figure 1.5 Newton's Third Law of Motion

28. Newton's Third Law: "For every action, there is an equal and opposite reaction."

29. In an aeroplane, the propeller moves and pushes back the air; consequently, the air pushes the propeller (and thus the aeroplane) in the opposite direction - forward. In a jet aeroplane, the engine pushes a blast of hot gases backward; the force of equal and opposite reaction pushes against the engine and forces the aeroplane forward.

Magnus Effect

30. In 1852, the German physicist and chemist, Heinrich Gustav Magnus (1802–1870), made experimental studies of the aerodynamic forces on spinning spheres and cylinders. (The effect had already been mentioned by Newton in 1672, apparently in regard to spheres or tennis balls). These experiments led to the discovery of the Magnus Effect, which helps explain the theory of lift.

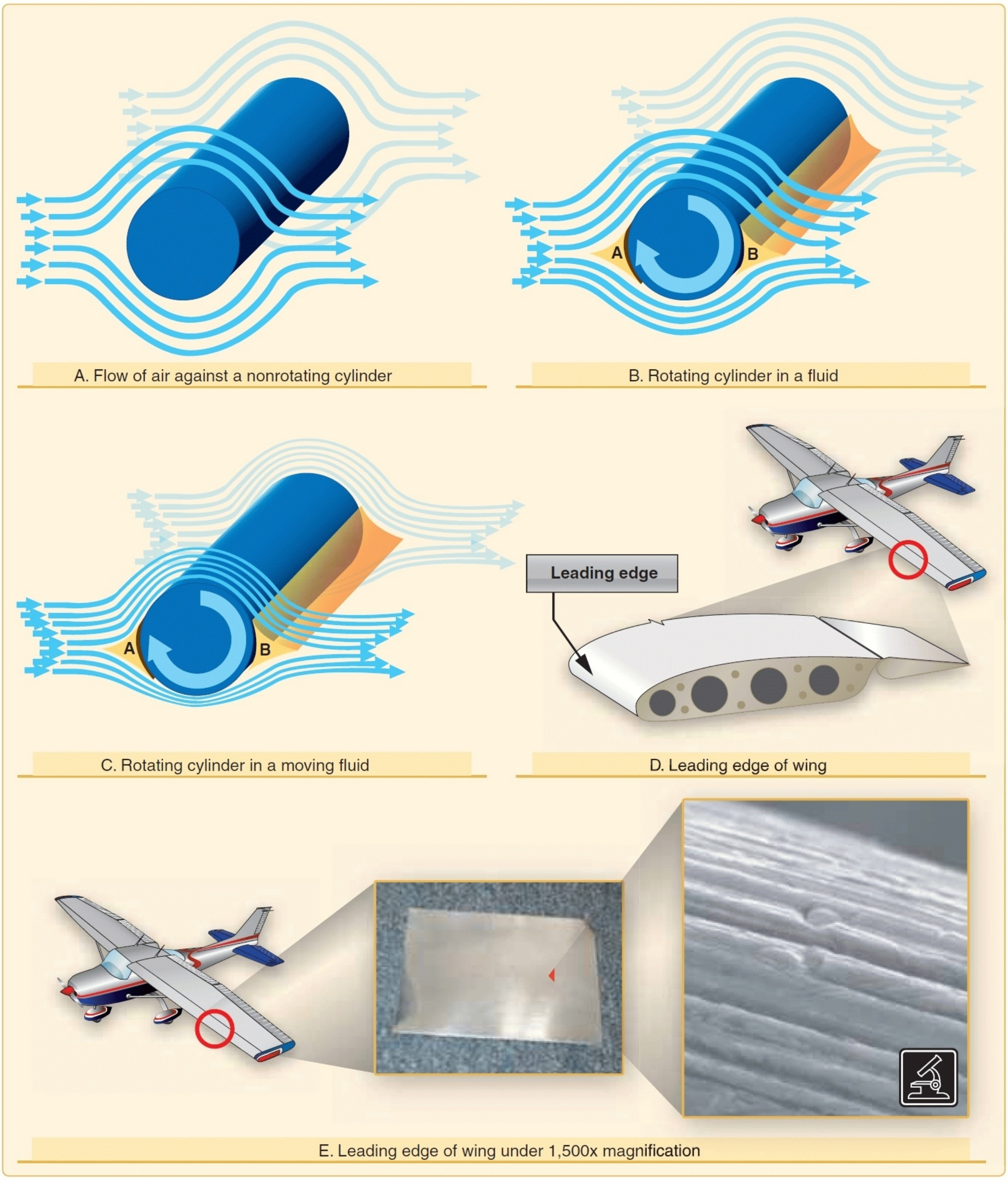


Figure 1.5 Airflow Circulation

Figure 1.5 A illustrates uniform circulation. B illustrates the increased airflow over the top of a rotating cylinder. The airflow speed is further increased when the rotating cylinder is in a moving stream of air (C). The air molecules near the surface of an object are slowed and almost stationary. D is an example of typical aircraft grade aluminum used in aircraft construction to include wings and leading edges of wings as shown in E (left). When magnified at 1,500x (E, right), polished aluminum is visibly rough. This demonstrates why airflow is affected by molecular irregularities of the surface.

Flow of Air Against a Non-rotating Cylinder

31. If air flows against a cylinder that is not rotating, the flow of air above and below the cylinder is identical and the forces are the same. [Figure1.5A]

A Rotating Cylinder in a Motionless Fluid

32. In Figure 1.5B, the cylinder is rotated clockwise and observed from the side while immersed in a fluid. The rotation of the cylinder affects the fluid surrounding the cylinder. The flow around the rotating cylinder differs from the flow around a stationary cylinder due to resistance caused by two factors: viscosity and friction.

Viscosity

33. Viscosity is the property of a fluid or semifluid that causes it to resist flowing. This resistance to flow is measurable due to the molecular tendency of fluids to adhere to each other to some extent. High-viscosity fluids resist flow; low-viscosity fluids flow easily.

34. Similar amounts of oil and water poured down two identical ramps demonstrate the difference in viscosity. The water seems to flow freely while the oil flows much more slowly. Since molecular resistance to motion underlies viscosity, grease is very viscous because its molecules resist flow. Hot lava is another example of a viscous fluid. All fluids are viscous and have a resistance to flow whether this resistance is observed or not. Air is an example of a fluid whose viscosity can not be observed.

35. Since air has viscosity properties, it will resist flow to some extent. In the case of the rotating cylinder within an immersed fluid (oil, water, or air), the fluid (no matter what it is) resists flowing over the cylinder's surface.

Friction

36. Friction is the second factor at work when a fluid flows around a rotating cylinder. Friction is the resistance one surface or object encounters when moving over another and exists between a fluid and the surface over which it flows. If identical fluids are poured down the ramp, they flow in the same manner and at the same speed. If one ramp's surface is coated with small pebbles, the flow down the two ramps differs significantly. The rough surface ramp impedes the flow of the fluid due to resistance from the surface (friction). It is important to remember that all surfaces, no matter how smooth they appear, are not smooth and impede the flow of a fluid. Both the surface of a wing and the rotating cylinder have a certain roughness, albeit at a microscopic level, causing resistance for a fluid to flow. This reduction in velocity of the airflow about a surface is caused by skin friction or drag.

37. W hen passing over a surface, m olecules actually adhere (stick, cling) to the surface, illustrated by the rotating cylinder in a fluid that is not moving. Thus,

a. In the case of the rotating cylinder, air particles near the surface that resist motion have a relative velocity near zero. The roughness of the surface impedes their motion.

b. Due to the viscosity of the fluid, the molecules on the surface entrain, or pull, the surrounding flow above it in the direction of rotation due to the adhesion of the fluid to itself.

38. There is also a difference in flow around the rotating cylinder and in flow around a non-rotating cylinder. The molecules at the surface of the rotating cylinder are not in motion relative to the cylinder; they are moving clockwise with the cylinder. Due to viscosity, these molecules entrain others above them resulting in an increase in fluid flow in the clockwise direction. Substituting air for other fluids results in a higher velocity of air movement above the cylinder simply because more molecules are moving in a clockwise direction.

A Rotating Cylinder in a Moving Fluid

39. W hen the cylinder rotates in a fluid that is also moving, the result is a higher circulatory flow in the direction of the rotating cylinder. [Figure 1.5C] By adding fluid motion, the magnitude of the flow increases.

40. The highest differences of velocity are 90° from the relative motion between the cylinder and the airflow. Additionally, and as shown in Figure 1.6, at point "A," a stagnation point exists where the air stream impacts (impinges) on the front of the aerofoil's surface and splits; some air goes over and some

under. Another stagnation point exists at "B," where the two airstreams rejoin and resume at identical velocities. When viewed from the side, an upwash is created ahead of the aerofoil and downwash at the rear.

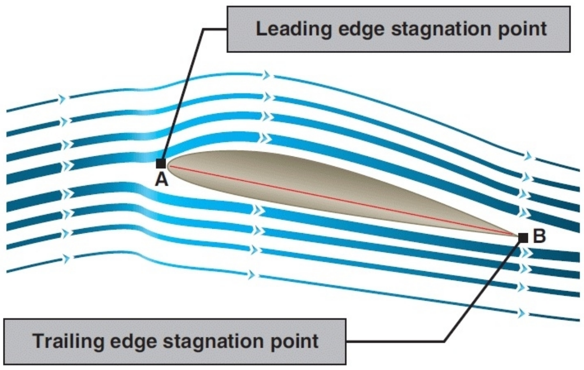


Figure 1.6 Airflow Circulation Around an Aerofoil Section

Air circulation around an aerofoil occurs when the front stagnation point is below the leading edge and the aft stagnation point is beyond the trailing edge.

40. In the case of Figure 1.6, the highest velocity is at the top of the aerofoil with the lowest velocity at the bottom. Because these velocities are associated with an object (in this case, an aerofoil) they are called local velocities as they do not exist outside the lift-producing system, in this case an aerofoil. This concept can be readily applied to a wing or other lifting surface. Because there is a difference of velocity above and below the wing, the result is a higher pressure at the bottom of the wing and a lower pressure on the top of the wing.

41. This low-pressure area produces an upward force known as the Magnus Effect, the physical phenomenon whereby an object's rotation affects its path through a fluid, to include air. Two early aerodynamicists, Martin Kutta and Nicolai Joukowski, eventually measured and calculated the forces for the lift equation on a rotating cylinder (the Kutta-Joukowski theorem).

42. To summarize the Magnus effect, an aerofoil with a positive AOA develops air circulation about the upper surface of the wing. Its sharp trailing edge forces the rear stagnation point to be aft of the trailing edge, while the front stagnation point falls below the leading edge. [Figure 1.6]

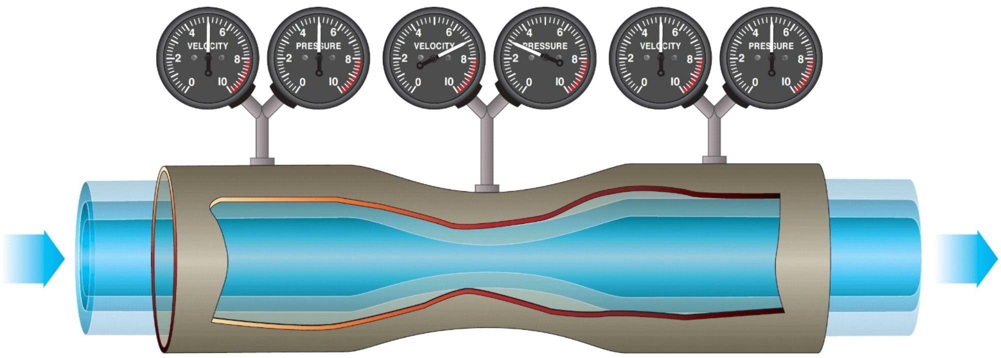


Figure 1.7 Air pressure decreases in a venturi tube

Bernoulli's Principle of Differential Pressure

43. A half-century after Newton formulated his laws, Daniel Bernoulli, a Swiss mathematician, explained how the pressure of a moving fluid (liquid or gas) varies with its speed of motion. Bernoulli's Principle states that as the velocity of a moving fluid (liquid or gas) increases, the pressure within the fluid decreases. This principle explains what happens to air passing over the curved top of the aeroplane wing. A practical application of Bernoulli's Principle is the venturi tube. The venturi tube has an air inlet that narrows to a throat (constricted point) and an outlet section that increases in diameter toward the rear. The

diameter of the outlet is the same as that of the inlet. At the throat, the airflow speeds up and the pressure decreases; at the outlet, the airflow slows and the pressure increases. [Figure 1.7]

44. Since air is recognized as a fluid and it is accepted that it must follow the above laws, one can begin to see how and why an aeroplane wing develops lift. As the wing moves through the air, the flow of air across the curved top surface increases in velocity creating a low-pressure area.

45. Although Newton, Magnus, Bernoulli, and hundreds of other early scientists who studied the physical laws of the universe did not have the sophisticated laboratories available today, they provided great insight to the contemporary viewpoint of how lift is created.

Aerofoil Design

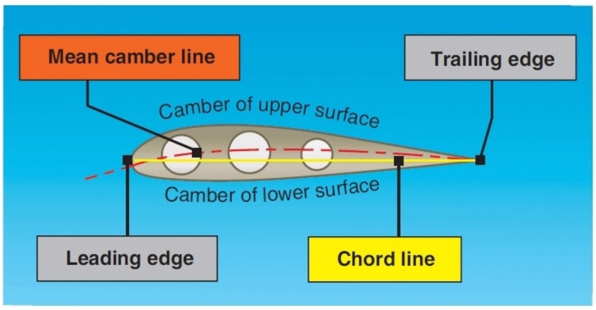


Figure 1.8 Typical aerofoil section

46. An aerofoil is a structure designed to obtain reaction upon its surface from the air through which it moves or that moves past such a structure. Air acts in various ways when submitted to different pressures and velocities; but this discussion is confined to the parts of an aircraft that a pilot is most concerned with in flight—namely, the aerofoils designed to produce lift. By looking at a typical aerofoil profile, such as the cross section of a wing, one can see several obvious characteristics of design. [Figure 1.8] Notice that there is a difference in the curvatures (called cambers) of the upper and lower surfaces of the aerofoil. The camber of the upper surface is more pronounced than that of the lower surface, which is usually somewhat flat.

NOTE: The two extremities of the aerofoil profile also differ in appearance. The end, which faces forward in flight, is called the leading edge, and is rounded; the other end, the trailing edge, is quite narrow and tapered.

47. A reference line often used in discussing the aerofoil is the chord line, a straight line drawn through the profile connecting the extremities of the leading and trailing edges. The distance from this chord line to the upper and lower surfaces of the wing denotes the magnitude of the upper and lower camber at any point. Another reference line, drawn from the leading edge to the trailing edge, is the mean camber line. This mean line is equidistant at all points from the upper and lower surfaces. An aerofoil is constructed in such a way that its shape takes advantage of the air's response to certain physical laws. This develops two actions from the air mass: a positive pressure lifting action from the air mass below the wing, and a negative pressure lifting action from lowered pressure above the wing.

48. As the air stream strikes the relatively flat lower surface of a wing or rotor blade when inclined at a small angle to its direction of motion, the air is forced to rebound downward, causing an upward reaction in positive lift. At the same time, the air stream striking the upper curved section of the leading edge is deflected upward. An aerofoil is shaped to cause an action on the air, and forces air downward, which provides an equal reaction from the air, forcing the aerofoil upward. If a wing is constructed so that it causes a lift force greater than the weight of the aircraft, the aircraft will fly. If all the lift required were obtained merely from the deflection of air by the lower surface of the wing, an aircraft would only need a flat wing like a kite. However, the balance of the lift needed to support the aircraft comes from the flow of air above the wing. Herein lies the key to flight.

49. It is neither accurate nor useful to assign specific values to the percentage of lift generated by the upper surface of an aerofoil versus that generated by the lower surface. These are not constant values and vary, not only with flight conditions, but also with different wing designs.

50. Different aerofoils have different flight characteristics. Many thousands of aerofoils have been tested in wind tunnels and in actual flight, but no one aerofoil has been found that satisfies every flight requirement. The weight, speed, and purpose of each aircraft dictate the shape of its aerofoil. The most efficient aerofoil for producing the greatest lift is one

that has a concave, or “scooped out” lower surface. As a fixed design, this type of aerofoil sacrifices too much speed while producing lift and is not suitable for high-speed flight. Advancements in engineering have made it possible for today’s high-speed jets to take advantage of the concave aerofoil’s high lift characteristics. Leading edge (Kreuger) flaps and trailing edge (Fowler) flaps, when extended from the basic wing structure, literally change the aerofoil shape into the classic concave form, thereby generating much greater lift during slow flight conditions.

51. On the other hand, an aerofoil that is perfectly streamlined and offers little wind resistance sometimes does not have enough lifting power to take the aeroplane off the ground. Thus, modern aeroplanes have aerofoils that strike a medium between extremes in design. The shape varies according to the needs of the aeroplane for which it is designed. Figure 1.9 shows some of the more common aerofoil sections.

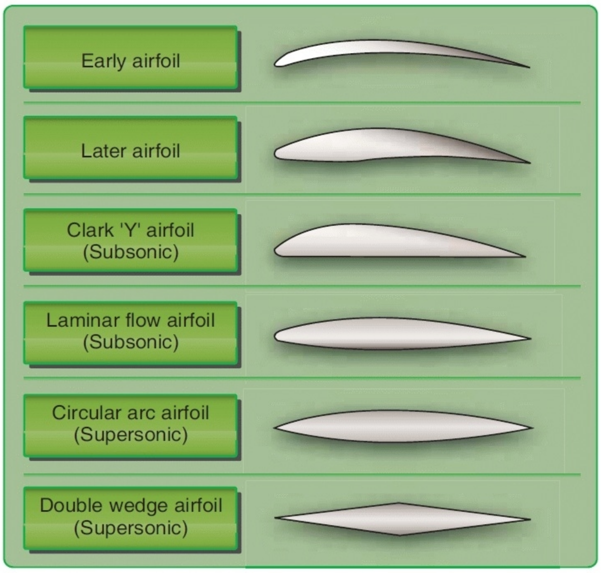


Figure 1.9 Common Aerofoil Sections

Low Pressure Above

52. In a wind tunnel or in flight, an aerofoil is simply a streamlined object inserted into a moving stream of air. If the aerofoil profile were in the shape of a teardrop, the speed and the pressure changes of the air passing over the top and bottom would be the same on both sides. But if the teardrop shaped aerofoil were cut in half lengthwise, a form resembling the basic aerofoil (wing) section would result. If the aerofoil were then inclined so the airflow strikes it at an angle (angle of attack -AOA), the air moving over the upper surface would be forced to move faster than the air moving along the bottom of the aerofoil. This increased velocity reduces the pressure above the aerofoil. Applying Bernoulli’s Principle of Pressure, the increase in the speed of the air across the top of an aerofoil produces a drop in pressure. This lowered pressure is a component of total lift. The pressure difference between the upper and lower surface of a wing alone does not account for the total lift force produced.

53. The downward backward flow from the top surface of an aerofoil creates a downwash. This downwash meets the flow from the bottom of the aerofoil at the trailing edge. Applying Newton’s third law, the reaction of this downward backward flow results in an upward forward force on the aerofoil.

High Pressure Below

54. A certain amount of lift is generated by pressure conditions underneath the aerofoil. Because of the manner in which air flows underneath the aerofoil, a positive pressure results, particularly at higher angles of attack. But there is another aspect to this airflow that must be considered. At a point close to the leading edge, the airflow is virtually stopped (stagnation point) and then gradually increases speed. At some point near the trailing edge, it again reaches a velocity equal to that on the upper surface. In conformance with Bernoulli’s principle, where the airflow was slowed beneath the aerofoil, a positive upward pressure was created i.e., as the fluid speed decreases, the pressure must increase. Since the pressure differential between the upper and lower surface of the aerofoil increases, total lift increases. Both Bernoulli’s Principle and Newton’s Laws are in operation whenever lift is being generated by an aerofoil.

Pressure Distribution

55. From experiments conducted on wind tunnel models and on full size aeroplanes, it has been determined that as air flows along the surface of a wing at different angles of attack, there are regions along the surface where the pressure is negative, or less than atmospheric, and regions where the pressure is positive, or greater than atmospheric. This negative pressure on the upper surface creates a relatively larger force on the wing than is caused by the positive

pressure resulting from the air striking the lower wing surface. Figure 1.10 shows the pressure distribution along an aerofoil at three different angles of attack. The average of the pressure variation for any given angle of attack is referred to as the centre of pressure (CP). Aerodynamic force acts through this CP. At high angles of attack, the CP moves forward, while at low angles of attack the CP moves aft. In the design of wing structures, this CP travel is very important, since it affects the position of the air loads imposed on the wing structure in both low and high AOA conditions. An aeroplane's aerodynamic balance and controllability are governed by changes in the CP.

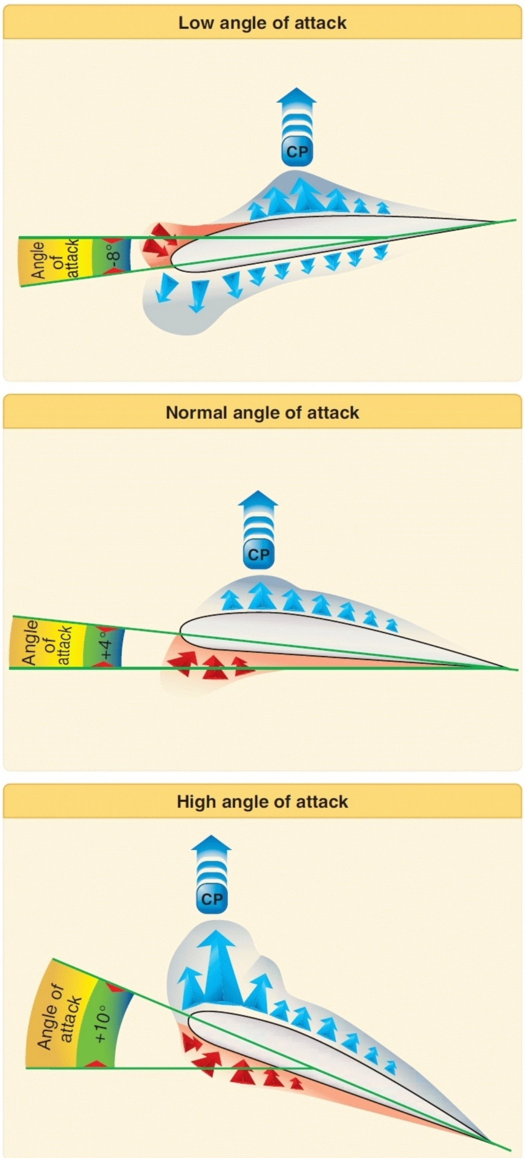


Figure 1.10 Pressure distribution on an aerofoil and CP changes with AOA

Aerofoil Behavior

56. Although specific examples can be cited in which each of the principles predict and contribute to the formation of lift, lift is a complex subject. The production of lift is much more complex than a simple differential pressure between upper and lower aerofoil surfaces. In fact, many lifting aerofoils do not have an upper surface longer than the bottom, as in the case of symmetrical aerofoils. These are seen in high-speed aircraft having symmetrical wings, or on symmetrical rotor blades for many helicopters whose upper and lower surfaces are identical. In both examples, the relationship of the aerofoil with the oncoming airstream (angle) is all that is different. A paper aeroplane, which is simply a flat plate, has a bottom and top exactly the same shape and length. Yet these aerofoils do produce lift, and "flow turning" is partly (or fully) responsible for creating lift.

57. As an aerofoil moves through air, the aerofoil is inclined against the airflow, producing a different flow caused by the aerofoil's relationship to the oncoming air. Think of a hand being placed outside the car window at a high speed. If the hand is inclined in one direction or another, the hand will move upward or downward. This is caused by deflection, which in turn causes the air to turn about the object within the air stream. As a result of this change, the velocity about the object changes in both magnitude and direction, in turn resulting in a measurable velocity force and direction.

A Third Dimension

58. To this point the discussion has centred on the flow across the upper and lower surfaces of an aerofoil. W hile most of the lift is produced by these two dimensions, a third dimension, the tip of the aerofoil also has an aerodynamic effect. The high pressure area on the bottom of an aerofoil pushes around the tip to the low-pressure area on the top. [Figure 1.11] This action creates a rotating flow called a tip vortex. The vortex flows behind the aerofoil creating a downwash that extends back to the trailing edge of the aerofoil. This downwash results in an overall reduction in lift for the affected portion of the aerofoil. Manufacturers have developed different methods to counteract this action. W inglets can be added to the tip of an aerofoil to reduce this flow. The winglets act as a dam preventing the vortex from forming. W inglets can be on the top or bottom of the aerofoil. Another method of countering the flow is to taper the aerofoil tip, reducing the

pressure differential and smoothing the airflow around the tip.

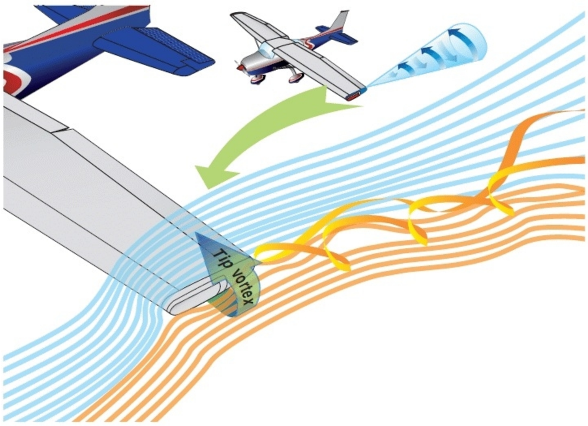


Figure 1.11 Wingtip Vortex

Summary

59. Modern general aviation aircraft have what may be considered high performance characteristics. Therefore, it is increasingly necessary that pilots appreciate and understand the principles upon which the art of flying is based.

AERODYNAMICS OF FLIGHT

Forces Acting on the Aircraft

60. Thrust, drag, lift, and weight are forces that act upon all aircraft in flight. Understanding how these forces work and knowing how to control them with the use of power and flight controls are essential to flight. This chapter discusses the aerodynamics of flight - how design, weight, load factors, and gravity affect an aircraft during flight manoeuvres. The four forces acting on an aircraft in straight-and-level, un-accelerated flight are thrust, drag, lift, and weight. They are defined as follows:

- Thrust - the forward force produced by the powerplant/propeller or rotor. It opposes or overcomes the force of drag. As a general rule, it acts parallel to the longitudinal axis. However, this is not always the case, as explained later.

- Drag - a rearward, retarding force caused by disruption of airflow by the wing, rotor, fuselage, and other protruding objects. Drag opposes thrust, and acts rearward parallel to the relative wind.

- W eight - the combined load of the aircraft itself, the crew, the fuel, and the cargo or baggage. W eight pulls the aircraft downward because of the force of gravity. It opposes lift, and acts vertically downward through the aircraft's centre of gravity (CG).

- Lift - opposes the downward force of weight, is produced by the dynamic effect of the air acting on the aerofoil, and acts perpendicular to the flightpath through the centre of pressure.

61. In steady flight, the sum of these opposing forces is always zero. There can be no unbalanced forces in steady, straight flight based upon Newton's Third Law, which states that for every action or force there is an equal, but opposite, reaction or force. This is true whether flying level or when climbing or descending.

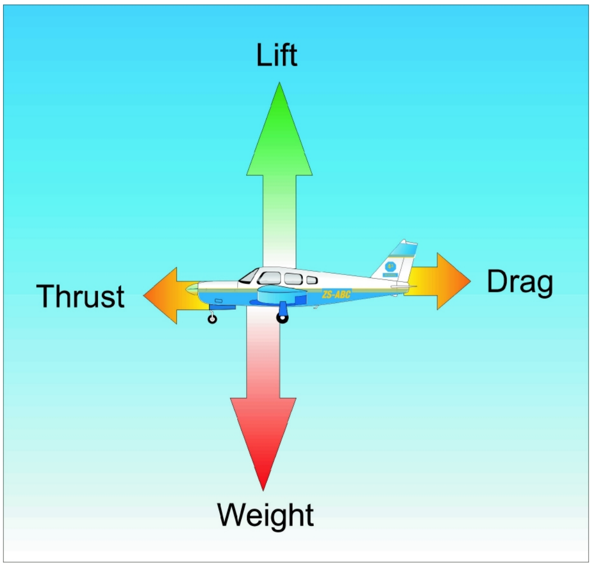


Fig 1.12 Four Forces

62. It does not mean the four forces are equal. It means the opposing forces are equal to, and thereby cancel, the effects of each other. In Figure 1.12 the force vectors of thrust, drag, lift, and weight are not equal in value. The usual explanation states (without stipulating that thrust and drag do not equal weight and lift) that thrust equals drag and lift equals weight. Although basically true, this statement can be

misleading. It should be understood that in straight, level, un-accelerated flight, it is true that the opposing lift/weight forces are equal. They are also greater than the opposing forces of thrust/drag that are equal only to each other.

63. Therefore, in steady flight:

- The sum of all upward forces (not just lift) equals the sum of all downward forces (not just weight).
- The sum of all forward forces (not just thrust) equals the sum of all backward forces (not just drag).

64. This refinement of the old “thrust equals drag; lift equals weight” formula explains that a portion of thrust is directed upward in climbs and acts as if it were lift while a portion of weight is directed backward and acts as if it were drag. [Figure 1.13]

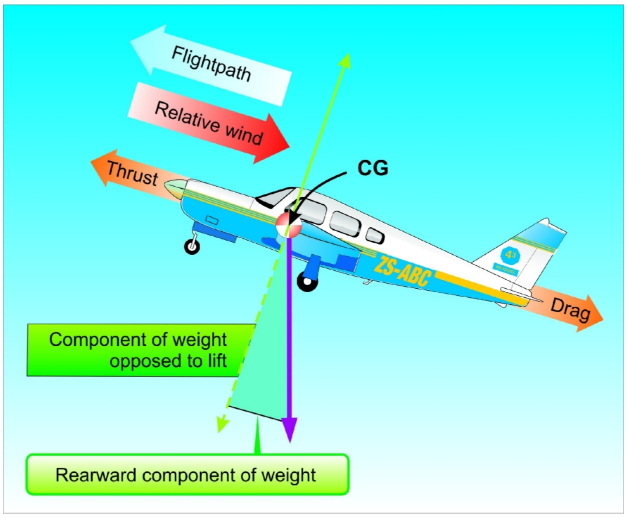


Figure 1.13 Force vectors during a stabilised climb

65. In glides, a portion of the weight vector is directed forward, and, therefore, acts as thrust. In other words, any time the flightpath of the aircraft is not horizontal, lift, weight, thrust, and drag vectors must each be broken down into two components.

66. Discussions of the preceding concepts are frequently omitted in aeronautical texts/handbooks/ manuals. The reason is not that they are inconsequential, but because the main ideas with respect to the aerodynamic forces acting upon an aeroplane in flight can be presented in their most essential elements without being involved in the technicalities of the aerodynamicist. In point of fact, considering only level flight, and normal climbs and glides in a steady state, it is still true that lift provided by the wing or rotor is the primary upward force, and weight is the primary downward force.

67. By using the aerodynamic forces of thrust, drag, lift, and weight, pilots can fly a controlled, safe flight. A more detailed discussion of these forces follows.

Thrust

68. For an aircraft to move, thrust must be exerted and be greater than drag. The aircraft will continue to move and gain speed until thrust and drag are equal. In order to maintain a constant airspeed, thrust and drag must remain equal, just as lift and weight must be equal to maintain a constant altitude. If in level flight, the engine power is reduced, the thrust is lessened, and the aircraft slows down. As long as the thrust is less than the drag, the aircraft continues to decelerate until its airspeed is insufficient to support it in the air.

69. Likewise, if the engine power is increased, thrust becomes greater than drag and the airspeed increases. As long as the thrust continues to be greater than the drag, the aircraft continues to accelerate. W hen drag equals thrust, the aircraft flies at a constant airspeed.

70. Straight-and-level flight may be sustained at a wide range of speeds. The pilot coordinates angle of attack (AOA) - the acute angle between the chord line of the aerofoil and the direction of the relative wind - and thrust in all speed regimes if the aircraft is to be held in level flight. Roughly, these regimes can be grouped in three categories: low-speed flight, cruising flight, and high-speed flight. W hen the airspeed is low, the AOA must be relatively high if the balance between lift and weight is to be maintained. [Figure 1.13]. If thrust decreases and airspeed decreases, lift becomes less than weight and the aircraft starts to descend. To maintain level flight, the pilot can increase the AOA by an amount which will generate a lift force again equal to the weight of the aircraft. W hile the aircraft will be flying more slowly, it will still maintain level flight if the pilot has properly coordinated thrust and AOA.

71. Straight-and-level flight in the slow-speed regime provides some interesting conditions relative to

the equilibrium of forces because with the aircraft in a

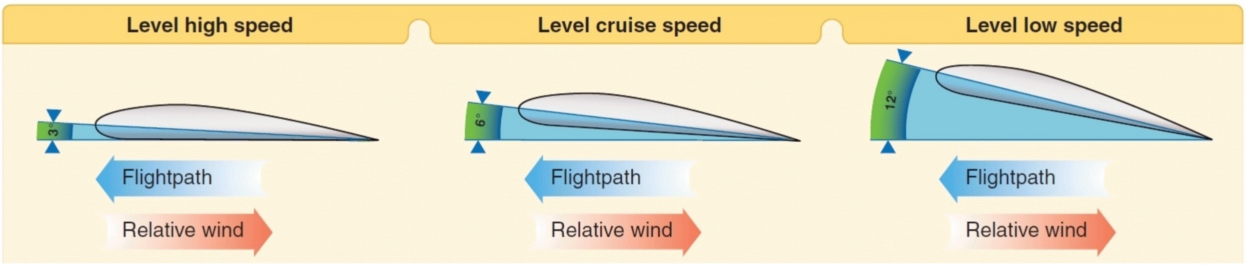


Figure 1.13 Angle of attack at various speeds

nose-high attitude, there is a vertical component of thrust that helps support it. For one thing, wing loading tends to be less than would be expected. Most pilots are aware that an aeroplane will stall, other conditions being equal, at a slower speed with the power on than with the power off. (Induced airflow over the wings from the propeller also contributes to this.) However, if analysis is restricted to the four forces as they are usually defined during slow-speed flight the thrust is equal to drag, and lift is equal to weight. During straight-and-level flight when thrust is increased and the airspeed increases, the AOA must be decreased. That is, if changes have been coordinated, the aircraft will remain in level flight, but at a higher speed when the proper relationship between thrust and AOA is established.

72. If the AOA were not coordinated (decreased) with an increase of thrust, the aircraft would climb. But decreasing the AOA modifies the lift, keeping it equal to the weight, and the aircraft remains in level flight. Level flight at even slightly negative AOA is possible at very high speed. It is evident then, that level flight can be performed with any AOA between stalling angle and the relatively small negative angles found at high speed.

73. Some aircraft have the ability to change the direction of the thrust rather than changing the AOA. This is accomplished either by pivoting the engines or by vectoring the exhaust gases. [Figure 1.14]

Drag

74. Drag is the force that resists movement of an aircraft through the air. There are two basic types: parasite drag and induced drag. The first is called parasite because it in no way functions to aid flight, while the second, induced drag, is a result of an aerofoil developing lift.

Parasite Drag

75. Parasite drag is comprised of all the forces that work to slow an aircraft's movement. As the term parasite implies, it is the drag that is not associated with the production of lift. This includes the displacement of the air by the aircraft, turbulence generated in the airstream, or a hindrance of air moving over the surface of the aircraft and aerofoil. There are three types of parasite drag: form drag, interference drag, and skin friction.

Form Drag

76. Form drag is the portion of parasite drag generated by the aircraft due to its shape and airflow around it. Examples include the engine cowlings, antennas, and the aerodynamic shape of other components. W hen the air has to separate to move around a moving aircraft and its components, it eventually rejoins after passing the body. How quickly and smoothly it rejoins is representative of the resistance that it creates which requires additional force to overcome. [Figure 1.15]

Figure 1.14 Some aircraft can change the direction of thrust

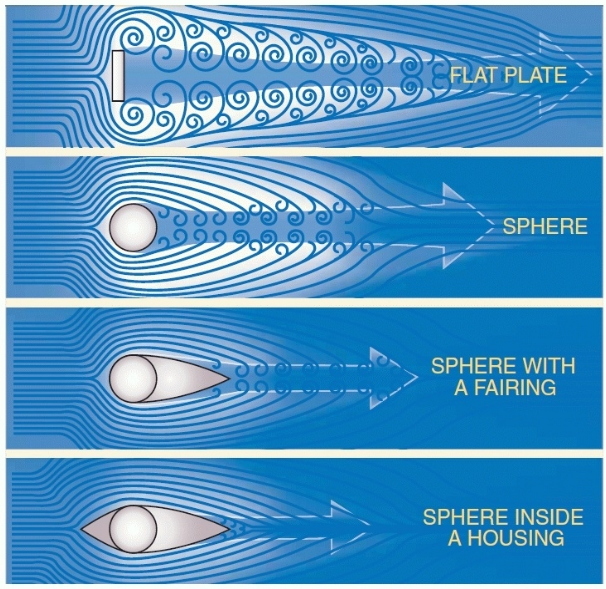


Figure 1.15 Form Drag

77. Notice how the flat plate in Figure 4-5 causes the air to swirl around the edges until it eventually rejoins downstream. Form drag is the easiest to reduce when designing an aircraft. The solution is to streamline as many of the parts as possible.

Interference Drag

78. Interference drag comes from the intersection of airstreams that creates eddy currents, turbulence, or restricts smooth airflow. For example, the intersection of the wing and the fuselage at the wing root has significant interference drag. Air flowing around the fuselage collides with air flowing over the wing, merging into a current of air different from the two original currents. The most interference drag is observed when two surfaces meet at perpendicular angles. Fairings are used to reduce this tendency. If a jet fighter carries two identical wing tanks, the overall drag is greater than the sum of the individual tanks because both of these create and generate interference drag. Fairings and distance between lifting surfaces and external components (such as radar antennas hung from wings) reduce interference drag. [Figure 1.16]

Skin Friction Drag

79. Skin friction drag is the aerodynam ic resistance due to the contact of moving air with the surface of an aircraft. Every surface, no matter how apparently smooth, has a rough, ragged surface when viewed under a microscope. The air molecules, which come in direct contact with the surface of the wing, are virtually motionless. Each layer of molecules above the surface moves slightly faster until the molecules are moving at the velocity of the air moving around the aircraft. This speed is called the free-stream velocity. The area between the wing and the free-stream velocity level is about as wide as a playing card and is called the boundary layer. At the top of the boundary layer, the molecules increase velocity and move at the same speed as the molecules outside the boundary layer. The actual speed at which the molecules move depends upon the shape of the wing, the viscosity (stickiness) of the air through which the wing or aerofoil is moving, and its compressibility (how much it can be com pacted).

80. The airflow outside of the boundary layer reacts to the shape of the edge of the boundary layer just as it would to the physical surface of an object. The boundary layer gives any object an "effective" shape that is usually slightly different from the physical shape. The boundary layer may also separate from the body, thus creating an effective shape much different from the physical shape of the object. This change in the physical shape of the boundary layer causes a dramatic decrease in lift and an increase in drag. W hen this happens, the aerofoil has stalled.

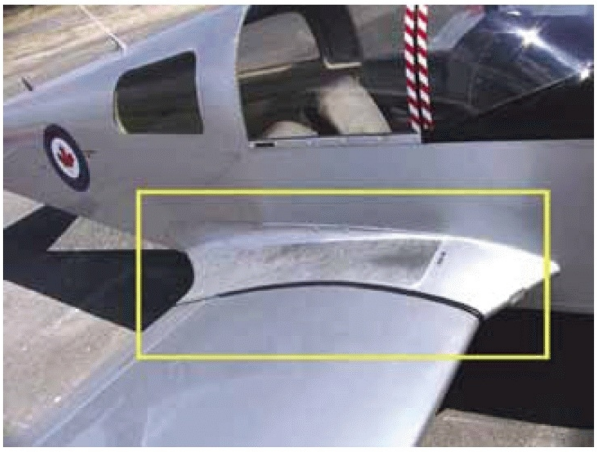


Figure 1.16 Interference Drag

81. In order to reduce the effect of skin friction drag, aircraft designers utilize flush mount rivets and remove any irregularities which may protrude above the wing surface. In addition, a smooth and glossy finish aids in transition of air across the surface of the wing. Since dirt on an aircraft disrupts the free flow of air and increases drag, keep the surfaces of an aircraft clean and waxed.

Figure 1.17 Wingtip vortex from a crop duster

Induced Drag

82. The second basic type of drag is induced drag. It is an established physical fact that no system that does work in the mechanical sense can be 100 percent efficient. This means that whatever the nature of the system, the required work is obtained at the expense of certain additional work that is dissipated or lost in the system. The more efficient the system, the smaller this loss.

83. In level flight the aerodynamic properties of a wing or rotor produce a required lift, but this can be obtained only at the expense of a certain penalty. The name given to this penalty is induced drag. Induced drag is inherent whenever an aerofoil is producing lift and, in fact, this type of drag is inseparable from the production of lift. Consequently, it is always present if lift is produced.

84. An aerofoil (wing or rotor blade) produces the lift force by making use of the energy of the free airstream. W henever an aerofoil is producing lift, the pressure on the lower surface of it is greater than that on the upper surface (Bernoulli's Principle). As a result, the air tends to flow from the high pressure area below the tip upward to the low pressure area on the upper surface. In the vicinity of the tips, there is a tendency for these pressures to equalize, resulting in a lateral flow outward from the underside to the upper surface. This lateral flow imparts a rotational velocity to the air at the tips, creating vortices, which trail behind the aerofoil.

85. W hen the aircraft is viewed from the tail, these vortices circulate counterclockwise about the right tip and clockwise about the left tip. [Figure 1.17] Bearing in mind the direction of rotation of these vortices, it can be seen that they induce an upward flow of air beyond the tip, and a downwash flow behind the wing's trailing edge. This induced downwash has nothing in common with the downwash that is necessary to produce lift. It is, in fact, the source of induced drag.

86. The greater the size and strength of the vortices and consequent downwash component on the net airflow over the aerofoil, the greater the induced drag effect becomes. This downwash over the top of the aerofoil at the tip has the same effect as bending the lift vector rearward; therefore, the lift is slightly aft of perpendicular to the relative wind, creating a rearward lift component. This is induced drag.

87. In order to create a greater negative pressure on the top of an aerofoil, the aerofoil can be inclined to a higher AOA. If the AOA of a symmetrical aerofoil were zero, there would be no pressure differential, and consequently, no downwash component and no induced drag. In any case, as AOA increases, induced drag increases proportionally. To state this another way - the lower the airspeed the greater the AOA required to produce lift equal to the aircraft's weight and, therefore, the greater induced drag. The amount of induced drag varies inversely with the square of the airspeed.

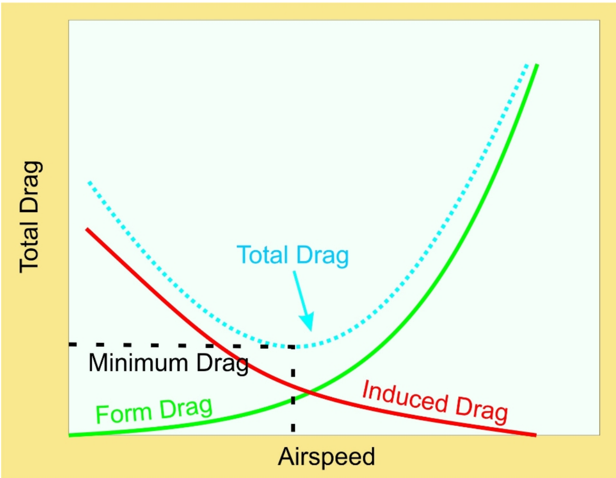


Figure 1.18 Drag versus speed

88. Conversely, parasite drag increases as the square of the airspeed. Thus, as airspeed decreases to near the stalling speed, the total drag becomes greater, due mainly to the sharp rise in induced drag. Similarly, as the airspeed reaches the terminal velocity

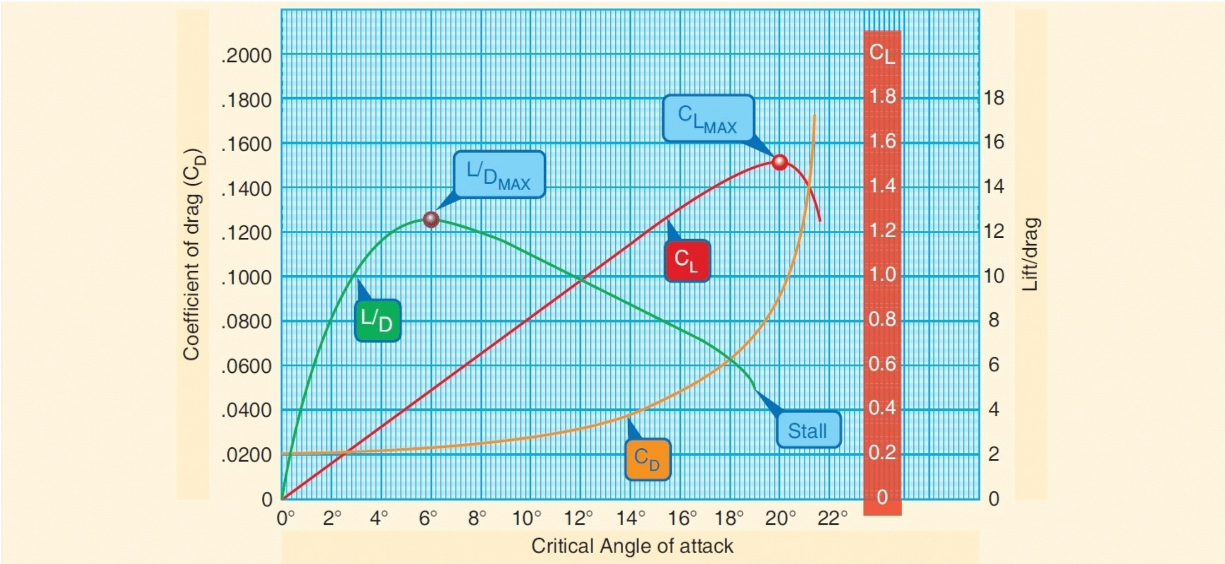


Figure 1.19 Lift coefficients at various angles of attack

of the aircraft, the total drag again increases rapidly, due to the sharp increase of parasite drag. As seen in Figure 1.18, at some given airspeed, total drag is at its minimum amount. In figuring the maximum endurance and range of aircraft, the power required to overcome drag is at a minimum if drag is at a minimum.

Lift/Drag Ratio

89. Drag is the price paid to obtain lift. The lift to drag ratio (L/D) is the amount of lift generated by a wing or aerofoil compared to its drag. A ratio of L/D indicates aerofoil efficiency. Aircraft with higher L/D ratios are more efficient than those with lower L/D ratios. In un-accelerated flight with the lift and drag data steady, the proportions of the C_L and coefficient of drag (C_D) can be calculated for specific AOA. [Figure 1.19] The L/D ratio is determined by dividing the C_L by the C_D which is the same as dividing the lift equation by the drag equation. All terms except coefficients cancel out.

L = Lift in pounds
D = Drag

W here L is the lift force in pounds, C_L is the lift coefficient, ñ is density expressed in slugs per cubic feet, V is velocity in feet per second, q is dynamic pressure per square feet, and S is the wing area in square feet.

C_D = Ratio of drag pressure to dynam ic pressure. Typically at low angles of attack, the drag coefficient is low and small changes in angle of attack create only slight changes in the drag coefficient. At high angles of attack, small changes in the angle of attack cause significant changes in drag.

$$L = \frac{C_L . ñ . V^2 . S}{2}$$

$$D = \frac{C_D . ñ . V^2 . S}{2}$$

90. The above formulas represent the coefficient of lift (C_L) and the coefficient of drag (C_D) respectively. The shape of an aerofoil and other life producing devices (i.e., flaps) effect the production of lift and alter with changes in the AOA. The lift/drag ratio is used to express the relation between lift and drag and is determined by dividing the lift coefficient by the drag coefficient, C_L/C_D.

91. Notice in Figure 1.19 that the lift curve (red) reaches its maximum for this particular wing section at 20° AOA, and then rapidly decreases. 15° AOA is therefore the stalling angle. The drag curve (yellow) increases very rapidly from 14° AOA and completely overcomes the lift curve at 21° AOA. The lift/drag ratio (green) reaches its maximum at 6° AOA, meaning that at this angle, the most lift is obtained for the least amount of drag.

92. Note that the maximum lift/drag ratio (L/D_{MAX}) occurs at one specific C_L and AOA. If the aircraft is operated in steady flight at L/D_{MAX}, the total drag is at

a minimum. Any AOA lower or higher than that for L/D_{MAX} reduces the L/D ratio and consequently increases the total drag for a given aircraft's lift. Figure 1-19 depicts the L/D_{MAX} by the lowest portion of the orange line labelled "total drag." The configuration of an aircraft has a great effect on the L/D ratio.

Weight

93. Gravity is the pulling force that tends to draw all bodies to the centre of the earth. The CG may be considered as a point at which all the weight of the aircraft is concentrated. If the aircraft were supported at its exact CG, it would balance in any attitude. It will be noted that CG is of major importance in an aircraft, for its position has a great bearing upon stability. The location of the CG is determined by the general design of each particular aircraft. The designers determine how far the centre of pressure (CP) will travel. They then fix the CG forward of the centre of pressure for the corresponding flight speed in order to provide an adequate restoring moment to retain flight equilibrium.

94. W eight has a definite relationship to lift. This relationship is simple, but important in understanding the aerodynamics of flying. Lift is the upward force on the wing acting perpendicular to the relative wind. Lift is required to counteract the aircraft's weight (which is caused by the force of gravity acting on the mass of the aircraft). This weight (gravity) force acts downward through the aeroplane's CG. In stabilized level flight, when the lift force is equal to the weight force, the aircraft is in a state of equilibrium and neither gains nor loses altitude. If lift becomes less than weight, the aircraft loses altitude. W hen lift is greater than weight, the aircraft gains altitude.

Lift

95. The pilot can control the lift. Any time the control yoke or stick is moved fore or aft, the AOA is changed. As the AOA increases, lift increases (all other factors being equal). W hen the aircraft reaches the maximum AOA, lift begins to diminish rapidly. This is the stalling AOA, known as C_{L-MAX} critical AOA. Examine Figure 1.19, noting how the C_L increases until the critical AOA is reached, then decreases rapidly with any further increase in the AOA.

96. Before proceeding further with the topic of lift and how it can be controlled, velocity must be interjected. The shape of the wing or rotor cannot be effective unless it continually keeps "attacking" new air. If an aircraft is to keep flying, the lift-producing aerofoil must keep moving. In a helicopter or gyro-plane this is accomplished by the rotation of the rotor blades. For other types of aircraft such as aeroplanes, weightshift control, or gliders, air must be moving across the lifting surface. This is accomplished by the forward speed of the aircraft. Lift is proportional to the square of the aircraft's velocity. For example, an aeroplane travelling at 200 knots has four times the lift as the same aeroplane travelling at 100 knots, if the AOA and other factors remain constant.

97. Actually, an aircraft could not continue to travel in level flight at a constant altitude and maintain the same AOA if the velocity is increased. The lift would increase and the aircraft would climb as a result of the increased lift force. Therefore, to maintain the lift and weight forces in balance, and to keep the aircraft straight and level (not accelerating upward) in a state of equilibrium, as velocity is increased, lift must be decreased. This is normally accomplished by reducing the AOA by lowering the nose. Conversely, as the aircraft is slowed, the decreasing velocity requires increasing the AOA to maintain lift sufficient to maintain flight. There is, of course, a limit to how far the AOA can be increased, if a stall is to be avoided.

98. All other factors being constant, for every AOA there is a corresponding airspeed required to maintain altitude in steady, unaccelerated flight (true only if maintaining "level flight"). Since an aerofoil always stalls at the same AOA, if increasing weight, lift must also be increased. The only method of increasing lift is by increasing velocity if the AOA is held constant just short of the "critical," or stalling, AOA. Lift and drag also vary directly with the density of the air. Density is affected by several factors: pressure, temperature, and humidity. At an altitude of 18,000 feet, the density of the air has one-half the density of air at sea level. In order to maintain its lift at a higher altitude, an aircraft must fly at a greater true airspeed for any given AOA.

99. W arm air is less dense than cool air, and moist air is less dense than dry air. Thus, on a hot humid day, an aircraft must be flown at a greater true airspeed for any given AOA than on a cool, dry day.

100. If the density factor is decreased and the total lift must equal the total weight to remain in flight, it

follows that one of the other factors must be increased. The factor usually increased is the airspeed or the AOA, because these are controlled directly by the pilot.

101. Lift varies directly with the wing area, provided there is no change in the wing's planform. If the wings have the same proportion and aerofoil sections, a wing with a planform area of 200 square feet lifts twice as much at the same AOA as a wing with an area of 100 square feet.

102. Two major aerodynamic factors from the pilot's viewpoint are lift and velocity because they can be controlled readily and accurately. Of course, the pilot can also control density by adjusting the altitude and can control wing area if the aircraft happens to have flaps of the type that enlarge wing area. However, for most situations, the pilot controls lift and velocity to manoeuvre an aircraft. For instance, in straight-and level flight, cruising along at a constant altitude, altitude is maintained by adjusting lift to match the aircraft's velocity or cruise airspeed, while maintaining a state of equilibrium in which lift equals weight. In an approach to landing, when the pilot wishes to land as slowly as practical, it is necessary to increase lift to near maximum to maintain lift equal to the weight of the aircraft.

Wingtip Vortices

Formation of Vortices

103. The action of the aerofoil that gives an aircraft lift also causes induced drag. W hen an aerofoil is flown at a positive AOA, a pressure differential exists between the upper and lower surfaces of the aerofoil. The pressure above the wing is less than atmospheric pressure and the pressure below the wing is equal to or greater than atmospheric pressure. Since air always moves from high pressure toward low pressure, and the path of least resistance is toward the aerofoil's tips, there is a spanwise movement of air from the bottom of the aerofoil outward from the fuselage around the tips. This flow of air results in "spillage" over the tips, thereby setting up a whirlpool of air called a " vortex." [Figure 1.20]

104. At the same time, the air on the upper surface has a tendency to flow in toward the fuselage and off the trailing edge. This air current forms a similar vortex at the inboard portion of the trailing edge of the aerofoil, but because the fuselage limits the inward flow, the vortex is insignificant. Consequently, the deviation in flow direction is greatest at the outer tips where the unrestricted lateral flow is the strongest.

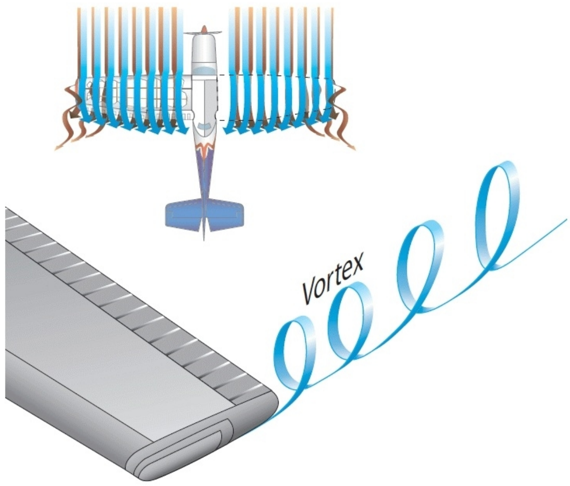


Figure 1.20 Wingtip vortices

105. As the air curls upward around the tip, it combines with the wash to form a fast-spinning trailing vortex. These vortices increase drag because of energy spent in producing the turbulence. W henever an aerofoil is producing lift, induced drag occurs, and wingtip vortices are created.

106. Just as lift increases with an increase in AOA, induced drag also increases. This occurs because as the AOA is increased, there is a greater pressure difference between the top and bottom of the aerofoil, and a greater lateral flow of air; consequently, this causes more violent vortices to be set up, resulting in more turbulence and more induced drag. In Figure 1-20, it is easy to see the formation of wingtip vortices. The intensity or strength of the vortices is directly proportional to the weight of the aircraft and inversely proportional to the wingspan and speed of the aircraft. The heavier and slower the aircraft, the greater the AOA and the stronger the wingtip vortices. Thus, an aircraft will create wingtip vortices with maximum strength occurring during the takeoff, climb, and landing phases of flight. These vortices lead to a particularly dangerous hazard to flight, wake turbulence.

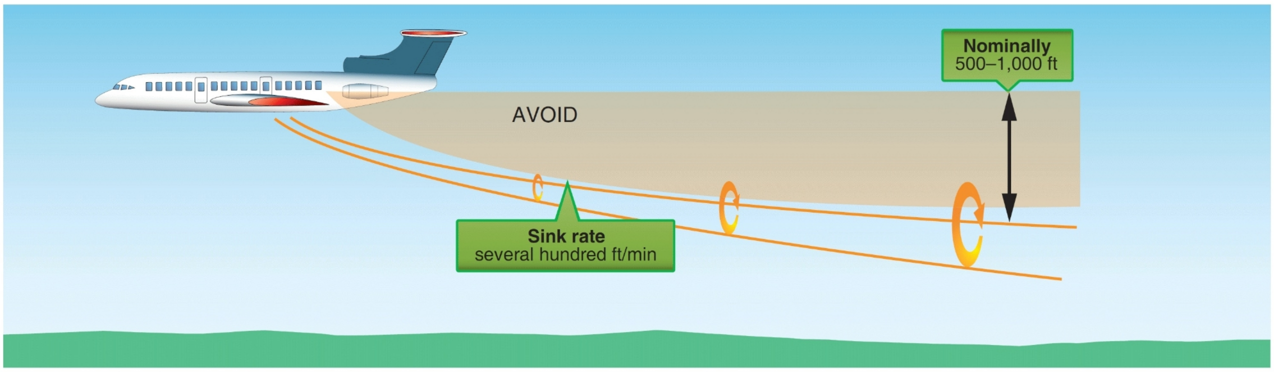


Figure 1.21 Avoid following another aircraft at an altitude within 1000 feet

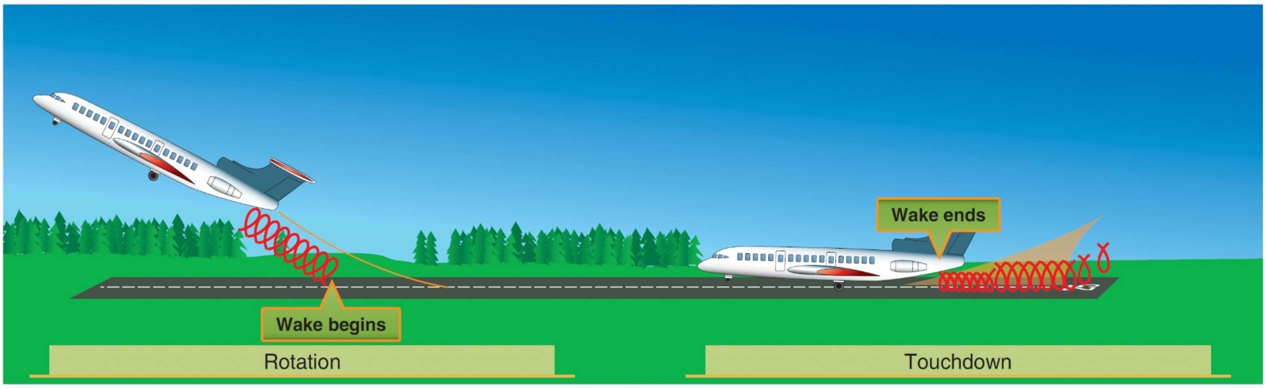


Figure 1.22 Avoid turbulence from another aircraft

107. W ingtip vortices are greatest when the generating aircraft is "heavy, clean, and slow." This condition is most commonly encountered during approaches or departures because an aircraft's AOA is at the highest to produce the lift necessary to land or take off. To minimize the chances of flying through an aircraft's wake turbulence:

- Avoid flying through another aircraft's flightpath.
- Rotate prior to the point at which the preceding aircraft rotated, when taking off behind another aircraft.
- Avoid following another aircraft on a similar flightpath at an altitude within 1,000 feet. [Figure 1.21] • Approach the runway above a preceding aircraft's path when landing behind another aircraft, and touch down after the point at which the other aircraft wheels contacted the runway. [Figure 1.22]

108. A hovering helicopter generates a down wash from its main rotor(s) similar to the vortices of an aeroplane. Pilots of small aircraft should avoid a hovering helicopter by at least three rotor disc diameters to avoid the effects of this down wash. In forward flight this energy is transformed into a pair of strong, high-speed trailing vortices similar to wing-tip vortices of larger fixed-wing aircraft. Helicopter vortices should be avoided because helicopter forward flight airspeeds are often very slow and can generate exceptionally strong wake turbulence.

109. W ind is an important factor in avoiding wake turbulence because wingtip vortices drift with the wind at the speed of the wind. For example, a wind speed of 10 knots causes the vortices to drift at about 1,000 feet in a minute in the wind direction. W hen following another aircraft, a pilot should consider wind speed and direction when selecting an intended takeoff or landing point. If a pilot is unsure of the other aircraft's takeoff or landing point, approximately 3 m inutes provides a margin of safety that allows wake turbulence dissipation.

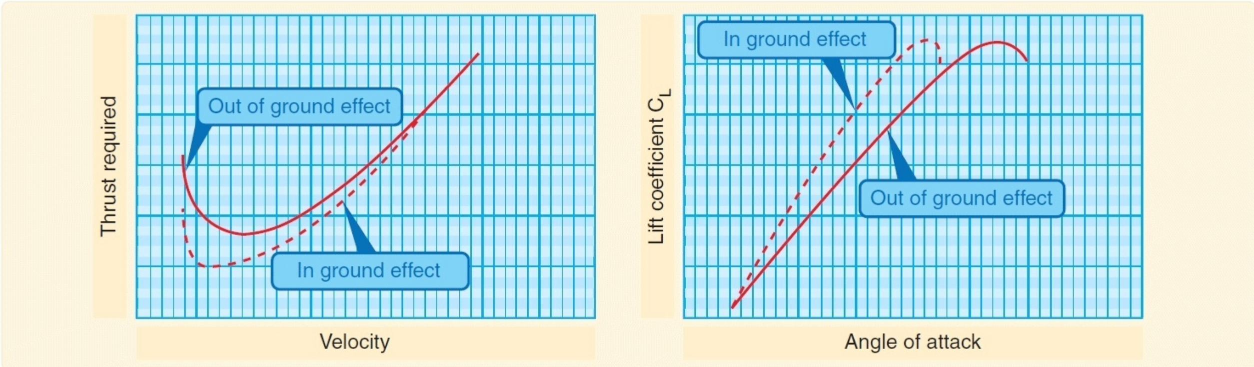


Figure 1.23 Ground effect changes lift and drag

Ground Effect

110. It is possible to fly an aircraft just clear of the ground (or water) at a slightly slower airspeed than that required to sustain level flight at higher altitudes. This is the result of a phenomenon better known of than understood even by some experienced pilots.

111. W hen an aircraft in flight comes within several feet of the surface, ground or water, a change occurs in the three dimensional flow pattern around the aircraft because the vertical component of the airflow around the wing is restricted by the surface. This alters the wing's upwash, downwash, and wingtip vortices. [Figure 1.24] Ground effect, then, is due to the interference of the ground (or water) surface with the airflow patterns about the aircraft in flight.

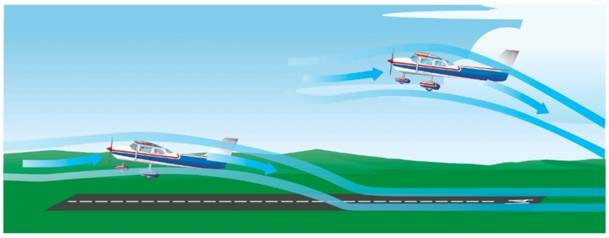


Figure 1.24 Ground effect changes airflow

112. W hile the aerodynamic characteristics of the tail surfaces and the fuselage are altered by ground effect, the principal effects due to proximity of the ground are the changes in the aerodynam ic characteristics of the wing. As the wing encounters ground effect and is maintained at a constant lift coefficient, there is consequent reduction in the upwash, downwash, and wingtip vortices.

113. Induced drag is a result of the aerofoil's work of sustaining the aircraft, and a wing or rotor lifts the aircraft simply by accelerating a mass of air downward. It is true that reduced pressure on top of an aerofoil is essential to lift, but that is only one of the things contributing to the overall effect of pushing an air mass downward. The more downwash there is, the harder the wing pushes the mass of air down. At high angles of attack, the amount of induced drag is high; since this corresponds to lower airspeeds in actual flight, it can be said that induced drag predominates at low speed.

114. However, the reduction of the wingtip vortices due to ground effect alters the spanwise lift distribution and reduces the induced AOA and induced drag. Therefore, the wing will require a lower AOA in ground effect to produce the same CL. If a constant AOA is maintained, an increase in CL results. [Figure 1.23]

115. Ground effect also alters the thrust required versus velocity. Since induced drag predominates at low speeds, the reduction of induced drag due to ground effect will cause the most significant reduction of thrust required (parasite plus induced drag) at low speeds.

116. The reduction in induced flow due to ground effect causes a significant reduction in induced drag but causes no direct effect on parasite drag. As a result of the reduction in induced drag, the thrust required at low speeds will be reduced. Due to the change in upwash, downwash, and wingtip vortices, there may be a change in position (installation) error of the airspeed system, associated with ground effect. In the majority of cases, ground effect will cause an increase in the local pressure at the static source and produce a lower indication of airspeed and altitude. Thus, an aircraft may be airborne at an indicated

airspeed less than that normally required.

117. In order for ground effect to be of significant magnitude, the wing must be quite close to the ground. One of the direct results of ground effect is the variation of induced drag with wing height above the ground at a constant C_L. When the wing is at a height equal to its span, the reduction in induced drag is only 1.4 percent. However, when the wing is at a height equal to one-fourth its span, the reduction in induced drag is 23.5 percent and, when the wing is at a height equal to one-tenth its span, the reduction in induced drag is 47.6 percent. Thus, a large reduction in induced drag will take place only when the wing is very close to the ground. Because of this variation, ground effect is most usually recognized during the liftoff for takeoff or just prior to touchdown when landing.

118. During the takeoff phase of flight, ground effect produces some important relationships. An aircraft leaving ground effect after takeoff encounters just the reverse of an aircraft entering ground effect during landing; i.e., the aircraft leaving ground effect will:

- Require an increase in AOA to maintain the same C_L
- Experience an increase in induced drag and thrust required.
- Experience a decrease in stability and a nose-up change in moment.
- Experience a reduction in static source pressure and increase in indicated airspeed.

119. Ground effect must be considered during takeoffs and landings. For example, if a pilot fails to understand the relationship between the aircraft and ground effect during takeoff, a hazardous situation is possible because the recommended takeoff speed may not be achieved. Due to the reduced drag in ground effect, the aircraft may seem capable of takeoff well below the recommended speed. As the aircraft rises out of ground effect with a deficiency of speed, the greater induced drag may result in marginal initial climb performance. In extreme conditions, such as high gross weight, high density altitude, and high temperature, a deficiency of airspeed during takeoff may permit the aircraft to become airborne but be incapable of sustaining flight out of ground effect. In this case, the aircraft may become airborne initially with a deficiency of speed, and then settle back to the runway.

120. A pilot should not attempt to force an aircraft to become airborne with a deficiency of speed. The manufacturer's recommended takeoff speed is necessary to provide adequate initial climb performance. It is also important that a definite climb be established before a pilot retracts the landing gear or flaps. Never retract the landing gear or flaps prior to establishing a positive rate of climb, and only after achieving a safe altitude.

121. If, during the landing phase of flight, the aircraft is brought into ground effect with a constant AOA, the aircraft experiences an increase in C_L and a reduction in the thrust required, and a "floating" effect may occur. Because of the reduced drag and power-off deceleration in ground effect, any excess speed at the point of flare may incur a considerable "float" distance. As the aircraft nears the point of touchdown, ground effect is most realized at altitudes less than the wingspan. During the final phases of the approach as the aircraft nears the ground, a reduced power setting is necessary or the reduced thrust required would allow the aircraft to climb above the desired glidepath (GP).

Axes of an Aircraft

122. The axes of an aircraft are three imaginary lines that pass through an aircraft's CG. The axes can be considered as imaginary axles around which the aircraft turns. The three axes pass through the CG at 90 angles to each other. The axis from nose to tail is the longitudinal axis, the axis that passes from wingtip to wingtip is the lateral axis, and the axis that passes vertically through the CG is the vertical axis. Whenever an aircraft changes its flight attitude or position in flight, it rotates about one or more of the three axes. [Figure 1.25]

123. The aircraft's motion about its longitudinal axis resembles the roll of a ship from side to side. In fact, the names used to describe the motion about an aircraft's three axes were originally nautical terms. They have been adapted to aeronautical terminology due to the similarity of motion of aircraft and seagoing ships. The motion about the aircraft's longitudinal axis is "roll," the motion about its lateral axis is "pitch," and

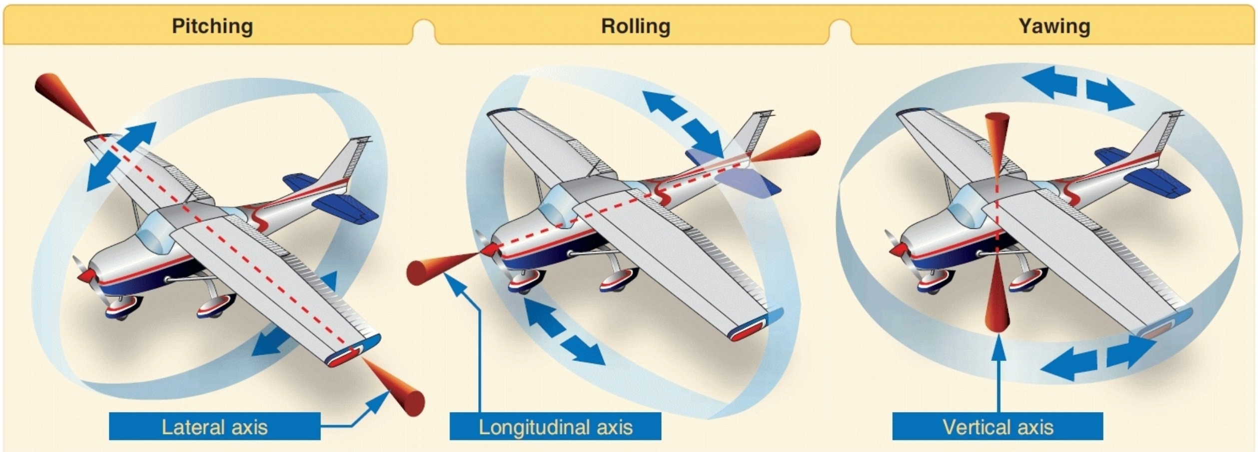


Figure 1.25 Axes of an aeroplane

the motion about its vertical axis is "yaw." Yaw is the horizontal (left and right) movement of the aircraft's nose.

124. The three motions of the conventional aeroplane (roll, pitch, and yaw) are controlled by three control surfaces. Roll is controlled by the ailerons; pitch is controlled by the elevators; yaw is controlled by the rudder. The use of these controls is explained in Flight Controls. Other types of aircraft may utilize different methods of controlling the movements about the various axes.

Figure 1.26 A weight-shift control aircraft

125. For example, weight-shift control aircraft (microlights) control two axes, roll and pitch, using an "A" frame suspended from the flexible wing in a three-wheeled pod. These aircraft are controlled by pushing against a horizontal bar (called a control bar) in roughly the same way hang glider pilots fly. [Figure 1.26] They are termed weight-shift control aircraft because the pilot controls the aircraft by shifting the CG. In the case of powered parachutes, aircraft control is accomplished by altering the aerofoil via steering lines.

126. A powered parachute wing is a parachute that has a cambered upper surface and a flatter under surface. The two surfaces are separated by ribs that act as cells, which open to the airflow at the leading edge and have internal ports to allow lateral airflow. The principle at work holds that the cell pressure is greater than the outside pressure, thereby forming a wing that maintains its aerofoil shape in flight. The pilot and passenger sit in tandem in front of the engine which is located at the rear of a vehicle. The airframe is attached to the parachute via four attachment points and lines. Control is accomplished by both power and the changing of the aerofoil via the control lines. [Figure 1.27]

Figure 1.27 A powered parachute

Moment and Moment Arm

127. A study of physics shows that a body that is free to rotate will always turn about its CG. In aerodynamic terms, the mathematical measure of an aircraft's tendency to rotate about its CG is called a "moment." A moment is said to be equal to the product of the force applied and the distance at which the force is applied. (A moment arm is the distance from a datum [reference point or line] to the applied force.) For aircraft weight and balance com putations, "moments" are expressed in terms of the distance of the arm times the aircraft's weight, or simply, inch-pounds.

128. Aircraft designers locate the fore and aft position of the aircraft's CG as nearly as possible to the 20 percent point of the mean aerodynamic chord (MAC). If the thrust line is designed to pass horizontally through the CG, it will not cause the aircraft to pitch when power is changed, and there will be no difference in moment due to thrust for a power-on or power-off condition of flight. Although designers have some control over the location of the drag forces, they are not always able to make the resultant drag forces pass through the CG of the aircraft. However, the one item over which they have the greatest control is the size and location of the tail. The objective is to make the moments (due to thrust, drag, and lift) as small as possible and, by proper location of the tail, to provide the means of balancing an aircraft longitudinally for any condition of flight.

129. The pilot has no direct control over the location of forces acting on the aircraft in flight, except for controlling the centre of lift by changing the AOA. Such a change, however, immediately involves changes in other forces. Therefore, the pilot cannot independently change the location of one force without changing the effect of others. For example, a change in airspeed involves a change in lift, as well as a change in drag and a change in the up or down force on the tail. As forces such as turbulence and gusts act to displace the aircraft, the pilot reacts by providing opposing control forces to counteract this displacement.

130. Some aircraft are subject to changes in the location of the CG with variations of load. Trimming devices are used to counteract the forces set up by fuel burn-off, and loading or off-loading of passengers or cargo. Elevator trim tabs and adjustable horizontal stabilizers comprise the most common devices provided to the pilot for trimming for load variations. Over the wide ranges of balance during flight in large aircraft, the force which the pilot has to exert on the controls would become excessive and fatiguing if means of trimming were not provided.

Aircraft Design Characteristics

131. Each aircraft handles somewhat differently because each resists or responds to control pressures in its own way. For example, a training aircraft is quick to respond to control applications, while a transport aircraft feels heavy on the controls and responds to control pressures more slowly. These features can be designed into an aircraft to facilitate the particular purpose of the aircraft by considering certain stability and manoeuvring requirements. The following discussion summarizes the more important aspects of an aircraft's stability, manoeuvrability and controllability qualities; how they are analysed; and their relationship to various flight conditions.

Stability

132. Stability is the inherent quality of an aircraft to correct for conditions that may disturb its equilibrium, and to return to or to continue on the original flightpath. It is primarily an aircraft design characteristic. The flightpaths and attitudes an aircraft flies are limited by the aerodynamic characteristics of the aircraft, its propulsion system, and its structural strength. These limitations indicate the maximum performance and manoeuvrability of the aircraft. If the aircraft is to provide maximum utility, it must be safely controllable to the full extent of these limits without exceeding the pilot's strength or requiring exceptional flying ability. If an aircraft is to fly straight and steady along any arbitrary flightpath, the forces acting on it must be in static equilibrium. The reaction of any body when its equilibrium is disturbed is referred to as stability. The two types of stability are static and dynamic.

Static Stability

133. Static stability refers to the initial tendency, or direction of movement, back to equilibrium. In aviation, it refers to the aircraft's initial response when disturbed from a given AOA, slip, or bank.

- Positive static stability - initial tendency of the

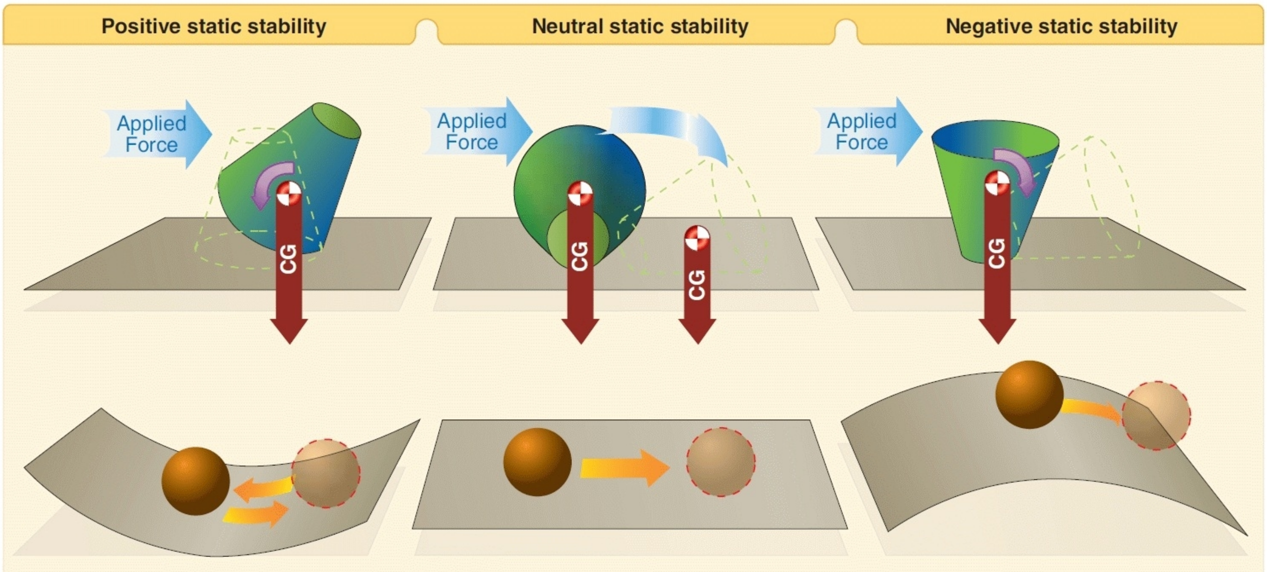


Figure 1.28 Types of static stability

aircraft to return to the original state of equilibrium after being disturbed [Figure 1.28]

- Neutral static stability - initial tendency of the aircraft to remain in a new condition after its equilibrium has been disturbed [Figure 1.28]

- Negative static stability - initial tendency of the aircraft to continue away from the original state of equilibrium after being disturbed [Figure 1.28]

Dynamic Stability

134. Static stability has been defined as the initial tendency to return to equilibrium that the aircraft displays after being disturbed from its trim m ed condition. Occasionally, the initial tendency is different or opposite from the overall tendency, so a distinction must be made between the two. Dynamic stability refers to the aircraft response over time when disturbed from a given AOA, slip, or bank. This type of stability also has three subtypes: [Figure 1.29]

- Positive dynam ic stability - over tim e, the motion of the displaced object decreases in amplitude and, because it is positive, the object displaced returns toward the equilibrium state.

- Neutral dynamic stability - once displaced, the displaced object neither decreases nor increases in amplitude. A worn automobile shock absorber exhibits this tendency.

- Negative dynam ic stability - over tim e, the motion of the displaced object increases and becomes more divergent.

135 Stability in an aircraft affects two areas significantly:

- Manoeuvrability - the quality of an aircraft that permits it to be manoeuvred easily and to withstand the stresses im posed by manoeuvres. It is governed by the aircraft's weight, inertia, size and location of flight controls, structural strength, and powerplant. It too is an aircraft design characteristic.

- Controllability - the capability of an aircraft to respond to the pilot's control, especially with regard to flightpath and attitude. It is the quality of the aircraft's response to the pilot's control application when manoeuvring the aircraft, regardless of its stability characteristics.

Longitudinal Stability (Pitching)

136. In designing an aircraft, a great deal of effort is spent in developing the desired degree of stability around all three axes. But longitudinal stability about the lateral axis is considered to be the most affected by certain variables in various flight conditions.

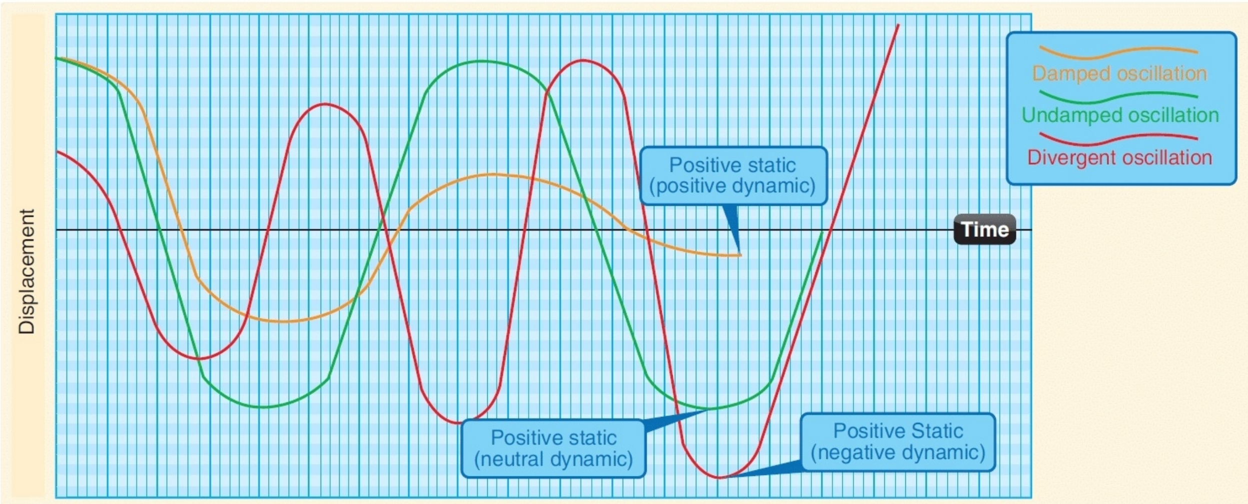


Figure 1.29 Damped vs undamped stability

137. Longitudinal stability is the quality that makes an aircraft stable about its lateral axis. It involves the pitching motion as the aircraft's nose moves up and down in flight. A longitudinally unstable aircraft has a tendency to dive or climb progressively into a very steep dive or climb, or even a stall. Thus, an aircraft with longitudinal instability becomes difficult and sometimes dangerous to fly.

138. Static longitudinal stability or instability in an aircraft, is dependent upon three factors:

a. Location of the wing with respect to the CG

b. Location of the horizontal tail surfaces with respect to the CG

c. Area or size of the tail surfaces

139. In analyzing stability, it should be recalled that a body free to rotate always turns about its CG.

140. To obtain static longitudinal stability, the relation of the wing and tail moments must be such that, if the moments are initially balanced and the aircraft is suddenly nose up, the wing moments and tail moments change so that the sum of their forces provides an unbalanced but restoring moment which, in turn, brings the nose down again. Similarly, if the aircraft is nose down, the resulting change in moments brings the nose back up.

141. The C_L in most asymmetrical aerofoils has a tendency to change its fore and aft positions with a change in the AOA. The C_L tends to move forward with an increase in AOA and to move aft with a decrease in AOA. This means that when the AOA of an aerofoil is increased, the C_L, by moving forward, tends to lift the leading edge of the wing still more. This tendency gives the wing an inherent quality of instability. (NOTE: C_L is also known as the centre of pressure (CP).) Figure 1.30 shows an aircraft in straight-and-level flight. The line CG-C_LT represents the aircraft's longitudinal axis from the CG to a point T on the horizontal stabilizer.

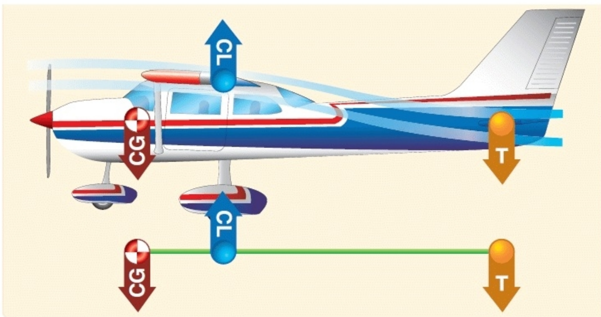


Figure 1.30 Longitudinal stability

142. Most aircraft are designed so that the wing's C_L is to the rear of the CG. This makes the aircraft "nose heavy" and requires that there be a slight downward force on the horizontal stabilizer in order to balance the aircraft and keep the nose from continually pitching downward. Compensation for this nose heaviness is provided by setting the horizontal stabilizer at a slight negative AOA. The downward force thus produced holds the tail down, counterbalancing the "heavy" nose. It is as if the line CG-C_LT were a lever with an upward force at C_L and

two downward forces balancing each other, one a strong force at the CG point and the other, a much lesser force, at point T (downward air pressure on the stabilizer). To better visualize this physics principle: If an iron bar were suspended at point C , with a heavy weight hanging on it at the CG, it would take downward pressure at point T to keep the "lever" in balance.

143. Even though the horizontal stabilizer may be level when the aircraft is in level flight, there is a downwash of air from the wings. This downwash strikes the top of the stabilizer and produces a downward pressure, which at a certain speed is just enough to balance the "lever." The faster the aircraft is flying, the greater this downwash and the greater the downward force on the horizontal stabilizer (except T-tails). [Figure 1.31] In aircraft with fixed-position horizontal stabilizers, the aircraft manufacturer sets the stabilizer at an angle that provides the best stability (or balance) during flight at the design cruising speed and power setting.

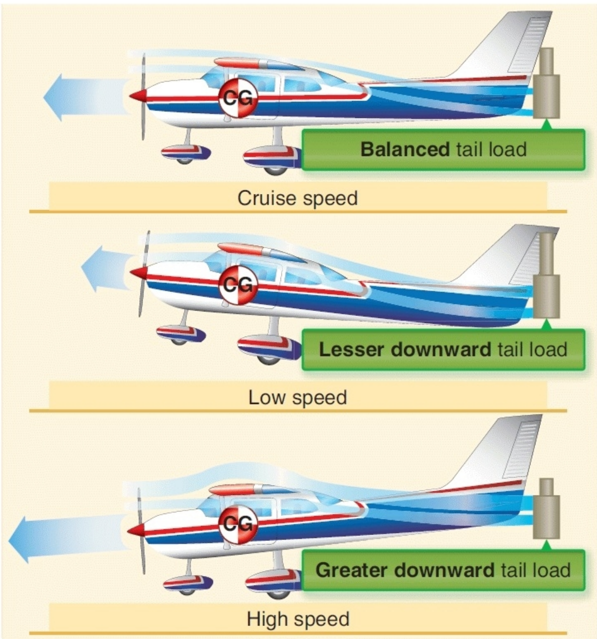


Figure 1.31 Effect of speed on downwash

144. If the aircraft's speed decreases, the speed of the airflow over the wing is decreased. As a result of this decreased flow of air over the wing, the downwash is reduced, causing a lesser downward force on the horizontal stabilizer. In turn, the characteristic nose heaviness is accentuated, causing the aircraft's nose to pitch down more. [Figure 1.32] This places the aircraft in a nose-low attitude, lessening the wing's AOA and drag and allowing the airspeed to increase. As the aircraft continues in the nose-low attitude and its speed increases, the downward force on the horizontal stabilizer is once again increased. Consequently, the tail is again pushed downward and the nose rises into a climbing attitude.

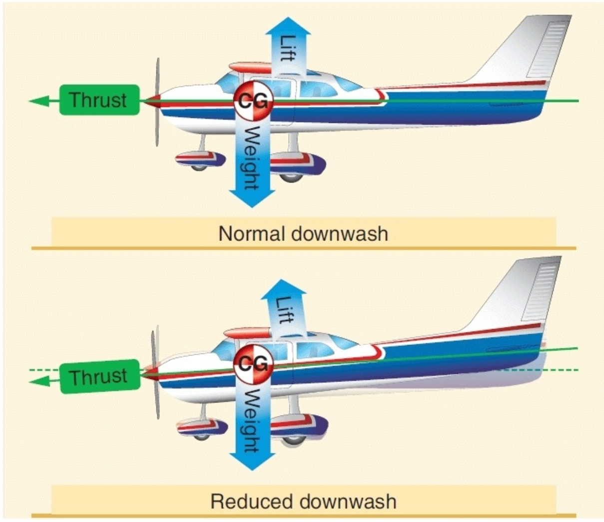


Figure 1.32 Reduced power allows pitch down

145. As this climb continues, the airspeed again decreases, causing the downward force on the tail to decrease until the nose lowers once more. Because the aircraft is dynamically stable, the nose does not lower as far this time as it did before. The aircraft acquires enough speed in this more gradual dive to start it into another climb, but the climb is not as steep as the preceding one.

146. After several of these diminishing oscillations, in which the nose alternately rises and lowers, the aircraft finally settles down to a speed at which the downward force on the tail exactly counteracts the tendency of the aircraft to dive. W hen this condition is attained, the aircraft is once again in balanced flight and continues in stabilized flight as long as this attitude and airspeed are not changed.

147. A similar effect is noted upon closing the throttle. The downwash of the wings is reduced and the force at T in Figure 1.30 is not enough to hold the horizontal stabilizer down. It seems as if the force at T on the lever were allowing the force of gravity to pull the nose down. This is a desirable characteristic because the aircraft is inherently trying to regain airspeed and reestablish the proper balance. Power or thrust can also have a destabilizing effect in that an increase of power may tend to make the nose rise. The aircraft designer can offset this by establishing a "high thrust line" wherein the line of thrust passes

above the CG. [Figures 1.33 and 1.34] In this case, as power or thrust is increased a moment is produced to counteract the down load on the tail. On the other hand, a very "low thrust line" would tend to add to the nose-up effect of the horizontal tail surface.

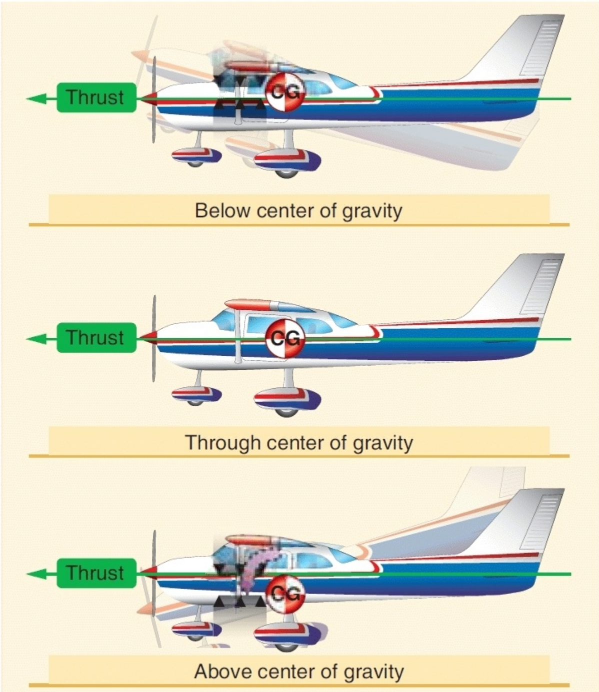


Figure 1.33 Thrust line affects longitudinal stability

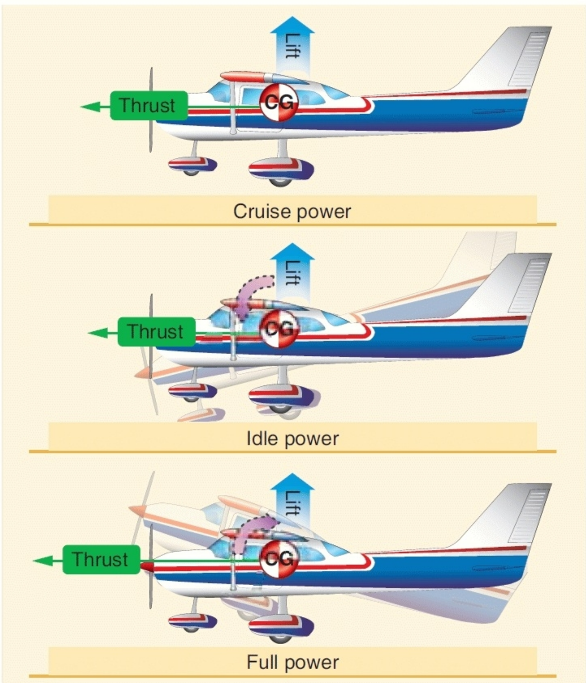


Figure 1.34 Power changes affect longitudinal stability

148. Conclusion: with CG forward of the C and with an aerodynamic tail-down force, the aircraft usually tries to return to a safe flying attitude.

149. The following is a simple demonstration of longitudinal stability. Trim the aircraft for "hands off" control in level flight. Then, momentarily give the controls a slight push to nose the aircraft down. If, within a brief period, the nose rises to the original position and then stops, the aircraft is statically stable. Ordinarily, the nose passes the original position (that of level flight) and a series of slow pitching oscillations follows. If the oscillations gradually cease, the aircraft has positive stability; if they continue unevenly, the aircraft has neutral stability; if they increase, the aircraft is unstable.

Lateral Stability (Rolling)

150. Stability about the aircraft's longitudinal axis, which extends from the nose of the aircraft to its tail, is called lateral stability. This helps to stabilize the lateral or "rolling effect" when one wing gets lower than the wing on the opposite side of the aircraft. There are four main design factors that make an aircraft laterally stable: dihedral, sweepback, keel effect, and weight distribution.

Dihedral

151. The most common procedure for producing lateral stability is to build the wings with an angle of one to three degrees above perpendicular to the longitudinal axis. The wings on either side of the aircraft join the fuselage to form a slight V or angle called "dihedral." The amount of dihedral is measured by the angle made by each wing above a line parallel to the lateral axis.

152. Dihedral involves a balance of lift created by the wings' AOA on each side of the aircraft's longitudinal axis. If a momentary gust of wind forces one wing to rise and the other to lower, the aircraft banks. W hen the aircraft is banked without turning, the tendency to sideslip or slide downward toward the lowered wing occurs. [Figure 1.35] Since the wings have dihedral, the air strikes the lower wing at a much greater AOA than the higher wing. The increased AOA on the lower wing creates more lift than the higher wing. Increased lift causes the lower wing to begin to rise upward. As the wings approach the level position,

the AOA on both wings once again are equal, causing the rolling tendency to subside. The effect of dihedral is to produce a rolling tendency to return the aircraft to a laterally balanced flight condition when a sideslip occurs. The restoring force may move the low wing up too far, so that the opposite wing now goes down. If so, the process is repeated, decreasing with each lateral oscillation until a balance for wings-level flight is finally reached.

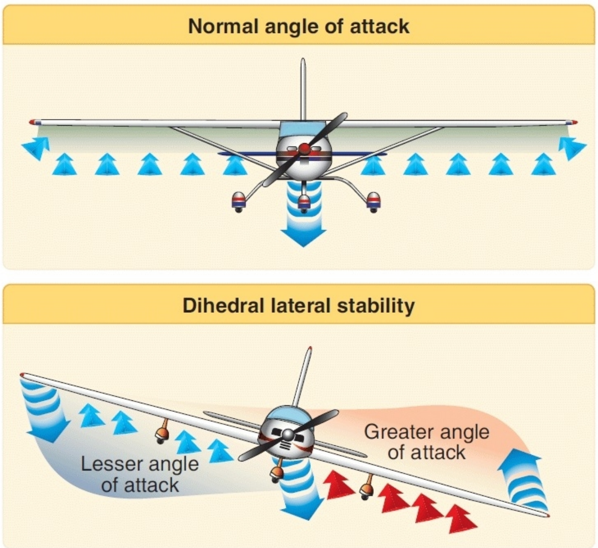


Figure 1.35 Dihedral for lateral stability

153. Conversely, excessive dihedral has an adverse effect on lateral manoeuvreing qualities. The aircraft may be so stable laterally that it resists an intentional rolling motion. For this reason, aircraft that require fast roll or banking characteristics usually have less dihedral than those designed for less m anoeuvreability.

Sweepback

154. Sweepback is an addition to the dihedral that increases the lift created when a wing drops from the level position. A sweptback wing is one in which the leading edge slopes backward. W hen a disturbance causes an aircraft with sweepback to slip or drop a wing, the low wing presents its leading edge at an angle that is perpendicular to the relative airflow. As a result, the low wing acquires more lift, rises, and the aircraft is restored to its original flight attitude. Sweepback also contributes to directional stability. W hen turbulence or rudder application causes the aircraft to yaw to one side, the right wing presents a longer leading edge perpendicular to the relative airflow. The airspeed of the right wing increases and it acquires more drag than the left wing. The additional drag on the right wing pulls it back, turning the aircraft back to its original path.

Keel Effect and Weight Distribution

155. An aircraft always has the tendency to turn the longitudinal axis of the aircraft into the relative wind. This "weather vane" tendency is similar to the keel of a ship and exerts a steadying influence on the aircraft laterally about the longitudinal axis. W hen the aircraft is disturbed and one wing dips, the fuselage weight acts like a pendulum returning the aeroplane to its original attitude.

156. Laterally stable aircraft are constructed so that the greater portion of the keel area is above and behind the CG. [Figure 1.36] Thus, when the aircraft slips to one side, the combination of the aircraft's weight and the pressure of the airflow against the upper portion of the keel area (both acting about the CG) tends to roll the aircraft back to wings-level flight.

Figure 1.36 Keel area for lateral stability

Vertical Stability (Yawing)

157. Stability about the aircraft's vertical axis (the sideways moment) is called yawing or directional stability. Yawing or directional stability is the most easily achieved stability in aircraft design. The area of the vertical fin and the sides of the fuselage aft of the CG are the prime contributors which make the aircraft act like the well known weather vane or arrow, pointing its nose into the relative wind.

158. In examining a weather vane, it can be seen that if exactly the same amount of surface were exposed to the wind in front of the pivot point as behind it, the forces fore and aft would be in balance and little or no directional m ovem ent would r e s u lt. Consequently, it is necessary to have a greater surface

aft of the pivot point than forward of it.

159. Similarly, the aircraft designer must ensure positive directional stability by making the side surface greater aft than ahead of the CG. [Figure 1.37] To provide additional positive stability to that provided by the fuselage, a vertical fin is added. The fin acts similarly to the feather on an arrow in maintaining straight flight. Like the weather vane and the arrow, the farther aft this fin is placed and the larger its size, the greater the aircraft's directional stability.

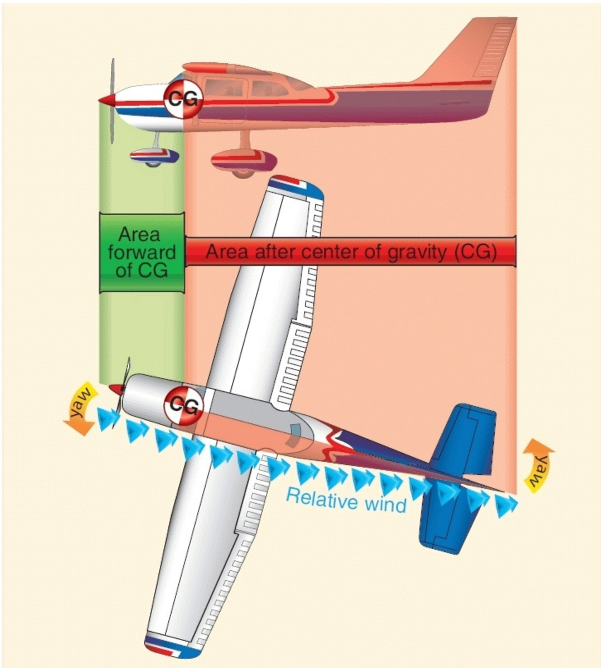


Figure 1.37 Fuselage and fin for vertical stability

160. If an aircraft is flying in a straight line, and a sideward gust of air gives the aircraft a slight rotation about its vertical axis (i.e., to the right), the motion is retarded and stopped by the fin because while the aircraft is rotating to the right, the air is striking the left side of the fin at an angle. This causes pressure on the left side of the fin, which resists the turning motion and slows down the aircraft's yaw. In doing so, it acts somewhat like the weather vane by turning the aircraft into the relative wind. The initial change in direction of the aircraft's flightpath is generally slightly behind its change of heading. Therefore, after a slight yawing of the aircraft to the right, there is a brief moment when the aircraft is still moving along its original path, but its longitudinal axis is pointed slightly to the right.

161. The aircraft is then momentarily skidding sideways, and during that moment (since it is assumed that although the yawing motion has stopped, the excess pressure on the left side of the fin still persists) there is necessarily a tendency for the aircraft to be turned partially back to the left. That is, there is a momentary restoring tendency caused by the fin. This restoring tendency is relatively slow in developing and ceases when the aircraft stops skidding. W hen it ceases, the aircraft is flying in a direction slightly different from the original direction. In other words, it will not return of its own accord to the original heading; the pilot must reestablish the initial heading.

162. A minor improvement of directional stability may be obtained through sweepback. Sweepback is incorporated in the design of the wing primarily to delay the onset of compressibility during high-speed flight. In lighter and slower aircraft, sweepback aids in locating the centre of pressure in the correct relationship with the CG. A longitudinally stable aircraft is built with the centre of pressure aft of the CG.

163. Because of structural reasons, aircraft designers sometimes cannot attach the wings to the fuselage at the exact desired point. If they had to mount the wings too far forward, and at right angles to the fuselage, the centre of pressure would not be far enough to the rear to result in the desired amount of longitudinal stability. By building sweepback into the wings, however, the designers can move the centre of pressure toward the rear. The amount of sweepback and the position of the wings then place the centre of pressure in the correct location.

164. The contribution of the wing to static directional stability is usually small. The swept wing provides a stable contribution depending on the amount of sweepback, but the contribution is relatively small when compared with other components.

Free Directional Oscillations (Dutch Roll)

165. Dutch roll is a coupled lateral/directional oscillation that is usually dynamically stable but is unsafe in an aircraft because of the oscillatory nature. The damping of the oscillatory mode may be weak or strong depending on the properties of the particular aircraft.

166. If the aircraft has a right wing pushed down, the positive sideslip angle corrects the wing laterally before the nose is realigned with the relative wind. As the wing corrects the position, a lateral directional

oscillation can occur resulting in the nose of the aircraft making a figure eight on the horizon as a result of two oscillations (roll and yaw), which, although of about the same magnitude, are out of phase with each other.

167. In most modern aircraft, except high-speed swept wing designs, these free directional oscillations usually die out automatically in very few cycles unless the air continues to be gusty or turbulent. Those aircraft with continuing Dutch roll tendencies are usually equipped with gyro-stabilized yaw dampers. Manufacturers try to reach a midpoint between too much and too little directional stability. Because it is more desirable for the aircraft to have "spiral instability" than Dutch roll tendencies, most aircraft are designed with that characteristic.

Spiral Instability

168. Spiral instability exists when the static directional stability of the aircraft is very strong as compared to the effect of its dihedral in maintaining lateral equilibrium. W hen the lateral equilibrium of the aircraft is disturbed by a gust of air and a sideslip is introduced, the strong directional stability tends to yaw the nose into the resultant relative wind while the comparatively weak dihedral lags in restoring the lateral balance. Due to this yaw, the wing on the outside of the turning moment travels forward faster than the inside wing and, as a consequence, its lift becomes greater. This produces an over-banking tendency which, if not corrected by the pilot, results in the bank angle becoming steeper and steeper. At the same time, the strong directional stability that yaws the aircraft into the relative wind is actually forcing the nose to a lower pitch attitude. A slow downward spiral begins which, if not counteracted by the pilot, gradually increases into a steep spiral dive. Usually the rate of divergence in the spiral motion is so gradual the pilot can control the tendency without any difficulty.

169. All aircraft are affected to some degree by this characteristic, although they may be inherently stable in all other normal parameters. This tendency explains why an aircraft cannot be flown "hands off" indefinitely.

170. Much research has gone into the development of control devices (wing leveler) to correct or eliminate this instability. The pilot must be careful in application of recovery controls during advanced stages of this spiral condition or excessive loads may be imposed on the structure. Improper recovery from spiral instability leading to in-flight structural failures has probably contributed to more fatalities in general aviation aircraft than any other factor. Since the airspeed in the spiral condition builds up rapidly, the application of back elevator force to reduce this speed and to pull the nose up only "tightens the turn," increasing the load factor. The results of the prolonged uncontrolled spiral are in-flight structural failure or crashing into the ground, or both. The most common recorded causes for pilots who get into this situation are: loss of horizon reference, inability to control the aircraft by reference to instruments, or a combination of both.

Aerodynamic Forces in Flight Manoeuvres

Forces in Turns

171. If an aircraft were viewed in straight-and-level flight from the front [Figure 1.38], and if the forces acting on the aircraft could be seen, lift and weight would be apparent: two forces. If the aircraft were in a bank it would be apparent that lift did not act directly opposite to the weight, rather it now acts in the direction of the bank. A basic truth about turns: when the aircraft banks, lift acts inward toward the centre of the turn, as well as upward.

172. Newton's First Law of Motion, the Law of Inertia, states that an object at rest or moving in a straight line remains at rest or continues to move in a straight line until acted on by some other force. An aircraft, like any moving object, requires a sideward force to make it turn. In a normal turn, this force is supplied by banking the aircraft so that lift is exerted inward, as well as upward. The force of lift during a turn is separated into two components at right angles to each other. One component, which acts vertically and opposite to the weight (gravity), is called the "vertical component of lift." The other, which acts horizontally toward the centre of the turn, is called the "horizontal component of lift," or centripetal force. The horizontal component of lift is the force that pulls the aircraft from a straight flightpath to make it turn. Centrifugal force is the "equal and opposite reaction" of the aircraft to the change in direction and acts equal and opposite to the horizontal component of lift. This explains why, in a correctly executed turn, the force that turns the aircraft is not supplied by the rudder. The rudder is used to correct any deviation between the

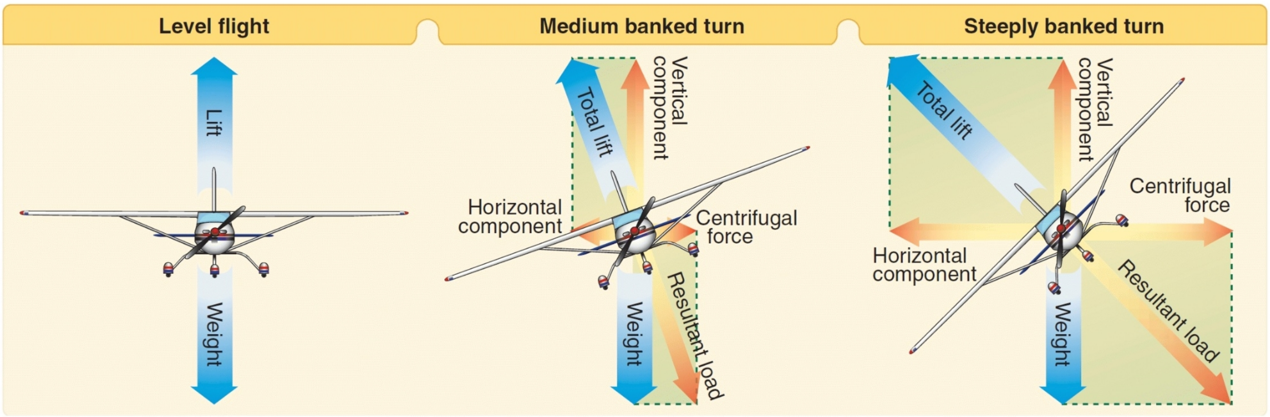


Figure 1.38 Forces in a normal coordinated turn

straight track of the nose and tail of the aircraft. A good turn is one in which the nose and tail of the aircraft track along the same path. If no rudder is used in a turn, the nose of the aircraft yaws to the outside of the turn. The rudder is used to bring the nose back in line with the relative wind.

173. An aircraft is not steered like a boat or a car. In order for an aircraft to turn, it must be banked. If it is not banked, there is no force available to cause it to deviate from a straight flightpath. Conversely, when an aircraft is banked, it turns, provided it is not slipping to the inside of the turn. Good directional control is based on the fact that the aircraft attempts to turn whenever it is banked. Pilots should keep this fact in mind when attempting to hold the aircraft in straight-and-level flight.

174. Merely banking the aircraft into a turn produces no change in the total amount of lift developed. Since the lift during the bank is divided into vertical and horizontal components, the amount of lift opposing gravity and supporting the aircraft's weight is reduced. Consequently, the aircraft loses altitude unless additional lift is created. This is done by increasing the AOA until the vertical component of lift is again equal to the weight. Since the vertical component of lift decreases as the bank angle increases, the AOA must be progressively increased to produce sufficient vertical lift to support the aircraft's weight. An important fact for pilots to remember when making constant altitude turns is that the vertical component of lift must be equal to the weight to maintain altitude.

175. At a given airspeed, the rate at which an aircraft turns depends upon the magnitude of the horizontal component of lift. It is found that the horizontal component of lift is proportional to the angle of bank - that is, it increases or decreases respectively as the angle of bank increases or decreases. As the angle of bank is increased, the horizontal component of lift increases, thereby increasing the ROT. Consequently, at any given airspeed, the ROT can be controlled by adjusting the angle of bank.

176. To provide a vertical component of lift sufficient to hold altitude in a level turn, an increase in the AOA is required. Since the drag of the aerofoil is directly proportional to its AOA, induced drag increases as the lift is increased. This, in turn, causes a loss of airspeed in proportion to the angle of bank. A small angle of bank results in a small reduction in airspeed while a large angle of bank results in a large reduction in airspeed. Additional thrust (power) must be applied to prevent a reduction in airspeed in level turns. The required amount of additional thrust is proportional to the angle of bank.

177. To compensate for added lift, which would result if the airspeed were increased during a turn, the AOA must be decreased, or the angle of bank increased, if a constant altitude is to be maintained. If the angle of bank is held constant and the AOA decreased, the ROT decreases. In order to maintain a constant-ROT as the airspeed is increased, the AOA must remain constant and the angle of bank increased.

178. An increase in airspeed results in an increase of the turn radius, and centrifugal force is directly proportional to the radius of the turn. In a correctly executed turn, the horizontal component of lift must be exactly equal and opposite to the centrifugal force. As the airspeed is increased in a constant rate level turn,

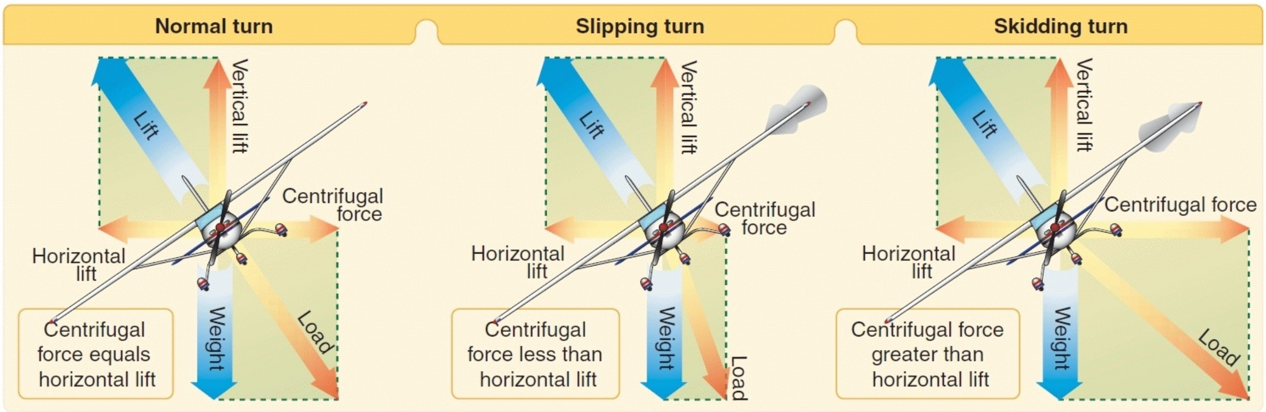


Figure 1.39 Normal, slipping, and skidding turns

the radius of the turn increases. This increase in the radius of turn causes an increase in the centrifugal force, which must be balanced by an increase in the horizontal component of lift, which can only be increased by increasing the angle of bank.

179. In a slipping turn, the aircraft is not turning at the rate appropriate to the bank being used, since the aircraft is yawed toward the outside of the turning flightpath. The aircraft is banked too much for the ROT, so the horizontal lift component is greater than the centrifugal force. [Figure 1.39] Equilibrium between the horizontal lift component and centrifugal force is reestablished by either decreasing the bank, increasing the ROT, or a combination of the two changes.

180. A skidding turn results from an excess of centrifugal force over the horizontal lift component, pulling the aircraft toward the outside of the turn. The rate of turn (ROT) is too great for the angle of bank. Correction of a skidding turn thus involves a reduction in the ROT, an increase in bank, or a combination of the two changes.

181. To maintain a given ROT, the angle of bank must be varied with the airspeed. This becomes particularly important in high-speed aircraft. For instance, at 400 miles per hour (mph), an aircraft must be banked approximately 44° to execute a standard-rate turn (3° per second). At this angle of bank, only about 79 percent of the lift of the aircraft comprises the vertical component of the lift. This causes a loss of altitude unless the AOA is increased sufficiently to compensate for the loss of vertical lift.

Forces in Climbs

182. For all practical purposes, the wing's lift in a steady state normal climb is the same as it is in a steady level flight at the same airspeed. Although the aircraft's flightpath changed when the climb was established, the AOA of the wing with respect to the inclined flightpath reverts to practically the same values, as does the lift. There is an initial momentary change as shown in Figure 1.40. During the transition from straight-and-level flight to a climb, a change in lift occurs when back elevator pressure is first applied. Raising the aircraft's nose increases the AOA and momentarily increases the lift. Lift at this moment is now greater than weight and starts the aircraft climbing. After the flightpath is stabilized on the upward incline, the AOA and lift again revert to about the level flight values.

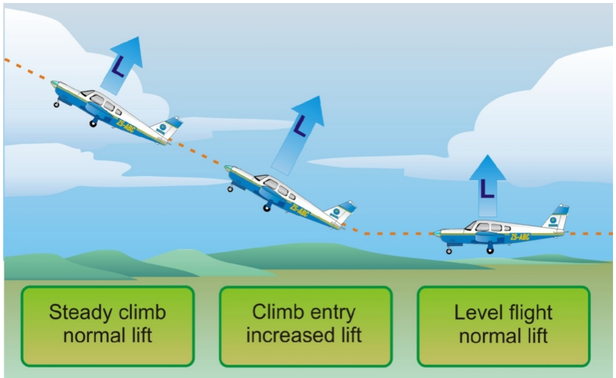


Figure 1.40 Changes in lift during climb entry

183. If the climb is entered with no change in power setting, the airspeed gradually diminishes because the thrust required to maintain a given airspeed in level

flight is insufficient to maintain the same airspeed in a climb. W hen the flightpath is inclined upward, a component of the aircraft's weight acts in the same direction as, and parallel to, the total drag of the aircraft, thereby increasing the total effective drag. Consequently, the total drag is greater than the power, and the airspeed decreases. The reduction in airspeed gradually results in a corresponding decrease in drag until the total drag (including the component of weight acting in the same direction) equals the thrust. [Figure 1.41] Due to momentum, the change in airspeed is gradual, varying considerably with differences in aircraft size, weight, total drag, and other factors. Consequently, the total drag is greater than the thrust, and the airspeed decreases.

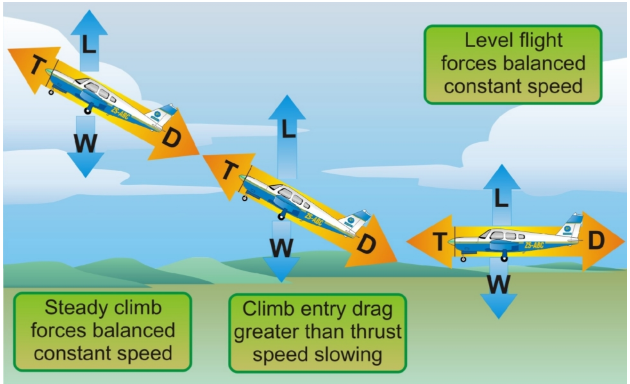


Figure 1.41 Changes in speed during climb entry

184. Generally, the forces of thrust and drag, and lift and weight, again become balanced when the airspeed stabilizes but at a value lower than in straight-and-level flight at the same power setting. Since the aircraft's weight is acting not only downward but rearward with drag while in a climb, additional power is required to maintain the same airspeed as in level flight. The amount of power depends on the angle of climb. W hen the climb is established steep enough so that there is insufficient power available, a slower speed results. The thrust required for a stabilized climb equals drag plus a percentage of weight dependent on the angle of climb. For example, a 10° climb would require thrust to equal drag plus 17% of weight. To climb straight up would require thrust to equal all of weight and drag. Therefore, the angle of climb for climb performance is dependent on the amount of excess power available to overcome a portion of weight. Note that aircraft are able to sustain a climb due to excess thrust. W hen the excess thrust is gone, the aircraft is no longer able to climb. At this point, the aircraft has reached its "absolute ceiling."

Forces in Descents

185. As in climbs, the forces which act on the aircraft go through definite changes when a descent is entered from straight-and- level flight. For the following example, the aircraft is descending at the same power as used in straight-and-level flight.

186. As forward pressure is applied to the control yoke to initiate the descent, the AOA is decreased momentarily. Initially, the momentum of the aircraft causes the aircraft to briefly continue along the same flightpath. For this instant, the AOA decreases causing the total lift to decrease. W ith weight now being greater than lift, the aircraft begins to descend. At the same time, the flightpath goes from level to a descending flightpath. Do not confuse a reduction in lift with the inability to generate sufficient lift to maintain level flight. The flightpath is being manipulated with available thrust in reserve and with the elevator.

187. To descend at the same airspeed as used in straight-and-level flight, the power must be reduced as the descent is entered. The component of weight acting forward along the flightpath increases as the angle of rate of descent increases and, conversely, decreases as the angle of rate of descent decreases. The component of weight acting forward along the flightpath increases as the angle of rate of descent increases and, conversely, decreases as the angle of rate of descent decreases.

Stalls

188. An aircraft stall results from a rapid decrease in lift caused by the separation of airflow from the wing's surface brought on by exceeding the critical AOA. A stall can occur at any pitch attitude or airspeed. Stalls are one of the most misunderstood areas of aerodynamics because pilots often believe an aerofoil stops producing lift when it stalls. In a stall, the wing does not totally stop producing lift. Rather, it can not generate adequate lift to sustain level flight.

189. Since the C_L increases with an increase in AOA, at some point the C_L peaks and then begins to drop off. This peak is called the $C_{L\text{-}MAX}$. The amount of lift the wing produces drops dramatically after exceeding the $C_{L\text{-}MAX}$ or critical AOA, but as stated above, it does not completely stop producing lift. In most straight-wing aircraft, the wing is designed to stall

at the wing root first. The wing root reaches its critical AOA first making the stall progress outward toward the wingtip. By having the wing root stall first, aileron effectiveness is maintained at the wingtips, maintaining controllability of the aircraft. Various design methods are used to achieve the stalling of the wing root first. In one design, the wing is “twisted” to a higher AOA at the wing root. Installing stall strips on the first 20 - 25 percent of the wing’s leading edge is another method to introduce a stall prematurely.

190. The wing never completely stops producing lift in a stalled condition. If it did, the aircraft would fall to the Earth. Most training aircraft are designed for the nose of the aircraft to drop during a stall, reducing the AOA and “unstalling” the wing. The “nose-down” tendency is due to the CL being aft of the CG. The CG range is very important when it comes to stall recovery characteristics. If an aircraft is allowed to be operated outside of the CG, the pilot may have difficulty recovering from a stall. The most critical CG violation would occur when operating with a CG which exceeds the rear limit. In this situation, a pilot may not be able to generate sufficient force with the elevator to counteract the excess weight aft of the CG. W ithout the ability to decrease the AOA, the aircraft continues in a stalled condition until it contacts the ground. The stalling speed of a particular aircraft is not a fixed value for all flight situations, but a given aircraft always stalls at the same AOA regardless of airspeed, weight, load factor, or density altitude. Each aircraft has a particular AOA where the airflow separates from the upper surface of the wing and the stall occurs. This critical AOA varies from 16° to 20° depending on the aircraft’s design. But each aircraft has only one specific AOA where the stall occurs.

191. There are three flight situations in which the critical AOA can be exceeded: low speed, high speed, and turning. The aircraft can be stalled in straight-and-level flight by flying too slowly. As the airspeed decreases, the AOA must be increased to retain the lift required for maintaining altitude. The lower the airspeed becomes, the more the AOA must be increased. Eventually, an AOA is reached which results in the wing not producing enough lift to support the aircraft which starts settling. If the airspeed is reduced further, the aircraft stalls, since the AOA has exceeded the critical angle and the airflow over the wing is disrupted.

192. Low speed is not necessary to produce a stall. The wing can be brought into an excessive AOA at any speed. For example, an aircraft is in a dive with an airspeed of 100 knots when the pilot pulls back sharply on the elevator control. [Figure 1.42] Gravity and centrifugal force prevent an immediate alteration of the flightpath, but the aircraft’s AOA changes abruptly from quite low to very high. Since the flightpath of the aircraft in relation to the oncoming air determines the direction of the relative wind, the AOA is suddenly increased, and the aircraft would reach the stalling angle at a speed much greater than the normal stall speed.

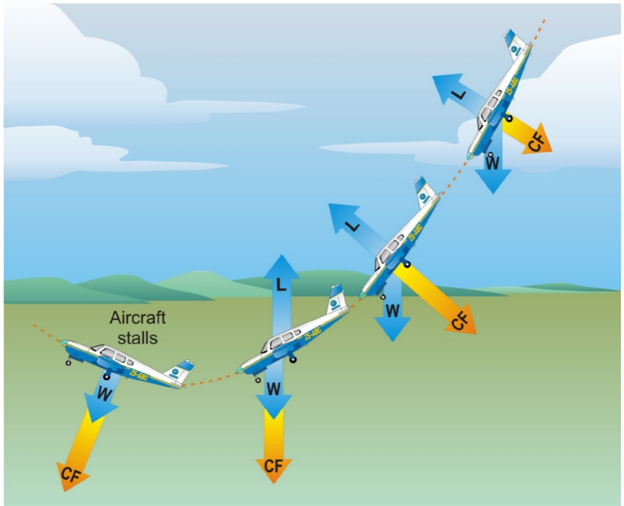


Figure 1.42 Forces exerted when pulling out of a dive

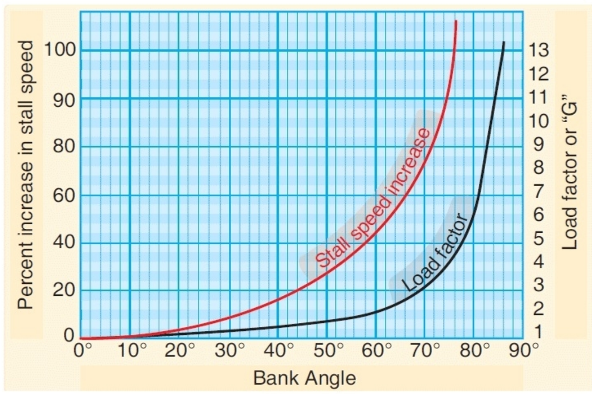


Figure 1.43 Increase in stall speed and load factor

193. The stalling speed of an aircraft is also higher in a level turn than in straight-and-level flight. [Figure 1-43] Centrifugal force is added to the aircraft’s weight and the wing must produce sufficient additional lift to counterbalance the load imposed by the combination of centrifugal force and weight. In a turn, the necessary additional lift is acquired by applying back pressure to

the elevator control. This increases the wing's AOA, and results in increased lift. The AOA must increase as the bank angle increases to counteract the increasing load caused by centrifugal force. If at any time during a turn the AOA becomes excessive, the aircraft stalls.

194. At this point, the action of the aircraft during a stall should be examined. To balance the aircraft aerodynamically, the CL is normally located aft of the CG. Although this makes the aircraft inherently nose-heavy, downwash on the horizontal stabilizer counteracts this condition. At the point of stall, when the upward force of the wing's lift and the downward tail force cease, an unbalanced condition exists. This allows the aircraft to pitch down abruptly, rotating about its CG. During this nose-down attitude, the AOA decreases and the airspeed again increases. The smooth flow of air over the wing begins again, lift returns, and the aircraft is again flying. Considerable altitude may be lost before this cycle is complete.

195. Aerofoil shape and degradation of that shape must also be considered in a discussion of stalls. For example, if ice, snow, and frost are allowed to accumulate on the surface of an aircraft, the smooth airflow over the wing is disrupted. This causes the boundary layer to separate at an AOA lower than that of the critical angle. Lift is greatly reduced, altering expected aircraft performance. If ice is allowed to accumulate on the aircraft during flight [Figure 4-44], the weight of the aircraft is increased while the ability to generate lift is decreased. As little as 0.8 millimeter of ice on the upper wing surface increases drag and reduces aircraft lift by 25 percent.

Figure 1.44 Inflight ice formation

196. Pilots can encounter icing in any season, anywhere in the country, at altitudes of up to 18,000 feet and sometimes higher. Small aircraft, including commuter planes, are most vulnerable because they fly at lower altitudes where ice is more prevalent. They also lack mechanisms common on jet aircraft that prevent ice buildup by heating the front edges of wings.

197. Icing can occur in clouds any time the temperature drops below freezing and super-cooled droplets build up on an aircraft and freeze. (Super-cooled droplets are still liquid even though the temperature is below 0° Celsius (C).

Basic Propeller Principles

198. The aircraft propeller consists of two or more blades and a central hub to which the blades are attached. Each blade of an aircraft propeller is essentially a rotating wing. As a result of their construction, the propeller blades are like aerofoils and produce forces that create the thrust to pull, or push, the aircraft through the air. The engine furnishes the power needed to rotate the propeller blades through the air at high speeds, and the propeller transforms the rotary power of the engine into forward thrust.

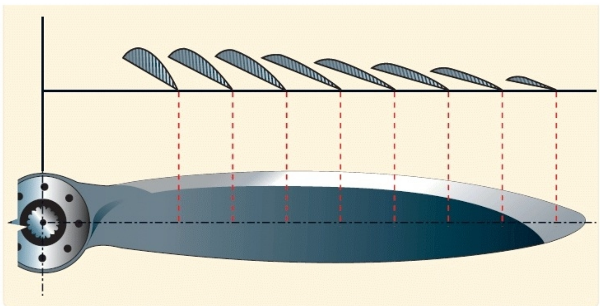


Figure 1.45 Aerofoil sections of a propeller

199. A cross-section of a typical propeller blade is shown in Figure 1.45. This section or blade element is an aerofoil comparable to a cross-section of an aircraft wing. One surface of the blade is cambered or curved, similar to the upper surface of an aircraft wing, while the other surface is flat like the bottom surface of a wing. The chord line is an imaginary line drawn through the blade from its leading edge to its trailing edge. As in a wing, the leading edge is the thick edge of the blade that meets the air as the propeller rotates. Blade angle, usually measured in degrees, is the angle between the chord of the blade and the plane of rotation and is measured at a specific point along the length of the blade. [Figure 4-46] Because m ost propellers have a flat blade "face," the chord line is often drawn along the face of the propeller blade. Pitch is not blade angle, but because pitch is largely determined by blade angle, the two terms are often

used interchangeably. An increase or decrease in one is usually associated with an increase or decrease in the other. The pitch of a propeller may be designated in inches. A propeller designated as a "74-48" would be 74 inches in length and have an effective pitch of 48 inches. The pitch is the distance in inches, which the propeller would screw through the air in one revolution if there were no slippage. W hen specifying a fixed-pitch propeller for a new type of aircraft, the manufacturer usually selects one with a pitch that operates efficiently at the expected cruising speed of the aircraft. Every fixed-pitch propeller must be a compromise because it can be efficient at only a given combination of airspeed and revolutions per minute (rpm). Pilots cannot change this combination in flight.

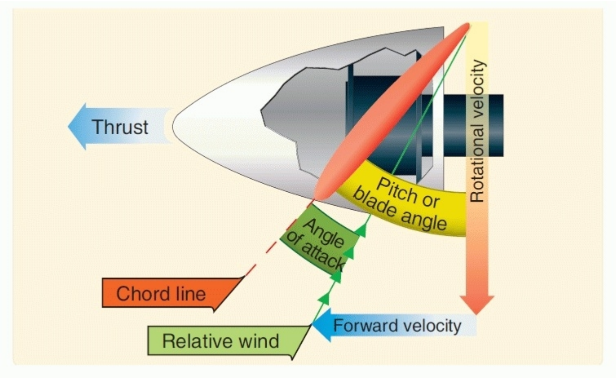


Figure 1.46 Propeller blade angle

200. W hen the aircraft is at rest on the ground with the engine operating, or moving slowly at the beginning of takeoff, the propeller efficiency is very low because the propeller is restrained from advancing with sufficient speed to permit its fixed-pitch blades to reach their full efficiency. In this situation, each propeller blade is turning through the air at an AOA that produces relatively little thrust for the amount of power required to turn it.

201. To understand the action of a propeller, consider first its motion, which is both rotational and forward. As shown by the vectors of propeller forces in Figure 1.46, each section of a propeller blade moves downward and forward. The angle at which this air (relative wind) strikes the propeller blade is its AOA. The air deflection produced by this angle causes the dynamic pressure at the engine side of the propeller blade to be greater than atmospheric pressure, thus creating thrust. The shape of the blade also creates thrust because it is cambered like the aerofoil shape of a wing. As the air flows past the propeller, the pressure on one side is less than that on the other. As in a wing, a reaction force is produced in the direction of the lesser pressure. The airflow over the wing has less pressure, and the force (lift) is upward. In the case of the propeller, which is mounted in a vertical instead of a horizontal plane, the area of decreased pressure is in front of the propeller, and the force (thrust) is in a forward direction. Aerodynamically, thrust is the result of the propeller shape and the AOA of the blade.

202. Thrust can be considered also in terms of the mass of air handled by the propeller. In these terms, thrust equals mass of air handled multiplied by slipstream velocity minus velocity of the aircraft. The power expended in producing thrust depends on the rate of air mass movement. On average, thrust constitutes approximately 80 percent of the torque (total horsepower absorbed by the propeller). The other 20 percent is lost in friction and slippage. For any speed of rotation, the horsepower absorbed by the propeller balances the horsepower delivered by the engine. For any single revolution of the propeller, the amount of air handled depends on the blade angle, which determines how big a "bite" of air the propeller takes. Thus, the blade angle is an excellent means of adjusting the load on the propeller to control the engine rpm .

203. The blade angle is also an excellent method of adjusting the AOA of the propeller. On constant-speed propellers, the blade angle must be adjusted to provide the most efficient AOA at all engine and aircraft speeds. Lift versus drag curves, which are drawn for propellers, as well as wings, indicate that the most efficient AOA is small, varying from +2 to +4 . The actual blade angle necessary to maintain this small AOA varies with the forward speed of the aircraft.

204. Fixed-pitch and ground-adjustable propellers are designed for best efficiency at one rotation and forward speed. They are designed for a given aircraft and engine combination. A propeller may be used that provides the maximum efficiency for takeoff, climb, cruise, or high-speed flight. Any change in these conditions results in lowering the efficiency of both the propeller and the engine. Since the efficiency of any machine is the ratio of the useful power output to the actual power input, propeller efficiency is the ratio of thrust horsepower to brake horsepower. Propeller efficiency varies from 50 to 87 percent, depending on how much the propeller "slips."

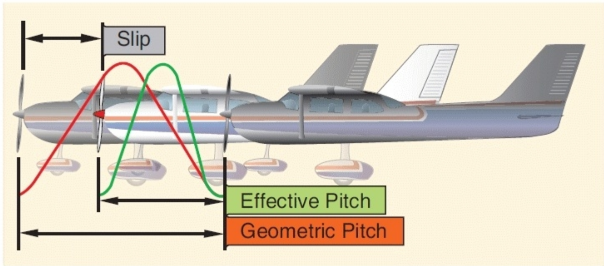


Figure 1.47 Propeller slippage

205. Propeller slip is the difference between the geometric pitch of the propeller and its effective pitch. [Figure 1.47] Geometric pitch is the theoretical distance a propeller should advance in one revolution; effective pitch is the distance it actually advances. Thus, geometric or theoretical pitch is based on no slippage, but actual or effective pitch includes propeller slippage in the air.

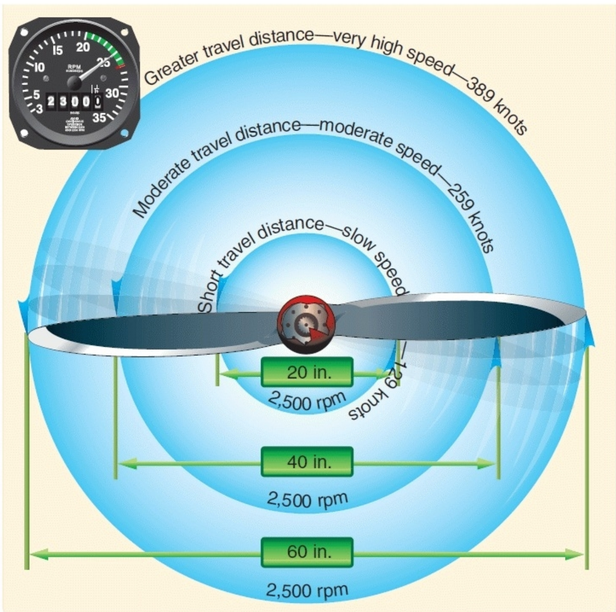


Figure 1.48 Propeller tips travel faster than the hub

206. The reason a propeller is "twisted" is that the outer parts of the propeller blades, like all things that turn about a central point, travel faster than the portions near the hub. [Figure 1.48] If the blades had the same geometric pitch throughout their lengths, portions near the hub could have negative AOAs while the propeller tips would be stalled at cruise speed. Twisting or variations in the geometric pitch of the blades permits the propeller to operate with a relatively constant AOA along its length when in cruising flight. Propeller blades are twisted to change the blade angle in proportion to the differences in speed of rotation along the length of the propeller, keeping thrust more nearly equalized along this length.

207. Usually 1 to 4 provides the most efficient lift/drag ratio, but in flight the propeller AOA of a fixed-pitch propeller varies - normally from 0 to 15 . This variation is caused by changes in the relative airstream, which in turn results from changes in aircraft speed. Thus, propeller AOA is the product of two motions: propeller rotation about its axis and its forward motion.

208. A constant-speed propeller autom atically keeps the blade angle adjusted for maximum efficiency for most conditions encountered in flight. During takeoff, when maximum power and thrust are required, the constant-speed propeller is at a low propeller blade angle or pitch. The low blade angle keeps the AOA small and efficient with respect to the relative wind. At the same time, it allows the propeller to handle a smaller mass of air per revolution. This light load allows the engine to turn at high rpm and to convert the maximum amount of fuel into heat energy in a given time. The high rpm also creates maximum thrust because, although the mass of air handled per revolution is small, the rpm and slipstream velocity are high, and with the low aircraft speed, there is maximum thrust.

209. After liftoff, as the speed of the aircraft increases, the constant speed propeller automatically changes to a higher angle (or pitch). Again, the higher blade angle keeps the AOA small and efficient with respect to the relative wind. The higher blade angle increases the mass of air handled per revolution. This decreases the engine rpm, reducing fuel consumption and engine wear, and keeps thrust at a maximum.

210. After the takeoff climb is established in an aircraft having a controllable-pitch propeller, the pilot reduces the power output of the engine to climb power by first decreasing the manifold pressure and then increasing the blade angle to lower the rpm.

211. At cruising altitude, when the aircraft is in level flight and less power is required than is used in takeoff or climb, the pilot again reduces engine power by

reducing the manifold pressure and then increasing the blade angle to decrease the rpm. Again, this provides a torque requirement to match the reduced engine power. Although the mass of air handled per revolution is greater, it is more than offset by a decrease in slipstream velocity and an increase in airspeed. The AOA is still small because the blade angle has been increased with an increase in airspeed.

Torque and P-Factor

212. To the pilot, " torque" (the left turning tendency of the aeroplane) is made up of four elements which cause or produce a twisting or rotating motion around at least one of the aeroplane's three axes. These four elements are:

a. Torque reaction from engine and propeller,

b. Corkscrewing effect of the slipstream,

c. Gyroscopic action of the propeller, and

d. Asymmetric loading of the propeller (P-factor).

Torque Reaction

213. Torque reaction involves Newton's Third Law of Physics - for every action, there is an equal and opposite reaction. As applied to the aircraft, this means that as the internal engine parts and propeller are revolving in one direction, an equal force is trying to rotate the aircraft in the opposite direction. [Figure 1.49]

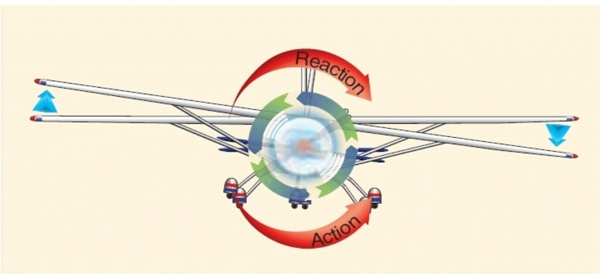


Figure 1.49 Torque reaction

213. W hen the aircraft is airborne, this force is acting around the longitudinal axis, tending to make the aircraft roll. To compensate for roll tendency, some of the older aircraft are rigged in a manner to create more lift on the wing that is being forced downward. The more modern aircraft are designed with the engine offset to counteract this effect of torque. NOTE: Most United States built aircraft engines rotate the propeller clockwise, as viewed from the pilot's seat. The discussion here is with reference to those engines.

214. Generally, the compensating factors are permanently set so that they compensate for this force at cruising speed, since most of the aircraft's operating lift is at that speed. However, aileron trim tabs permit further adjustment for other speeds.

215. W hen the aircraft's wheels are on the ground during the takeoff roll, an additional turning moment around the vertical axis is induced by torque reaction. As the left side of the aircraft is being forced down by torque reaction, more weight is being placed on the left main landing gear. This results in more ground friction, or drag, on the left tire than on the right, causing a further turning moment to the left. The magnitude of this moment is dependent on many variables. Some of these variables are:

a. Size and horsepower of engine,

b. Size of propeller and the rpm,

c. Size of the aircraft, and

d. Condition of the ground surface.

216. This yawing moment on the takeoff roll is corrected by the pilot's proper use of the rudder or rudder trim.

Corkscrew Effect

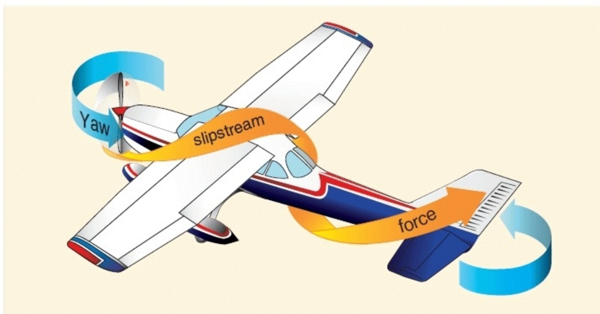


Figure 1.50 Corkscrewing slipstream

217. The high-speed rotation of an aircraft propeller gives a corkscrew or spiralling rotation to the slipstream. At high propeller speeds and low forward speed (as in the takeoffs and approaches to power-on

stalls), this spiralling rotation is very compact and exerts a strong sideward force on the aircraft's vertical tail surface. [Figure 1.50]

218. When this spiralling slipstream strikes the vertical fin it causes a turning moment about the aircraft's vertical axis. The more compact the spiral, the more prominent this force is. As the forward speed increases, however, the spiral elongates and becomes less effective. The corkscrew flow of the slipstream also causes a rolling moment around the longitudinal axis. Note that this rolling moment caused by the corkscrew flow of the slipstream is to the right, while the rolling moment caused by torque reaction is to the left - in effect one may be counteracting the other. However, these forces vary greatly and it is the pilot's responsibility to apply proper corrective action by use of the flight controls at all times. These forces must be counteracted regardless of which is the most prominent at the time.

Gyroscopic Action

219. Before the gyroscopic effects of the propeller can be understood, it is necessary to understand the basic principle of a gyroscope. All practical applications of the gyroscope are based upon two fundamental properties of gyroscopic action: rigidity in space and precession. The one of interest for this discussion is precession.

220. Precession is the resultant action, or deflection, of a spinning rotor when a deflecting force is applied to its rim. As can be seen in Figure 1.51, when a force is applied, the resulting force takes effect 90° ahead of and in the direction of rotation.

221. The rotating propeller of an aeroplane makes a very good gyroscope and thus has similar properties. Any time a force is applied to deflect the propeller out of its plane of rotation, the resulting force is 90° ahead of and in the direction of rotation and in the direction of application, causing a pitching moment, a yawing moment, or a combination of the two depending upon the point at which the force was applied. This element of torque effect has always been associated with and considered more prominent in tailwheel-type aircraft, and most often occurs when the tail is being raised during the takeoff roll. This change in pitch attitude has the same effect as applying a force to the top of the propeller's plane of rotation. The resultant force acting 90° ahead causes a yawing moment to the left around the vertical axis. The magnitude of this moment depends on several variables, one of which is the abruptness with which the tail is raised (amount of force applied). However, precession, or gyroscopic action, occurs when a force is applied to any point on the rim of the propeller's plane of rotation; the resultant force will still be 90° from the point of application in the direction of rotation. Depending on where the force is applied, the aeroplane is caused to yaw left or right, to pitch up or down, or a combination of pitching and yawing. It can be said that, as a result of gyroscopic action, any yawing around the vertical axis results in a pitching moment, and any pitching around the lateral axis results in a yawing moment. To correct for the effect of gyroscopic action, it is necessary for the pilot to properly use elevator and rudder to prevent undesired pitching and yawing.

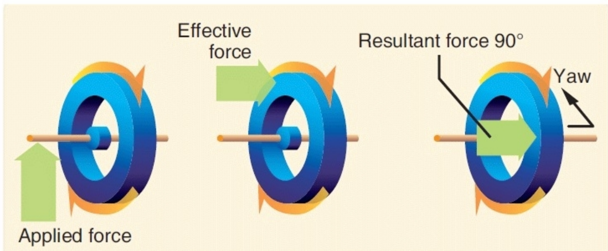


Figure 1.51 Gyroscopic precession

Asymmetric Loading (P-Factor)

222. When an aircraft is flying with a high AOA, the "bite" of the downward moving blade is greater than the "bite" of the upward moving blade. This moves the centre of thrust to the right of the prop disc area, causing a yawing moment toward the left around the vertical axis. To prove this explanation is complex because it would be necessary to work wind vector problems on each blade while considering both the AOA of the aircraft and the AOA of each blade.

223. This asymmetric loading is caused by the resultant velocity, which is generated by the combination of the velocity of the propeller blade in its plane of rotation and the velocity of the air passing horizontally through the propeller disc. With the aircraft being flown at positive AOAs, the right (viewed from the rear) or downgoing blade, is passing through an area of resultant velocity which is greater than that affecting the left or upgoing blade. Since the propeller

blade is an aerofoil, increased velocity m eans increased lift. The downgoing blade has more lift and tends to pull (yaw) the aircraft's nose to the left.

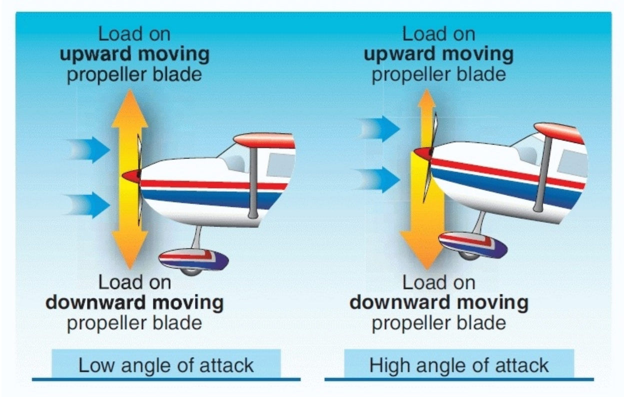


Figure 1.52 Asymmetrical loading of propeller (P factor)

224. W hen the aircraft is flying at a high AOA, the downward moving blade has a higher resultant velocity, creating more lift than the upward moving blade. [Figure 1.52] This might be easier to visualize if the propeller shaft was mounted perpendicular to the ground (like a helicopter). If there were no air movement at all, except that generated by the propeller itself, identical sections of each blade would have the same airspeed. W ith air moving horizontally across this vertically mounted propeller, the blade proceeding forward into the flow of air has a higher airspeed than the blade retreating with the airflow. Thus, the blade proceeding into the horizontal airflow is creating more lift, or thrust, moving the centre of thrust toward that blade. Visualize rotating the vertically mounted propeller shaft to shallower angles relative to the moving air (as on an aircraft). This unbalanced thrust then becomes proportionately smaller and continues getting smaller until it reaches the value of zero when the propeller shaft is exactly horizontal in relation to the moving air.

225. The effects of each of these four elements of torque vary in value with changes in flight situations. In one phase of flight, one of these elements may be more prominent than another. In another phase of flight, another element may be more prominent. The relationship of these values to each other varies with different aircraft - depending on the airframe, engine, and propeller combinations, as well as other design features. To maintain positive control of the aircraft in all flight conditions, the pilot must apply the flight controls as necessary to compensate for these varying values.

Load Factors

226. In aerodynamics, load factor is the ratio of the maximum load an aircraft can sustain to the gross weight of the aircraft. The load factor is measured in Gs (acceleration of gravity), a unit of force equal to the force exerted by gravity on a body at rest and indicates the force to which a body is subjected when it is accelerated. Any force applied to an aircraft to deflect its flight from a straight line produces a stress on its structure, and the amount of this force is the load factor. W hile a course in aerodynamics is not a prerequisite for obtaining a pilot's license, the competent pilot should have a solid understanding of the forces that act on the aircraft, the advantageous use of these forces, and the operating limitations of the aircraft being flown.

227. For example, a load factor of 3 means the total load on an aircraft's structure is three times its gross weight. Since load factors are expressed in terms of Gs, a load factor of 3 may be spoken of as 3 Gs, or a load factor of 4 as 4 Gs.

228. If an aircraft is pulled up from a dive, subjecting the pilot to 3 Gs, he or she would be pressed down into the seat with a force equal to three times his or her weight. Since modern aircraft operate at significantly higher speeds than older aircraft, increasing the magnitude of the load factor, this effect has become a primary consideration in the design of the structure of all aircraft.

229. W ith the structural design of aircraft planned to withstand only a certain amount of overload, a knowledge of load factors has become essential for all pilots. Load factors are important for two reasons:

a. It is possible for a pilot to impose a dangerous overload on the aircraft structure.

b. An increased load factor increases the stalling speed and makes stalls possible at seemingly safe flight speeds.

Load Factors in Aircraft Design

230. The answer to the question "How strong should an aircraft be?" is determined largely by the use to which the aircraft is subjected. This is a difficult problem because the maximum possible loads are much too high for use in efficient design. It is true that any pilot can make a very hard landing or an extremely sharp pull up from a dive, which would result in abnormal loads. However, such extremely abnormal loads must be dismissed somewhat if aircraft are built that take off quickly, land slowly, and carry worthwhile payloads.

231. The problem of load factors in aircraft design is how to determine the highest load factors that can be expected in normal operation under various operational situations. These load factors are called "limit load factors." For reasons of safety, it is required that the aircraft be designed to withstand these load factors without any structural damage. Although regulations require that the aircraft structure be capable of supporting one and one-half times these limit load factors without failure, it is accepted that parts of the aircraft may bend or twist under these loads and that some structural damage may occur.

232. This 1.5 load limit factor is called the "factor of safety" and provides, to some extent, for loads higher than those expected under normal and reasonable operation. This strength reserve is not something which pilots should willfully abuse; rather, it is there for protection when encountering unexpected conditions.

233. The above considerations apply to all loading conditions, whether they be due to gusts, manoeuvres, or landings. The gust load factor requirements now in effect are substantially the same as those that have been in existence for years. Hundreds of thousands of operational hours have proven them adequate for safety. Since the pilot has little control over gust load factors (except to reduce the aircraft's speed when rough air is encountered), the gust loading requirements are substantially the same for m ost general aviation type aircraft regardless of their operational use. Generally, the gust load factors control the design of aircraft which are intended for strictly non-aerobatic usage.

234. An entirely different situation exists in aircraft design with manoeuvring load factors. It is necessary to discuss this matter separately with respect to: (1) aircraft designed in accordance with the category system (i.e., normal, utility, acrobatic); and (2) older designs built according to requirements which did not provide for operational categories.

235. Aircraft designed under the category system are readily identified by a placard in the flight deck, which states the operational category (or categories) in which the aircraft is certificated. The maximum safe load factors (limit load factors) specified for aircraft in the various categories are:

CATEGORY	LIMIT LOAD FACTOR
Norm al[1]	3.8 to - 1.52
Utility (mild acrobatics, including spins)	4.4 to - 1.7
Aerobatic	6.0 to - 3.00

[1] For aircraft with gross weight of more than 4,000 pounds, the limit load factor is reduced. To the limit loads given above, a safety factor of 50 percent is added.

236. There is an upward graduation in load factor with the increasing severity of manoeuvres. The category system provides for maximum utility of an aircraft. If normal operation alone is intended, the required load factor (and consequently the weight of the aircraft) is less than if the aircraft is to be employed in training or acrobatic manoeuvres as they result in higher manoeuvring loads.

237. Aircraft that do not have the category placard are designs that were constructed under earlier engineering requirements in which no operational restrictions were specifically given to the pilots. For aircraft of this type (up to weights of about 4,000 pounds), the required strength is comparable to present day utility category aircraft, and the same types of operation are permissible. For aircraft of this type over 4,000 pounds, the load factors decrease with weight. These aircraft should be regarded as being comparable to the normal category aircraft designed under the category system, and they should be operated accordingly.

Load Factors in Steep Turns

238. In a constant altitude, coordinated turn in any aircraft, the load factor is the result of two forces:

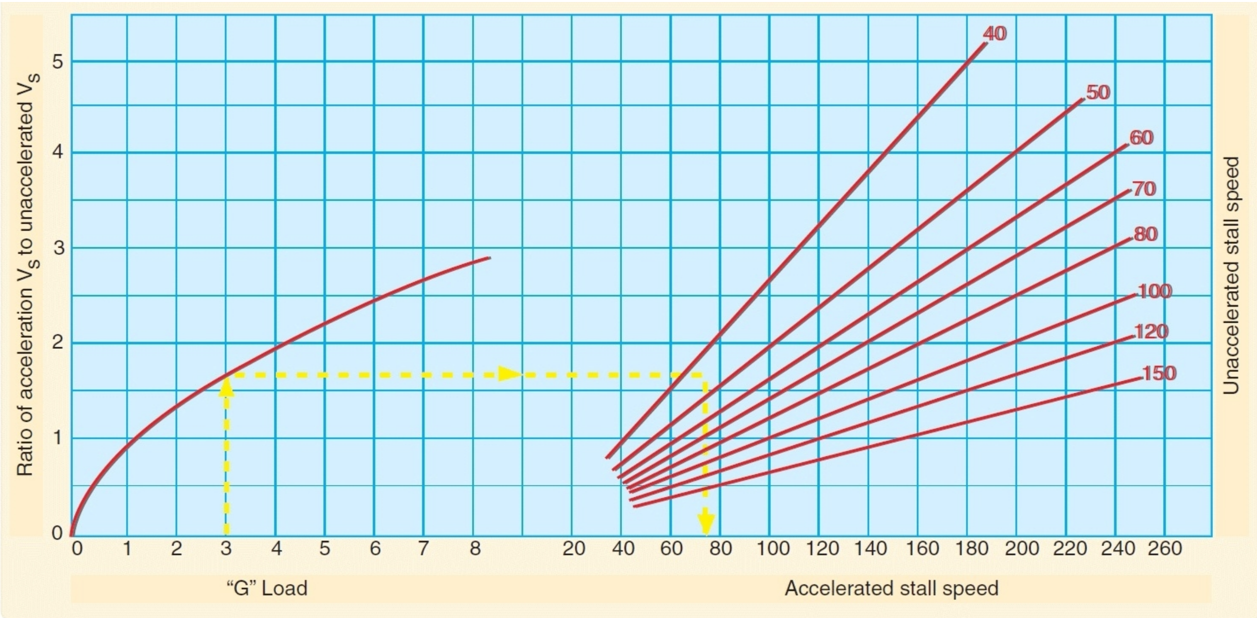


Figure 1.53 Load factor changes stall speed

centrifugal force and gravity. [Figure 1.54] For any given bank angle, the ROT varies with the airspeed - the higher the speed, the slower the ROT. This compensates for added centrifugal force, allowing the load factor to remain the same.

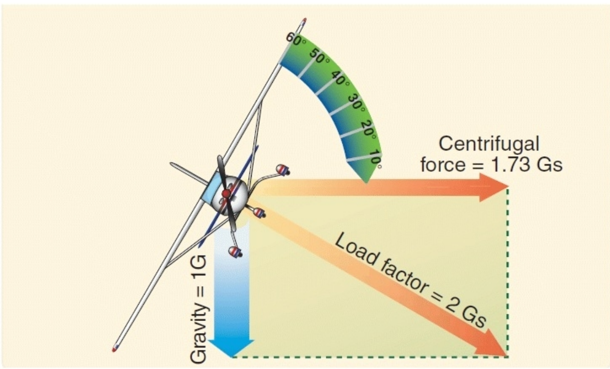


Figure 1.54 Two forces cause load factor during turns

239. Figure 1.55 reveals an important fact about turns - the load factor increases at a terrific rate after a bank has reached 45° or 50°. The load factor for any aircraft in a 60° bank is 2 Gs. The load factor in an 80 bank is 5.76 Gs. The wing must produce lift equal to these load factors if altitude is to be maintained.

240. It should be noted how rapidly the line denoting load factor rises as it approaches the 90° bank line, which it never quite reaches because a 90° banked, constant altitude turn is not mathematically possible. An aircraft may be banked to 90°, but not in a coordinated turn. An aircraft which can be held in a 90° banked slipping turn is capable of straight knife-edged flight. At slightly more than 80°, the load factor exceeds the limit of 6 Gs, the limit load factor of an acrobatic aircraft.

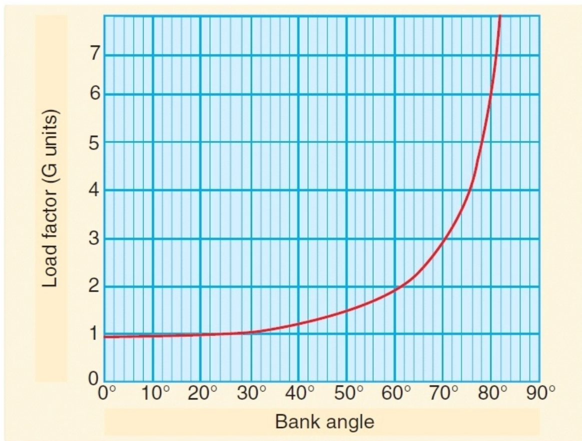


Figure 1.55 Angle of bank changes load factor

241. For a coordinated, constant altitude turn, the approximate maximum bank for the average general aviation aircraft is 60°. This bank and its resultant necessary power setting reach the limit of this type of aircraft. An additional 10° bank increases the load factor by approximately 1 G, bringing it close to the yield point established for these aircraft. [Figure 1.55]

Load Factors and Stalling Speeds

242. Any aircraft, within the limits of its structure, may be stalled at any airspeed. W hen a sufficiently high AOA is imposed, the smooth flow of air over an aerofoil breaks up and separates, producing an abrupt change of flight characteristics and a sudden loss of lift, which results in a stall.

243. A study of this effect has revealed that the aircraft's stalling speed increases in proportion to the square root of the load factor. This means that an aircraft with a normal un-accelerated stalling speed of 50 knots can be stalled at 100 knots by inducing a load factor of 4 Gs. If it were possible for this aircraft to withstand a load factor of nine, it could be stalled at a speed of 150 knots. A pilot should be aware:

- Of the danger of inadvertently stalling the aircraft by increasing the load factor, as in a steep turn or spiral;

- W hen intentionally stalling an aircraft above its design manoeuvring speed, a tremendous load factor is imposed.

244. Figure 1.55 shows that banking an aircraft greater than 72° in a steep turn produces a load factor of 3, and the stalling speed is increased significantly. If this turn is made in an aircraft with a normal un-accelerated stalling speed of 45 knots, the airspeed must be kept greater than 75 knots to prevent inducing a stall. A similar effect is experienced in a quick pull up, or any manoeuvre producing load factors above 1 G. This sudden, unexpected loss of control, particularly in a steep turn or abrupt application of the back elevator control near the ground, has caused many accidents.

245. Since the load factor is squared as the stalling speed doubles, tremendous loads may be imposed on structures by stalling an aircraft at relatively high airspeeds.

246. The maximum speed at which an aircraft may be stalled safely is now determined for all new designs. This speed is called the "design manoeuvring speed" (VA) and must be entered in the approved Aeroplane Flight Manual/Pilot's Operating Handbook (AFM/POH) of all recently designed aircraft. For older general aviation aircraft, this speed is approximately 1.7 times the normal stalling speed. Thus, an older aircraft which normally stalls at 60 knots must never be stalled at above 102 knots (60 knots x 1.7 = 102 knots). An aircraft with a normal stalling speed of 60 knots stalled at 102 knots undergoes a load factor equal to the square of the increase in speed, or 2.89 Gs (1.7 x 1.7 = 2.89 Gs). (The above figures are approximations to be considered as a guide, and are not the exact answers to any set of problems. The design manoeuvring speed should be determined from the particular aircraft's operating limitations provided by the m anufacturer.)

247. Since the leverage in the control system varies with different aircraft (some types employ "balanced" control surfaces while others do not), the pressure exerted by the pilot on the controls cannot be accepted as an index of the load factors produced in different aircraft. In most cases, load factors can be judged by the experienced pilot from the feel of seat pressure. Load factors can also be measured by an instrument called an "accelerometer," but this instrument is not common in general aviation training aircraft. The development of the ability to judge load factors from the feel of their effect on the body is important. A knowledge of these principles is essential to the development of the ability to estimate load factors.

248. A thorough knowledge of load factors induced by varying degrees of bank and the VA aids in the prevention of two of the most serious types of accidents:

a. Stalls from steep turns or excessive manoeuvring near the ground

b. Structural failures during acrobatics or other violent manoeuvres resulting from loss of control

Load Factors and Flight Manoeuvres

249. Critical load factors apply to all flight manoeuvres except un-accelerated straight flight where a load factor of 1 G is always present. Certain manoeuvres considered in this section are known to involve relatively high load factors.

Turns

250. Increased load factors are a characteristic of

all banked turns. As noted in the section on load factors in steep turns, load factors become significant to both flight performance and load on wing structure as the bank increases beyond approximately 45°.

251. The yield factor of the average light plane is reached at a bank of approximately 70° to 75°, and the stalling speed is increased by approximately one-half at a bank of approximately 63°.

Stalls

252. The normal stall entered from straight-and-level flight, or an un-accelerated straight climb, does not produce added load factors beyond the 1 G of straight-and-level flight. As the stall occurs, however, this load factor may be reduced toward zero, the factor at which nothing seems to have weight. The pilot experiences a sensation of “floating free in space.” If recovery is effected by snapping the elevator control forward, negative load factors (or those that impose a down load on the wings and raise the pilot from the seat) may be produced.

253. During the pull up following stall recovery, significant load factors are sometimes induced. These may be further increased inadvertently during excessive diving (and consequently high airspeed) and abrupt pull ups to level flight. One usually leads to the other, thus increasing the load factor. Abrupt pull ups at high diving speeds may impose critical loads on aircraft structures and may produce recurrent or secondary stalls by increasing the AOA to that of stalling.

254. As a generalization, a recovery from a stall made by diving only to cruising or design manoeuvring airspeed, with a gradual pull up as soon as the airspeed is safely above stalling, can be effected with a load factor not to exceed 2 or 2.5 Gs. A higher load factor should never be necessary unless recovery has been effected with the aircraft’s nose near or beyond the vertical attitude, or at extremely low altitudes to avoid diving into the ground.

Spins

255. A stabilized spin is not different from a stall in any element other than rotation and the same load factor considerations apply to spin recovery as apply to stall recovery. Since spin recoveries are usually effected with the nose much lower than is common in stall recoveries, higher airspeeds and consequently higher load factors are to be expected. The load factor in a proper spin recovery usually is found to be about 2.5 Gs.

256. The load factor during a spin varies with the spin characteristics of each aircraft, but is usually found to be slightly above the 1 G of level flight. There are two reasons for this:

a. Airspeed in a spin is very low, usually within 2 knots of the un-accelerated stalling speeds.

b. Aircraft pivots, rather than turns, while it is in a spin.

High Speed Stalls

257. The average light plane is not built to withstand the repeated application of load factors common to high speed stalls. The load factor necessary for these manoeuvres produces a stress on the wings and tail structure, which does not leave a reasonable margin of safety in most light aircraft.

258. The only way this stall can be induced at an airspeed above normal stalling involves the imposition of an added load factor, which may be accomplished by a severe pull on the elevator control. A speed of 1.7 times stalling speed (about 102 knots in a light aircraft with a stalling speed of 60 knots) produces a load factor of 3 Gs. Only a very narrow margin for error can be allowed for acrobatics in light aircraft. To illustrate how rapidly the load factor increases with airspeed, a high-speed stall at 112 knots in the same aircraft would produce a load factor of 4 Gs.

Chandelles and Lazy Eights

259. A chandelle is a maximum perform ance climbing turn beginning from approximately straight-and-level flight, and ending at the completion of a precise 180 of turn in a wings-level, nose-high attitude at the minimum controllable airspeed. In this flight manoeuvre, the aircraft is in a steep climbing turn and almost stalls to gain altitude while changing direction. A lazy eight derives its name from the manner in which the extended longitudinal axis of the aircraft is made to trace a flight pattern in the form of a figure “8” lying on its side. It would be difficult to make a definite

statement concerning load factors in these manoeuvres as both involve smooth, shallow dives and pull ups. The load factors incurred depend directly on the speed of the dives and the abruptness of the pull ups during these manoeuvres.

260. Generally, the better the manoeuvre is performed, the less extreme the load factor induced. A chandelle or lazy eight in which the pull-up produces a load factor greater than 2 Gs will not result in as great a gain in altitude, and in low-powered aircraft it may result in a net loss of altitude.

261. The smoothest pull up possible, with a moderate load factor, delivers the greatest gain in altitude in a chandelle and results in a better overall performance in both chandelles and lazy eights. The recommended entry speed for these manoeuvres is generally near the manufacturer's design manoeuvring speed which allows maximum development of load factors without exceeding the load limits.

Rough Air

262. All standard certificated aircraft are designed to withstand loads imposed by gusts of considerable intensity. Gust load factors increase with increasing airspeed, and the strength used for design purposes usually corresponds to the highest level flight speed. In extremely rough air, as in thunderstorms or frontal conditions, it is wise to reduce the speed to the design manoeuvring speed. Regardless of the speed held, there may be gusts that can produce loads which exceed the load limits.

263. Each specific aircraft is designed with a specific G loading that can be imposed on the aircraft without causing structural damage. There are two types of load factors factored into aircraft design, limit load and ultimate load. The limit load is a force applied to an aircraft that causes a bending of the aircraft structure that does not return to the original shape. The ultimate load is the load factor applied to the aircraft beyond the limit load and at which point the aircraft material experiences structural failure (breakage). Load factors lower than the limit load can be sustained without compromising the integrity of the aircraft structure.

264. Speeds up to but not exceeding the manoeuvring speed allows an aircraft to stall prior to experiencing an increase in load factor that would exceed the limit load of the aircraft. Most AFM/POH now include turbulent air penetration information, which help today's pilots safely fly aircraft capable of a wide range of speeds and altitudes. It is important for the pilot to remember that the maximum "never-exceed" placard dive speeds are determined for smooth air only. High speed dives or acrobatics involving speed above the known manoeuvring speed should never be practiced in rough or turbulent air.

Vg Diagram

266. The flight operating strength of an aircraft is presented on a graph whose vertical scale is based on load factor. [Figure 1.56] The diagram is called a Vg diagram - velocity versus G loads or load factor. Each aircraft has its own Vg diagram which is valid at a certain weight and altitude. The lines of maximum lift capability (curved lines) are the first items of importance on the Vg diagram. The aircraft in the Figure 1.56 is capable of developing no more than +1 G at 62 mph, the wing level stall speed of the aircraft. Since the maximum load factor varies with the square of the airspeed, the maximum positive lift capability of this aircraft is 2 G at 92 mph, 3 G at 112 mph, 4.4 G at 137 mph, and so forth. Any load factor above this line is unavailable aerodynamically (i.e., the aircraft cannot fly above the line of maximum lift capability because it stalls). The same situation exists for negative lift flight with the exception that the speed necessary to produce a given negative load factor is higher than that to produce the same positive load factor.

267. If the aircraft is flown at a positive load factor greater than the positive limit load factor of 4.4, structural damage is possible. W hen the aircraft is operated in this region, objectionable perm anent deformation of the primary structure may take place and a high rate of fatigue damage is incurred. Operation above the limit load factor must be avoided in normal operation.

268. There are two other points of importance on the Vg diagram. One point is the intersection of the positive limit load factor and the line of maximum positive lift capability. The airspeed at this point is the minimum airspeed at which the limit load can be developed aerodynamically. Any airspeed greater than this provides a positive lift capability sufficient to

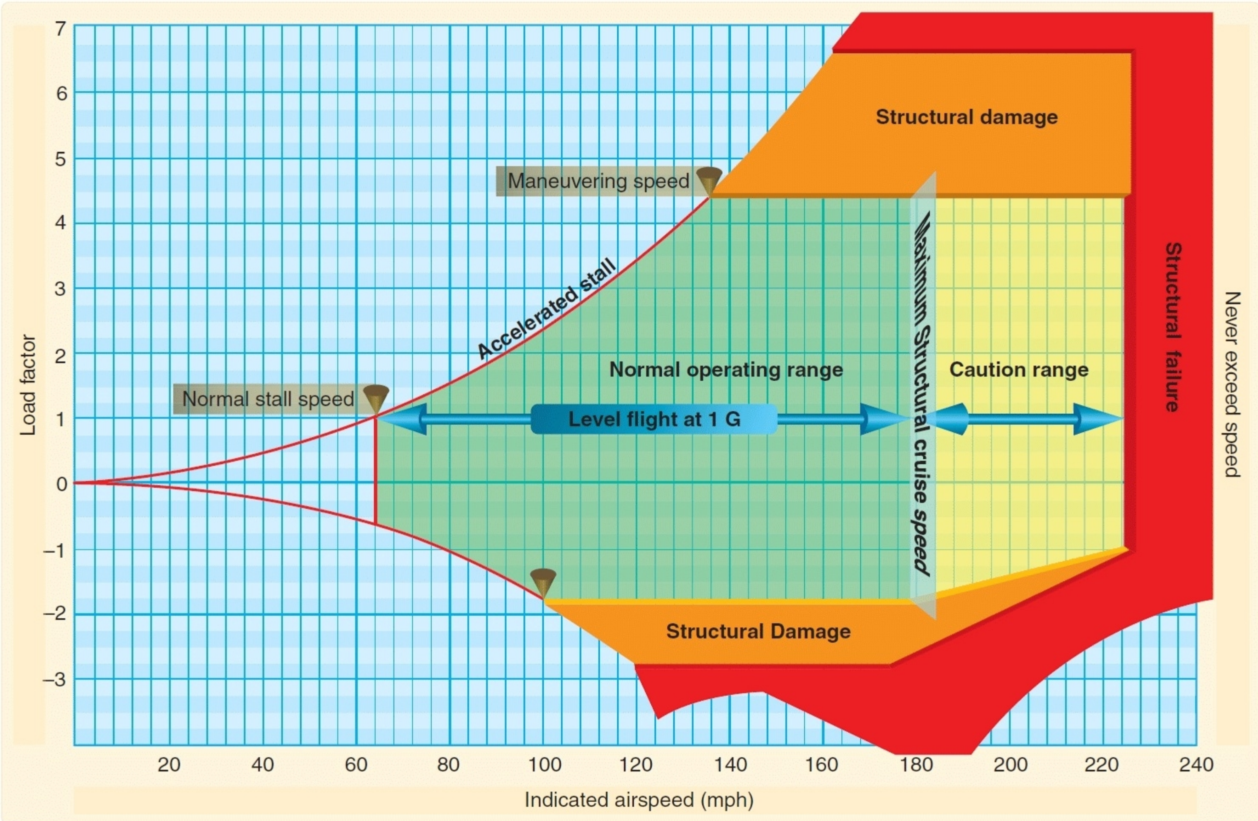


Figure 1.56 Typical Vg diagram

damage the aircraft. Conversely, any airspeed less than this does not provide positive lift capability sufficient to cause damage from excessive flight loads. The usual term given to this speed is “manoeuvring speed,” since consideration of subsonic aerodynamics would predict minimum usable turn radius or manoeuvrability to occur at this condition. The manoeuvre speed is a valuable reference point, since an aircraft operating below this point cannot produce a damaging positive flight load. Any combination of manoeuvre and gust cannot create damage due to excess airload when the aircraft is below the manoeuvre speed.

269. The other point of importance on the Vg diagram is the intersection of the negative limit load factor and line of maximum negative lift capability. Any airspeed greater than this provides a negative lift capability sufficient to damage the aircraft; any airspeed less than this does not provide negative lift capability sufficient to damage the aircraft from excessive flight loads.

270. The limit airspeed (or redline speed) is a design reference point for the aircraft - this aircraft is limited to 225 mph. If flight is attempted beyond the limit airspeed, structural damage or structural failure may result from a variety of phenomena.

271. The aircraft in flight is limited to a regime of airspeeds and Gs which do not exceed the limit (or redline) speed, do not exceed the limit load factor, and cannot exceed the maximum lift capability. The aircraft must be operated within this “envelope” to prevent structural damage and ensure the anticipated service lift of the aircraft is obtained. The pilot must appreciate the Vg diagram as describing the allowable combination of airspeeds and load factors for safe operation. Any manoeuvre, gust, or gust plus manoeuvre outside the structural envelope can cause structural damage and effectively shorten the service life of the aircraft.

Rate of Turn

272. The rate of turn (ROT) is the number of degrees (expressed in degrees per second) of heading change that an aircraft makes. The ROT can be determined by taking the constant of 1,091, multiplying it by the tangent of any bank angle and dividing that product by a given airspeed in knots as illustrated in Figure 1.57. If the airspeed is increased and the ROT

desired is to be constant, the angle of bank must be increased, otherwise, the ROT decreases. Likewise, if the airspeed is held constant, an aircraft's ROT increases if the bank angle is increased. The formula in Figures 1.58 through 1.60 depicts the relationship between bank angle and airspeed as they affect the ROT.

NOTE: All airspeed discussed in this section is true airspeed (TAS).

$$\text{ROT} = \frac{1{,}091 \times \text{tangent of the bank angle}}{\text{airspeed (in knots)}}$$

Example The rate of turn for an aircraft in a coordinated turn of 30° and traveling at 120 knots would have a ROT as follows.

$$\text{ROT} = \frac{1{,}091 \times \text{tangent of } 30^\circ}{120 \text{ knots}}$$

$$\text{ROT} = \frac{1{,}091 \times 0.5773 \text{ (tangent of } 30^\circ)}{120 \text{ knots}}$$

ROT = 5.25 degrees per second

Figure 1.57 Rate of turn for a given airspeed (knots, TAS) and bank angle

Example Suppose we were to increase the speed to 240 knots, what is the rate of turn? Using the same formula from above we see that:

$$\text{ROT} = \frac{1{,}091 \times \text{tangent of } 30^\circ}{240 \text{ knots}}$$

ROT = 2.62 degrees per second

An increase in speed causes a decrease in the rate of turn when using the same bank angle.

Figure 1.58 Rate of turn when increasing airspeed

Example Suppose we wanted to know what bank angle would give us a rate of turn of 5.25° per second at 240 knots. A slight rearrangement of the formula would indicate it will take a 49° angle of bank to achieve the same ROT used at the lower airspeed of 120 knots.

$$\text{ROT (5.25)} = \frac{1{,}091 \times \text{tangent of X}}{240 \text{ knots}}$$

$240 \times 5.25 = 1{,}091 \times \text{tangent of X}$

$\frac{240 \times 5.25}{1{,}091} = \text{tangent of X}$

$1.1549 = \text{tangent of X}$

$49^\circ = X$

Figure 1.59 To achieve the same rate of turn of an aircraft travelling at 120 knots, an increase of bank is required

272. Airspeed significantly effects an aircraft's ROT. If airspeed is increased, the ROT is reduced if using the same angle of bank used at the lower speed. Therefore, if airspeed is increased as illustrated in Figure 1.59, it can be inferred that the angle of bank must be increased in order to achieve the same ROT achieved in Figure 1.60.

273. W hat does this mean in practice? If a given airspeed and bank angle produces a specific ROT, additional conclusions can be made. Knowing the ROT is a given number of degrees of change per second, the number of seconds it takes to travel 360 (a circle) can be determined by simple division. For example, if moving at 120 knots with a 30 bank angle, the ROT is 5.25 per second and it takes 68.6 seconds (360 divided by 5.25 = 68.6 seconds) to make a complete circle. Likewise, if flying at 240 knots TAS and using a 30 angle of bank, the ROT is only about 2.63 per second and it takes about 137 seconds to complete a 360 circle. Looking at the formula, any increase in airspeed is directly proportional to the time the aircraft takes to travel an arc.

274. So why is this important to understand? Once the ROT is understood, a pilot can determine the distance required to make that particular turn which is explained in radius of turn.

Radius of Turn

275. The radius of turn is directly linked to the ROT, which explained earlier is a function of both bank angle and airspeed. If the bank angle is held constant and the airspeed is increased, the radius of the turn changes (increases). A higher airspeed causes the aircraft to travel through a longer arc due to a greater speed. An aircraft travelling at 120 knots is able to turn a 360 circle in a tighter radius than an aircraft travelling at 240 knots. In order to compensate for the increase in airspeed, the bank angle would need to be increased.

276. The radius of turn (R) can be computed using a simple formula. The radius of turn is equal to the velocity squared (V^2) divided by 11.26 times the tangent of the bank angle.

$$R = \frac{V^2}{11.26 \times \text{tangent of bank angle}}$$

277. Using the examples provided in Figures 1.58 through 1.59, the turn radius for each of the two speeds can be computed. Note that if the speed is doubled, the radius is squared.

120 knots

$$R = \frac{V^2}{11.26 \times \text{tangent of bank angle}}$$

$$R = \frac{120^2}{11.26 \times \text{tangent of } 30°}$$

$$R = \frac{14{,}400}{11.26 \times 0.5773}$$

$$R = 2{,}215 \text{ feet}$$

The radius of a turn required by an aircraft traveling at 120 knots and using a bank angle of 30° is 2,215 feet.

Figure 1.60 Radius at 120 knots with bank angle of 30°

240 knots

$$R = \frac{V^2}{11.26 \times \text{tangent of bank angle}}$$

$$R = \frac{240^2}{11.26 \times \text{tangent of } 30°}$$

$$R = \frac{57{,}600}{11.26 \times 0.57735}$$

$$R = 8{,}861 \text{ feet}$$

(four times the radius at 120 knots)

The radius of a turn required by an aircraft traveling at 240 knots using the same bank angle in *Figure 4-51* is 8,861 feet. Speed is a major factor in a turn.

Figure 1.61 Radius at 240 knots

278. Another way to determine the radius of turn is speed in using feet per second (fps), ð (3.1415) and the ROT. Using the example in paragraph 273, it was determined that an aircraft with a ROT of 5.25 degrees per second required 68.6 seconds to make a complete circle. An aircraft's speed (in knots) can be converted to fps by multiplying it by a constant of 1.69. Therefore, an aircraft travelling at 120 knots (TAS) travels at 202.8 fps. Knowing the speed in fps (202.8) multiplied by the time an aircraft takes to complete a circle (68.6 seconds) can determine the size of the circle; 202.8 times 68.6 equals 13,912 feet. Dividing by ð yields a diameter of 4,428 feet, which when divided by 2 equals a radius of 2,214 feet [Figure 1.62], a foot within that determined through use of the formula in Figure 1.60.

279 In Figure 1.63, the pilot enters a canyon and decides to turn 180 to exit. The pilot uses a 30 bank angle in his turn.

$$r = \frac{\dfrac{\text{speed (fps)} \times \dfrac{360}{\text{ROT}}}{\text{Pi } (\pi)}}{2}$$

$$r = \frac{\dfrac{202.8 \times 68.6}{\pi}}{2}$$

$$r = \frac{\dfrac{13{,}912}{\pi}}{2}$$

$$r = \frac{4{,}428}{2} = 2{,}214 \text{ feet}$$

Figure 1.62 Another formula that can be used for radius

Weight and Balance

280. The aircraft's weight and balance data is important information for a pilot that must be frequently reevaluated. Although the aircraft was weighed during the certification process, this data is not valid indefinitely. Equipment changes or modifications affect the weight and balance data. Too often pilots reduce the aircraft weight and balance into a "rule of thumb" such as: "If I have three passengers, I can load only 100 gallons of fuel; four passengers, 70 gallons."

281. W eight and balance computations should be part of every pre-flight briefing. Never assume three passengers are always of equal weight. Instead, do a full computation of all items to be loaded on the aircraft, including baggage, as well as the pilot and passenger. It is recommended that all bags be weighed to make a precise computation of how the aircraft CG is positioned.

282. The importance of the CG was stressed in the discussion of stability, controllability, and performance. Unequal load distribution causes accidents. A competent pilot understands and respects the effects of CG on an aircraft.

283. W eight and balance are critical components in the utilization of an aircraft to its fullest potential. The pilot must know how much fuel can be loaded onto the aircraft without violating CG limits, as well as weight limits to conduct long or short flights with or without a full complement of allowable passengers. For example, an aircraft has four seats and can carry 60 gallons of fuel. How many passengers can the aircraft safely carry? Can all those seats be occupied at all

times with the varying fuel loads? Four people who each weigh 150 pounds leads to a different weight and balance computation than four people who each weigh 200 pounds. The second scenario loads an additional 200 pounds onto the aircraft and is equal to about 30 gallons of fuel.

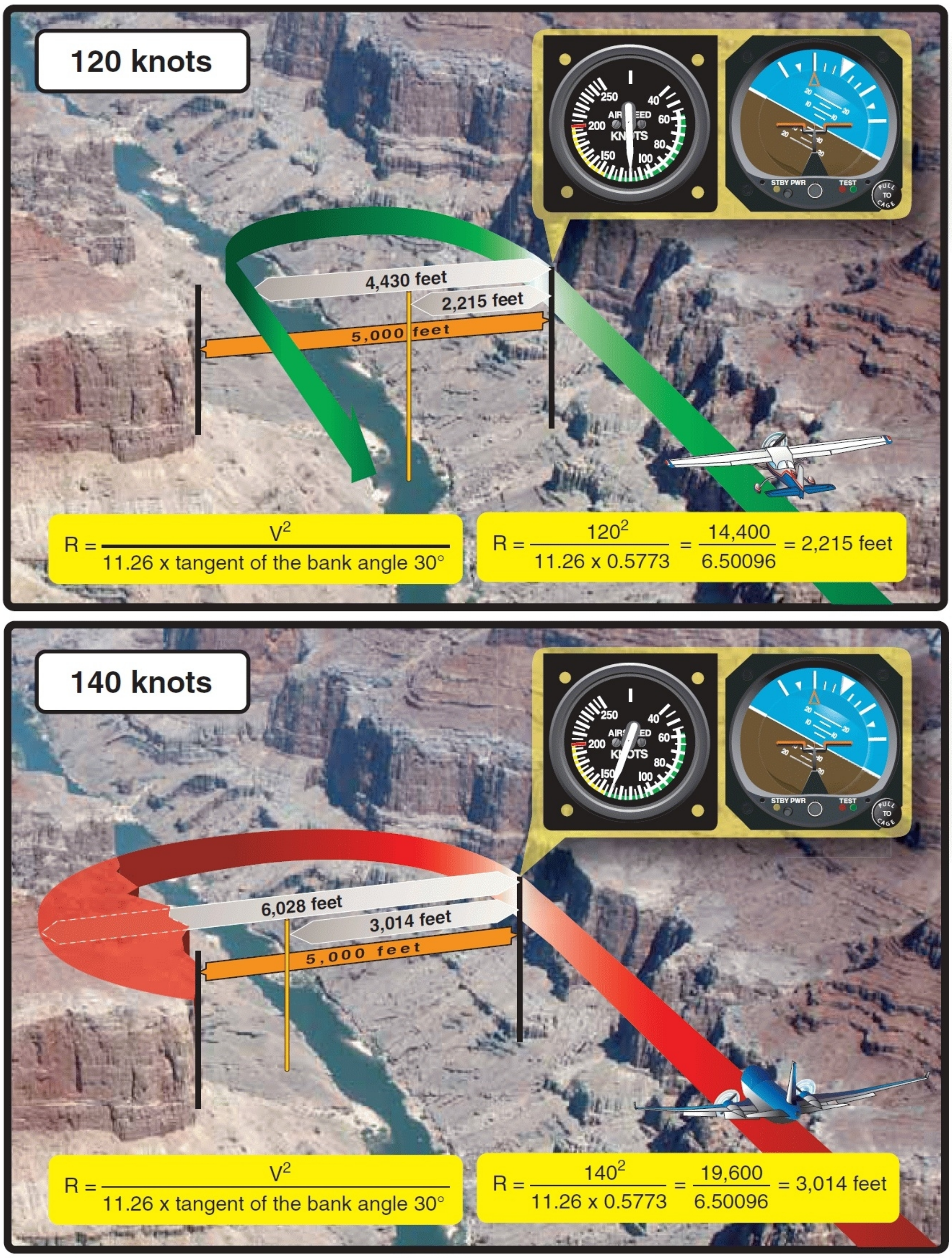


Figure 1.63. Two aircraft have flown into a canyon by error. The canyon is 5,000 feet across and has sheer cliffs on both sides. The pilot in the top image is flying at 120 knots. After realizing the error, the pilot banks hard and uses a 30 bank angle to reverse course. This aircraft requires about 4,000 feet to turn 180 , and makes it out of the canyon safely. The pilot in the bottom image is flying at 140 knots and also uses a 30 angle of bank in an attempt to reverse course. The aircraft, although flying just 20 knots faster than the aircraft in the top image, requires over 6,000 feet to reverse course to safety. Unfortunately, the canyon is only 5,000 feet across and the aircraft will hit the canyon wall. The point is that airspeed is the most influential factor in determining how much distance is required to turn. Many pilots have made the error of increasing the steepness of their bank angle when a simple reduction of speed would have been more appropriate.

284. The additional weight may or may not place the CG outside of the CG envelope, but the maximum gross weight could be exceeded. The excess weight can overstress the aircraft and degrade the perform ance.

285. Aircraft are certified for weight and balance for two principal reasons:

a. The effect of the weight on the aircraft's primary structure and its perform ance characteristics

b. The effect of the location of this weight on flight characteristics, particularly in stall and spin recovery and stability

286. Aircraft such as balloons and weight-shift control do not require weight and balance computations because the load is suspended below the lifting mechanism. The CG range in these types of aircraft is such that it is difficult to exceed loading limits. For example, the rear seat position and fuel of a weight-shift control aircraft are as close as possible to the hang point with the aircraft in a suspended attitude. Thus, load variations have little effect on the CG. This also holds true for the balloon basket or gondola. W hile it is difficult to exceed CG limits in these aircraft, pilots should never overload an aircraft because overloading causes structural damage and failures. W eight and balance computations are not required, but pilots should calculate weight and remain within the manufacturer's established limit.

Effect of Weight on Flight Performance

288. The takeoff/climb and landing performance of an aircraft are determined on the basis of its maximum allowable takeoff and landing weights. A heavier gross weight results in a longer takeoff run and shallower climb, and a faster touchdown speed and longer landing roll. Even a minor overload may make it impossible for the aircraft to clear an obstacle that normally would not be a problem during takeoff under more favourable conditions.

289. The detrimental effects of overloading on performance are not limited to the immediate hazards involved with takeoffs and landings. Overloading has an adverse effect on all climb and cruise performance which leads to overheating during climbs, added wear on engine parts, increased fuel consumption, slower cruising speeds, and reduced range.

290. The manufacturers of modern aircraft furnish weight and balance data with each aircraft produced. Generally, this information may be found in the approved AFM/POH and easy-to-read charts for determining weight and balance data are now provided. Increased performance and load-carrying capability of these aircraft require strict adherence to the operating limitations prescribed by the manufacturer. Deviations from the recommendations can result in structural damage or complete failure of the aircraft's structure. Even if an aircraft is loaded well within the maximum weight limitations, it is imperative that weight distribution be within the limits of CG location. The preceding brief study of aerodynamics and load factors points out the reasons for this precaution. The following discussion is background information into some of the reasons why weight and balance conditions are important to the safe flight of an aircraft. In some aircraft, it is not possible to fill all seats, baggage compartments, and fuel tanks, and still remain within approved weight or balance limits. For example, in several popular four-place aircraft, the fuel tanks may not be filled to capacity when four occupants and their baggage are carried. In a certain two-place aircraft, no baggage may be carried in the compartment aft of the seats when spins are to be practiced. It is important for a pilot to be aware of the weight and balance limitations of the aircraft being flown and the reasons for these limitations.

Effect of Weight on Aircraft Structure

291. The effect of additional weight on the wing structure of an aircraft is not readily apparent. Airworthiness requirements prescribe that the structure of an aircraft certificated in the normal category (in which acrobatics are prohibited) must be strong enough to withstand a load factor of 3.8 Gs to take care of dynamic loads caused by manoeuvring and gusts. This means that the primary structure of the aircraft can withstand a load of 3.8 times the approved gross weight of the aircraft without structural failure occurring. If this is accepted as indicative of the load factors that may be imposed during operations for which the aircraft is intended, a 100-pound overload imposes a potential structural overload of 380 pounds. The same consideration is even more impressive in the case of utility and acrobatic category aircraft, which

have load factor requirements of 4.4 and 6.0, respectively. Structural failures which result from overloading may be dramatic and catastrophic, but more often they affect structural com ponents progressively in a manner that is difficult to detect and expensive to repair. Habitual overloading tends to cause cumulative stress and damage that may not be detected during pre-flight inspections and result in structural failure later during completely norm al operations. The additional stress placed on structural parts by overloading is believed to accelerate the occurrence of metallic fatigue failures.

292. A knowledge of load factors imposed by flight manoeuvres and gusts emphasizes the consequences of an increase in the gross weight of an aircraft. The structure of an aircraft about to undergo a load factor of 3 Gs, as in recovery from a steep dive, must be prepared to withstand an added load of 300 pounds for each 100-pound increase in weight. It should be noted that this would be imposed by the addition of about 16 gallons of unneeded fuel in a particular aircraft. Certificated civil aircraft have been analysed structurally and tested for flight at the maximum gross weight authorized and within the speeds posted for the type of flights to be performed. Flights at weights in excess of this amount are quite possible and often are well within the performance capabilities of an aircraft. This fact should not mislead the pilot, as the pilot may not realize that loads for which the aircraft was not designed are being imposed on all or some part of the structure.

293. In loading an aircraft with either passengers or cargo, the structure must be considered. Seats, baggage compartments, and cabin floors are designed for a certain load or concentration of load and no more. For example, a light plane baggage compartment may be placarded for 20 pounds because of the limited strength of its supporting structure even though the aircraft may not be overloaded or out of CG limits with more weight at that location.

Effect of Weight on Stability and Controllability

294. Overloading also effects stability. An aircraft that is stable and controllable when loaded normally may have very different flight characteristics when overloaded. Although the distribution of weight has the most direct effect on this, an increase in the aircraft's gross weight may be expected to have an adverse effect on stability, regardless of location of the CG. The stability of many certificated aircraft is com pletely unsatisfactory if the gross weight is exceeded.

Effect of Load Distribution

295. The effect of the position of the CG on the load imposed on an aircraft's wing in flight is significant to climb and cruising performance. An aircraft with forward loading is "heavier" and consequently, slower than the same aircraft with the CG further aft.

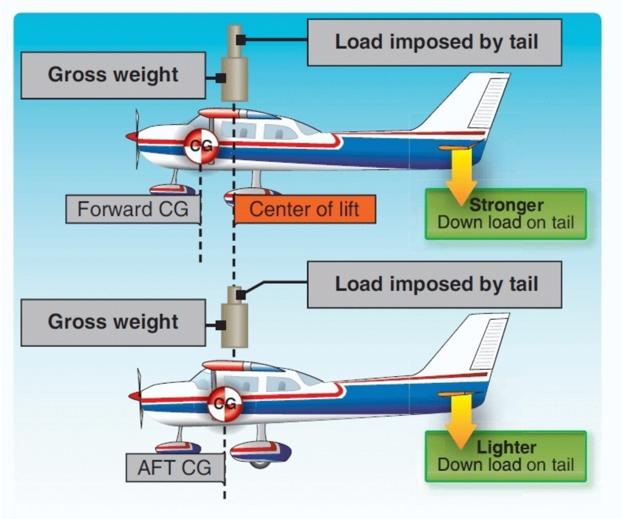


Figure 1.64 Effect of load distribution on balance

296. Figure 1.64 illustrates why this is true. W ith forward loading, "nose-up" trim is required in most aircraft to maintain level cruising flight. Nose-up trim involves setting the tail surfaces to produce a greater down load on the aft portion of the fuselage, which adds to the wing loading and the total lift required from the wing if altitude is to be maintained. This requires a higher AOA of the wing, which results in more drag and, in turn, produces a higher stalling speed. W ith aft loading and "nose-down" trim, the tail surfaces exert less down load, relieving the wing of that much wing loading and lift required to maintain altitude. The required AOA of the wing is less, so the drag is less, allowing for a faster cruise speed. Theoretically, a neutral load on the tail surfaces in cruising flight would produce the most efficient overall performance and fastest cruising speed, but it would also result in instability. Modern aircraft are designed to require a down load on the tail for stability and controllability. A zero indication on the trim tab control is not necessarily the same as "neutral trim" because of the force exerted by downwash from the wings and the fuselage on the tail surfaces.

297. The effects of the distribution of the aircraft's useful load have a significant influence on its flight characteristics, even when the load is within the CG limits and the maximum permissible gross weight. Important among these effects are changes in controllability, stability, and the actual load imposed on the wing.

298. Generally, an aircraft becomes less controllable, especially at slow flight speeds, as the CG is moved further aft. An aircraft which cleanly recovers from a prolonged spin with the CG at one position may fail completely to respond to normal recovery attempts when the CG is moved aft by one or two inches.

299. It is common practice for aircraft designers to establish an aft CG limit that is within one inch of the maximum which allows normal recovery from a one-turn spin. W hen certificating an aircraft in the utility category to permit intentional spins, the aft CG limit is usually established at a point several inches forward of that permissible for certification in the normal category.

300. Another factor affecting controllability, which has become more important in current designs of large aircraft, is the effect of long moment arms to the positions of heavy equipment and cargo. The same aircraft may be loaded to maximum gross weight within its CG limits by concentrating fuel, passengers, and cargo near the design CG, or by dispersing fuel and cargo loads in wingtip tanks and cargo bins forward and aft of the cabin.

301. W ith the same total weight and CG, manoeuvring the aircraft or maintaining level flight in turbulent air requires the application of greater control forces when the load is dispersed. The longer moment arms to the positions of the heavy fuel and cargo loads must be overcome by the action of the control surfaces. An aircraft with full outboard wing tanks or tip tanks tends to be sluggish in roll when control situations are marginal, while one with full nose and aft cargo bins tends to be less responsive to the elevator controls. The rearward CG limit of an aircraft is determined largely by considerations of stability. The original airworthiness requirements for a type certificate specify that an aircraft in flight at a certain speed dampens out vertical displacement of the nose within a certain number of oscillations. An aircraft loaded too far rearward may not do this. Instead, when the nose is momentarily pulled up, it may alternately climb and dive becoming steeper with each oscillation. This instability is not only uncomfortable to occupants, but it could even become dangerous by making the aircraft unmanageable under certain conditions.

302. The recovery from a stall in any aircraft becomes progressively more difficult as its CG moves aft. This is particularly important in spin recovery, as there is a point in rearward loading of any aircraft at which a "flat" spin develops. A flat spin is one in which centrifugal force, acting through a CG located well to the rear, pulls the tail of the aircraft out away from the axis of the spin, making it impossible to get the nose down and recover.

303. An aircraft loaded to the rear limit of its permissible CG range handles differently in turns and stall manoeuvres and has different landing characteristics than when it is loaded near the forward limit.

304. The forward CG limit is determined by a number of considerations. As a safety measure, it is required that the trimming device, whether tab or adjustable stabilizer, be capable of holding the aircraft in a normal glide with the power off. A conventional aircraft must be capable of a full stall, power-off landing in order to ensure minimum landing speed in emergencies. A tailwheel-type aircraft loaded excessively nose-heavy is difficult to taxi, particularly in high winds. It can be nosed over easily by use of the brakes, and it is difficult to land without bouncing since it tends to pitch down on the wheels as it is slowed down and flared for landing. Steering difficulties on the ground may occur in nosewheel-type aircraft, particularly during the landing roll and takeoff. To summarize the effects of load distribution:

- The CG position influences the lift and AOA of the wing, the amount and direction of force on the tail, and the degree of deflection of the stabilizer needed to supply the proper tail force for equilibrium. The latter is very important because of its relationship to elevator control force.

- The aircraft stalls at a higher speed with a forward CG location. This is because the stalling AOA is reached at a higher speed due to increased wing loading.

- Higher elevator control forces normally exist with a forward CG location due to the increased stabilizer deflection required to balance the aircraft.

- The aircraft cruises faster with an aft CG location because of reduced drag. The drag is reduced because a smaller AOA and less downward deflection of the stabilizer are required to support the aircraft and overcome the nose-down pitching tendency.

- The aircraft becomes less stable as the CG is moved rearward. This is because when the CG is moved rearward it causes an increase in the AOA. Therefore, the wing contribution to the aircraft's stability is now decreased, while the tail contribution is still stabilizing. W hen the point is reached that the wing and tail contributions balance, then neutral stability exists. Any CG movement further aft results in an unstable aircraft.

- A forward CG location increases the need for greater back elevator pressure. The elevator may no longer be able to oppose any increase in nose-down pitching. Adequate elevator control is needed to control the aircraft throughout the airspeed range down to the stall.

305. A detailed discussion and additional information relating to weight and balance can be found in Chapter 5 Flight Planning.

FLIGHT CONTROLS

Introduction

306. This section focuses on the flight control systems a pilot uses to control the forces of flight, and the aircraft's direction and attitude. It should be noted that flight control systems and characteristics can vary greatly depending on the type of aircraft flown. The most basic flight control system designs are mechanical and date back to early aircraft. They operate with a collection of mechanical parts such as rods, cables, pulleys, and sometimes chains to transmit the forces of the flight deck controls to the control surfaces. Mechanical flight control systems are still used today in small general and sport category aircraft where the aerodynamic forces are not excessive. [Figure 1.65]

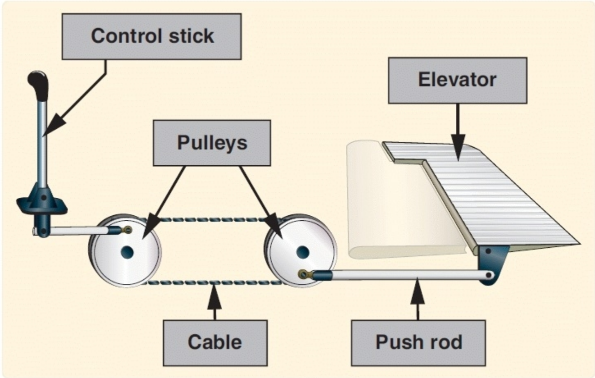


Figure 1.65 Mechanical flight control system

307. As aviation matured and aircraft designers learned more about aerodynamics, the industry produced larger and faster aircraft. Therefore, the aerodynamic forces acting upon the control surfaces increased exponentially. To make the control force required by pilots manageable, aircraft engineers designed more complex systems. At first, hydro-mechanical designs, consisting of a mechanical circuit and a hydraulic circuit, were used to reduce the complexity, weight, and limitations of mechanical flight controls systems. [Figure 1.66]

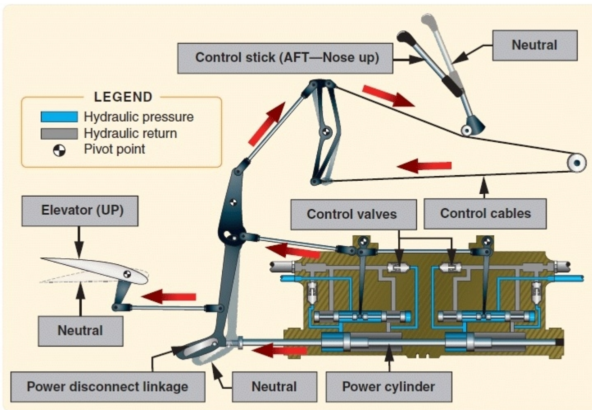


Figure 1.66 Hydromechanical flight control system

308. As aircraft became more sophisticated, the control surfaces were actuated by electric motors, digital computers, or fiber optic cables. Called "fly-by-wire," this flight control system replaces the physical connection between pilot controls and the flight control surfaces with an electrical interface. In addition, in some large and fast aircraft, controls are boosted by

hydraulically or electrically actuated systems. In both the fly-by-wire and boosted controls, the feel of the control reaction is fed back to the pilot by simulated m eans.

309. Current research at the National Aeronautics and Space Administration (NASA) Dryden Flight Research Centre involves Intelligent Flight Control Systems (IFCS). The goal of this project is to develop an adaptive neural network-based flight control system. Applied directly to flight control system feedback errors, IFCS provides adjustments to improve aircraft performance in normal flight as well as with system failures. W ith IFCS, a pilot is able to maintain control and safely land an aircraft that has suffered a failure to a control surface or damage to the airframe. It also improves mission capability, increases the reliability and safety of flight, and eases the pilot workload.

310. Today's aircraft employ a variety of flight control systems. For example, some aircraft in the sport pilot category rely on weight-shift control to fly while balloons use a standard burn technique. Helicopters utilize a cyclic to tilt the rotor in the desired direction along with a collective to manipulate rotor pitch and anti-torque pedals to control yaw. [Figure 1.67]

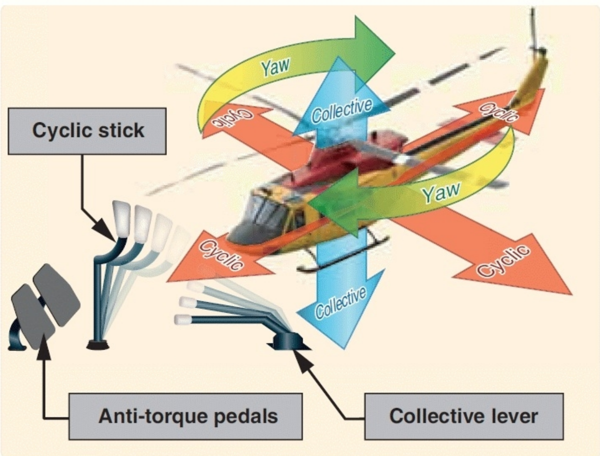


Figure 1.67 Helicopter flight control system

311. For additional information on flight control systems, refer to the appropriate handbook for information related to the flight control systems and characteristics of specific types of aircraft.

Flight Control Systems

Flight Controls

312. Aircraft flight control systems consist of primary and secondary systems. The ailerons, elevator (or stabilator), and rudder constitute the primary control system and are required to control an aircraft safely during flight. W ing flaps, leading edge devices, spoilers, and trim systems constitute the secondary control system and improve the perform ance characteristics of the aeroplane or relieve the pilot of excessive control forces.

Primary Flight Controls

313. Aircraft control systems are carefully designed to provide adequate responsiveness to control inputs while allowing a natural feel. At low airspeeds, the controls usually feel soft and sluggish, and the aircraft responds slowly to control applications. At higher airspeeds, the controls become increasingly firm and aircraft response is more rapid.

314. Movement of any of the three primary flight control surfaces (ailerons, elevator or stabilator, or rudder), changes the airflow and pressure distribution over and around the aerofoil. These changes affect the lift and drag produced by the aerofoil/control surface combination, and allow a pilot to control the aircraft about its three axes of rotation.

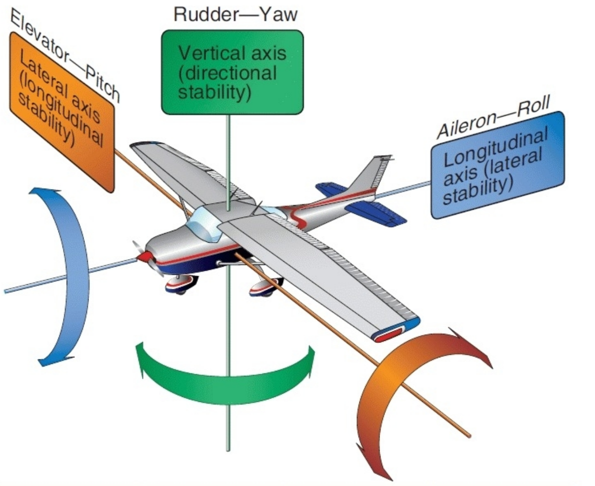
315. Design features limit the amount of deflection of flight control surfaces. For example, control-stop mechanisms may be incorporated into the flight control linkages, or movement of the control column and/or rudder pedals may be limited. The purpose of these design limits is to prevent the pilot from inadvertently over-controlling and over-stressing the aircraft during normal manoeuvres.

316. A properly designed aeroplane is stable and easily controlled during normal manoeuvring. Control surface inputs cause movement about the three axes of rotation. The types of stability an aeroplane exhibits also relate to the three axes of rotation. [Figure 1.68]

Ailerons

317 Ailerons control roll about the longitudinal axis. The ailerons are attached to the outboard trailing edge

of each wing and move in the opposite direction from each other. Ailerons are connected by cables, bellcranks, pulleys and/or push-pull tubes to a control wheel or control stick.



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 1.68 Aeroplane controls, movement, axes of rotation and type of stability

318. Moving the control wheel or control stick to the right causes the right aileron to deflect upward and the left aileron to deflect downward. The upward deflection of the right aileron decreases the camber resulting in decreased lift on the right wing. The corresponding downward deflection of the left aileron increases the camber resulting in increased lift on the left wing. Thus, the increased lift on the left wing and the decreased lift on the right wing causes the aeroplane to roll to the right.

Adverse Yaw

319. Since the downward deflected aileron produces more lift as evidenced by the wing raising, it also produces more drag. This added drag causes the wing to slow down slightly. This results in the aircraft yawing toward the wing which had experienced an increase in lift (and drag). From the pilot's perspective, the yaw is opposite the direction of the bank. The adverse yaw is a result of differential drag and the slight difference in the velocity of the left and right wings. [Figure 1.69]

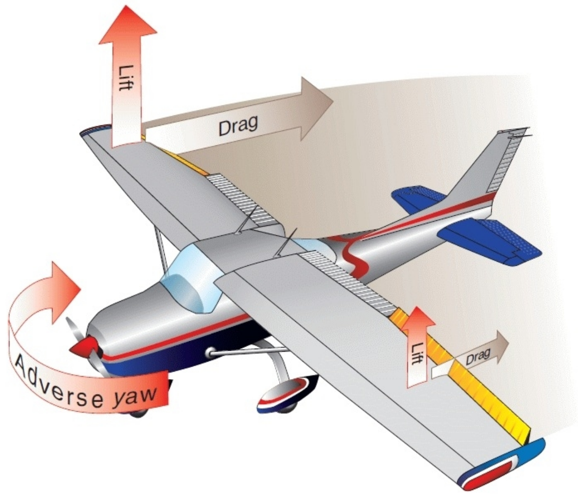


Figure 1.69 Adverse yaw is caused by higher drag on the outside wing, which is producing more lift

320. Adverse yaw becomes more pronounced at low airspeeds. At these slower airspeeds aerodynamic pressure on control surfaces is low and larger control inputs are required to effectively manoeuvre the aeroplane. As a result, the increase in aileron deflection causes an increase in adverse yaw. The yaw is especially evident in aircraft with long wing spans. Application of rudder is used to counteract adverse yaw. The amount of rudder control required is greatest at low airspeeds, high angles of attack, and with large aileron deflections. Like all control surfaces at lower airspeeds, the vertical stabilizer/rudder becomes less effective, and magnifies the control problem s associated with adverse yaw.

321. All turns are coordinated by use of ailerons, rudder, and elevator. Applying aileron pressure is necessary to place the aircraft in the desired angle of bank, while simultaneous application of rudder pressure is necessary to counteract the resultant adverse yaw. Additionally, because more lift is required during a turn than when in straight-and-level flight, the angle of attack (AOA) must be increased by applying elevator back pressure. The steeper the turn, the more elevator back pressure is needed.

322. As the desired angle of bank is established, aileron and rudder pressures should be relaxed. This stops the angle of bank from increasing, because the aileron and rudder control surfaces are in a neutral and streamlined position. Elevator back pressure should be held constant to maintain altitude. The roll-out from a

turn is similar to the roll-in, except the flight controls are applied in the opposite direction. Aileron and rudder are applied in the direction of the roll-out or toward the high wing. As the angle of bank decreases, the elevator back pressure should be relaxed as necessary to maintain altitude.

323. In an attempt to reduce the effects of adverse yaw, manufacturers have engineered four systems: differential ailerons, frise-type ailerons, coupled ailerons and rudder, and flaperons.

Differential Ailerons

324. W ith differential ailerons, one aileron is raised a greater distance than the other aileron is lowered for a given movement of the control wheel or control stick. This produces an increase in drag on the descending wing. The greater drag results from deflecting the up aileron on the descending wing to a greater angle than the down aileron on the rising wing. W hile adverse yaw is reduced, it is not eliminated completely. [Figure 1.70]

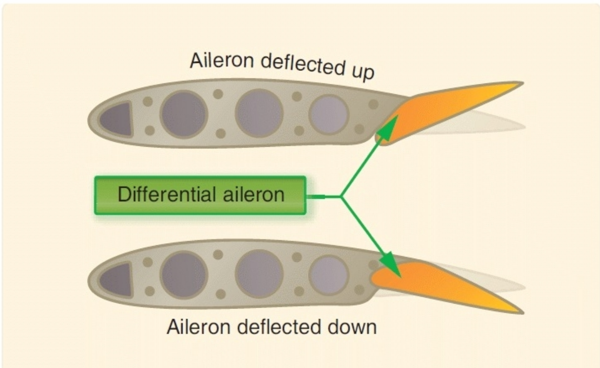


Figure 1.70 Differential ailerons

Frise-Type Ailerons

325. W ith a frise-type aileron, when pressure is applied to the control wheel or control stick, the aileron that is being raised pivots on an offset hinge. This projects the leading edge of the aileron into the airflow and creates drag. It helps equalize the drag created by the lowered aileron on the opposite wing and reduces adverse yaw. [Figure 1.72]

326. The frise-type aileron also forms a slot so air flows smoothly over the lowered aileron, making it more effective at high angles of attack. Frise-type ailerons may also be designed to function differentially. Like the differential aileron, the frise-type aileron does not eliminate adverse yaw entirely. Coordinated rudder application is still needed wherever ailerons are applied.

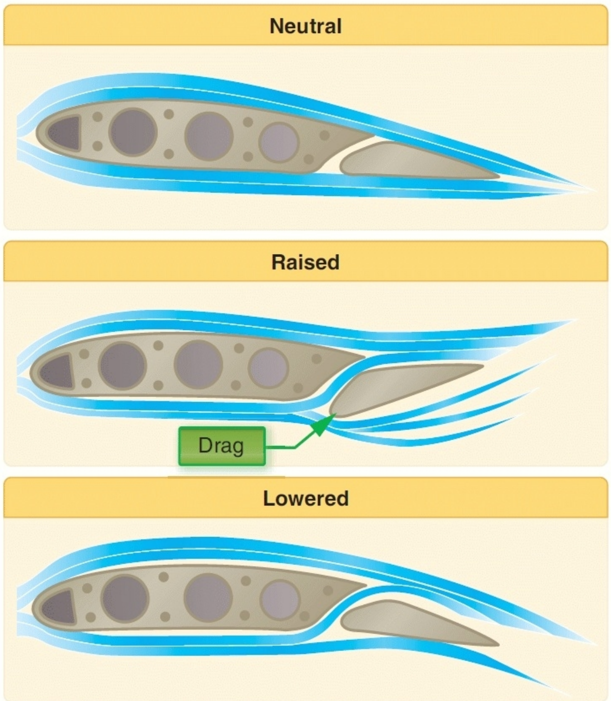


Figure 1.71 Frise-type ailerons

Coupled Ailerons and Rudder

327. Coupled ailerons and rudder are linked controls. This is accomplished with rudder-aileron interconnect springs, which help correct for aileron drag by automatically deflecting the rudder at the same time the ailerons are deflected. For example, when the control wheel or control stick is moved to produce a left roll, the interconnect cable and spring pulls forward on the left rudder pedal just enough to prevent the nose of the aircraft from yawing to the right. The force applied to the rudder by the springs can be overridden if it becomes necessary to slip the aircraft. [Figure 1.72]

Flaperons

328. 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.

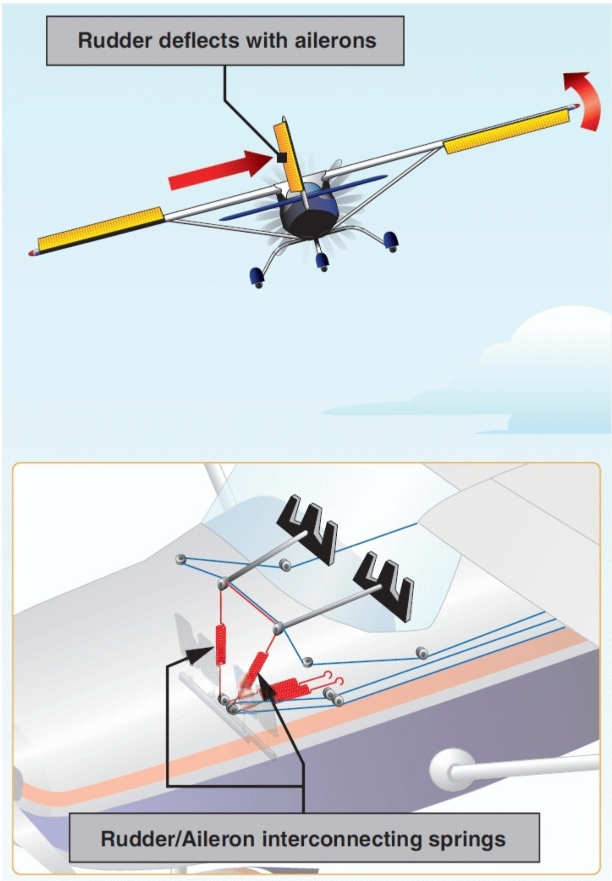


Figure 1.72 Coupled ailerons and rudder

Elevator

329. The elevator controls pitch about the lateral axis. Like the ailerons on small aircraft, the elevator is connected to the control column in the flight deck by a series of mechanical linkages. Aft movement of the control column deflects the trailing edge of the elevator surface up. This is usually referred to as up "elevator." [Figure 1.73]

330. The up-elevator position decreases the camber of the elevator and creates a downward aerodynamic force, which is greater than the normal tail-down force that exists in straight-and-level flight. The overall effect causes the tail of the aircraft to move down and the nose to pitch up. The pitching moment occurs about the centre of gravity (CG). The strength of the pitching moment is determined by the distance between the CG and the horizontal tail surface, as well as by the aerodynamic effectiveness of the horizontal tail surface. Moving the control column forward has the opposite effect. In this case, elevator cam ber increases, creating more lift (less tail-down force) on the horizontal stabilizer/elevator. This moves the tail upward and pitches the nose down. Again, the pitching moment occurs about the CG.

331. As mentioned earlier in the coverage on stability, power, thrust line, and the position of the horizontal tail surfaces on the empennage are factors in elevator effectiveness controlling pitch. For example, the horizontal tail surfaces may be attached near the lower part of the vertical stabilizer, at the midpoint, or at the high point, as in the T-tail design.

T-Tail

332. In a T-tail configuration, the elevator is above most of the effects of downwash from the propeller as well as airflow around the fuselage and/or wings during normal flight conditions. Operation of the elevators in this undisturbed air allows control movements that are consistent throughout most flight regimes. T -tail designs have become popular on many light and large aircraft, especially those with aft fuselage mounted engines because the T-tail configuration removes the tail from the exhaust blast of the engines. Seaplanes and amphibians often have T-tails in order to keep the horizontal surfaces as far from the water as possible. An additional benefit is reduced vibration and noise inside the aircraft.

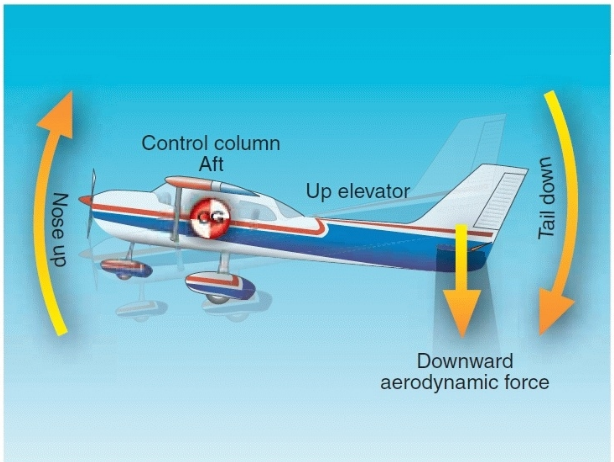


Figure 1.73 The elevator is the primary control for changing the pitch attitude of an aeroplane

333. At slow speeds, the elevator on a T-tail aircraft must be moved through a larger number of degrees of travel to raise the nose a given amount than on a conventional-tail aircraft. This is because the conventional-tail aircraft has the downwash from the

propeller pushing down on the tail to assist in raising the nose.

334. Since controls on aircraft are rigged so that increasing control forces are required for increased control travel, the forces required to raise the nose of a T-tail aircraft are greater than those for a conventional-tail aircraft. Longitudinal stability of a trimmed aircraft is the same for both types of configuration, but the pilot must be aware that the required control forces are greater at slow speeds during takeoffs, landings, or stalls than for similar size aircraft equipped with conventional tails.

335. T-tail aeroplanes also require additional design considerations to counter the problem of flutter. Since the weight of the horizontal surfaces is at the top of the vertical stabilizer, the moment arm created causes high loads on the vertical stabilizer which can result in flutter. Engineers must compensate for this by increasing the design stiffness of the vertical stabilizer, usually resulting in a weight penalty over conventional tail designs.

336. W hen flying at a very high AOA with a low airspeed and an aft CG, the T-tail aircraft may be susceptible to a deep stall. In a deep stall, the airflow over the horizontal tail is blanketed by the disturbed airflow from the wings and fuselage. In these circumstances, elevator or stabilator control could be diminished, making it difficult to recover from the stall. It should be noted that an aft CG is often a contributing factor in these incidents, since similar recovery problems are also found with conventional tail aircraft with an aft CG. [Figure 1.74]

Figure 1.74 Aeroplane with a T-tail design at high AOA and an aft CG

337. Since flight at a high AOA with a low airspeed and an aft CG position can be dangerous, many aircraft have systems to compensate for this situation. The systems range from control stops to elevator down springs. An elevator down spring assists in lowering the nose of the aircraft to prevent a stall caused by the aft CG position. The stall occurs because the properly trimmed aeroplane is flying with the elevator in a trailing edge down position, forcing the tail up and the nose down. In this unstable condition, if the aircraft encounters turbulence and slows down further, the trim tab no longer positions the elevator in the nose-down position. The elevator then streamlines, and the nose of the aircraft pitches upward, possibly resulting in a stall.

338. The elevator down spring produces a mechanical load on the elevator, causing it to move toward the nose-down position if not otherwise balanced. The elevator trim tab balances the elevator down spring to position the elevator in a trimmed position. W hen the trim tab becomes ineffective, the down spring drives the elevator to a nose-down position. The nose of the aircraft lowers, speed builds up, and a stall is prevented. [Figure 1.75]

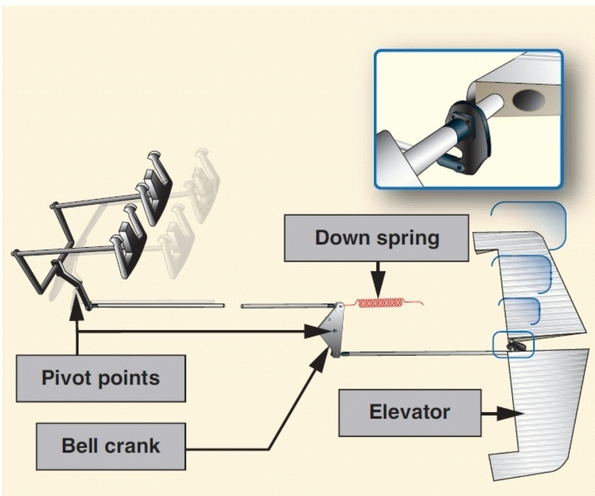


Figure 1.75 When the aerodynamic efficiency of the horizontal tail surface is inadequate due to an aft CG, an elevator down spring may be used to supply a mechanical load to lower the nose

339. The elevator must also have sufficient authority to hold the nose of the aircraft up during the round out for a landing. In this case, a forward CG may cause a problem. During the landing flare, power is usually reduced, which decreases the airflow over the empennage. This, coupled with the reduced landing

speed, makes the elevator less effective.

340. As this discussion demonstrates, pilots must understand and follow proper loading procedures, particularly with regard to the CG position. More information on aircraft loading, as well as weight and balance, is included in Chapter5, Flight Planning and Perform ance.

Stabilator

341. A stabilator is essentially a one-piece horizontal stabilizer that pivots from a central hinge point. W hen the control column is pulled back, it raises the stabilator's trailing edge, pulling the aeroplane's nose up. Pushing the control column forward lowers the trailing edge of the stabilator and pitches the nose of the aeroplane down.

342. Because stabilators pivot around a central hinge point, they are extremely sensitive to control inputs and aerodynamic loads. Antiservo tabs are incorporated on the trailing edge to decrease sensitivity. They deflect in the same direction as the stabilator. This results in an increase in the force required to move the stabilator, thus making it less prone to pilot-induced overcontrolling. In addition, a balance weight is usually incorporated in front of the main spar. The balance weight may project into the empennage or may be incorporated on the forward portion of the stabilator tips. [Figure 1.77]

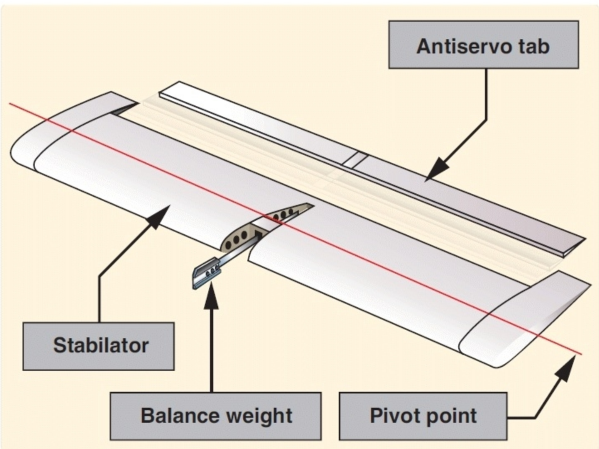


Figure 1.76 The stabilator is a one-piece horizontal tail surface that pivots up and down about a central hinge point

Canard

343. The canard design utilizes the concept of two lifting surfaces, the canard functioning as a horizontal stabilizer located in front of the main wings. In effect, the canard is an aerofoil 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 1.77]

Figure 1.77 The Piaggio P180 with a variable sweep canard design which provides longitudinal stability about the lateral axis

344. The canard design dates back to the pioneer days of aviation, most notably used on the W right 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 aerofoil 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.

Rudder

345. The rudder controls movement of the aircraft about its vertical axis. This motion is called yaw. Like the other primary control surfaces, the rudder is a movable surface hinged to a fixed surface, in this case to the vertical stabilizer, or fin. Moving the left or right rudder pedal controls the rudder.

346. W hen the rudder is deflected into the airflow,

a horizontal force is exerted in the opposite direction. [Figure 1.79] By pushing the left pedal, the rudder moves left. This alters the airflow around the vertical stabilizer/rudder, and creates a sideward lift that moves the tail to the right and yaws the nose of the aeroplane to the left. Rudder effectiveness increases with speed; therefore, large deflections at low speeds and small deflections at high speeds may be required to provide the desired reaction. In propeller-driven aircraft, any slipstream flowing over the rudder increases its effectiveness.

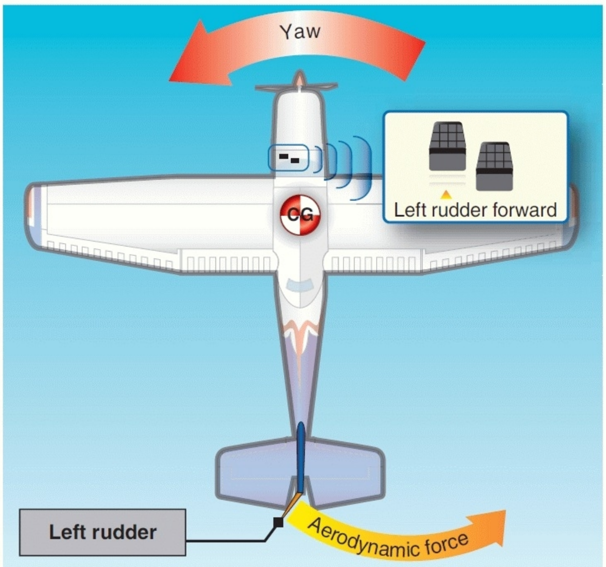


Figure 1.78 The effect of rudder

V-Tail

347. The V-tail design utilizes two slanted tail surfaces to perform the same functions as the surfaces of a conventional elevator and rudder configuration. The fixed surfaces act as both horizontal and vertical stabilizers. [Figure 1.79]

Figure 1.79 Beechcraft Bonanza

348. The movable surfaces, which are usually called ruddervators, are connected through a special linkage that allows the control wheel to move both surfaces simultaneously. On the other hand, displacement of the rudder pedals moves the surfaces differentially, thereby providing directional control. W hen both rudder and elevator controls are moved by the pilot, a control mixing mechanism moves each surface the appropriate amount. The control system for the V-tail is more complex than that required for a conventional tail. In addition, the V-tail design is more susceptible to Dutch roll tendencies than a conventional tail, and total reduction in drag is minimal.

Secondary Flight Controls

349. Secondary flight control systems may consist of wing flaps, leading edge devices, spoilers, and trim system s.

Flaps

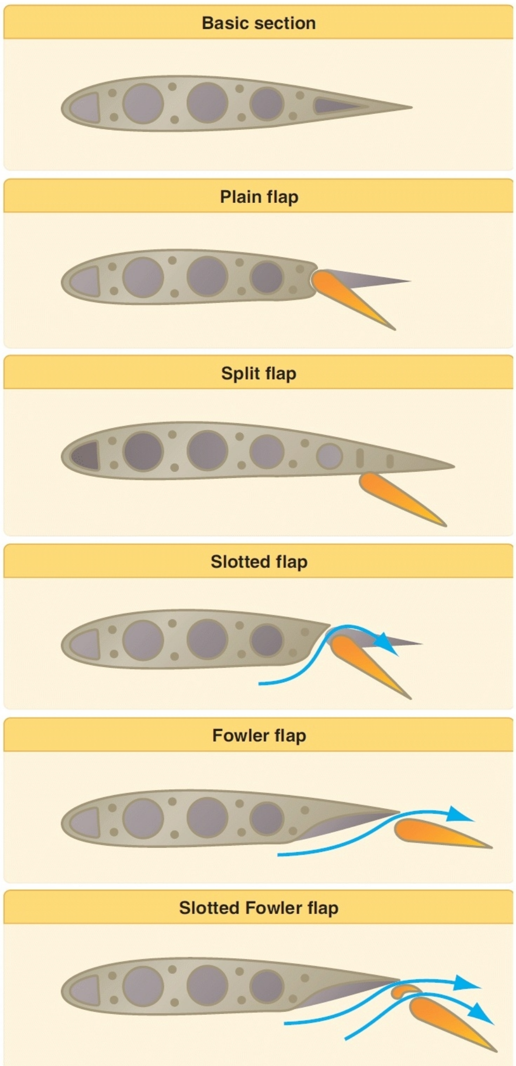


Figure 1.80 Five common types of flap

350. Flaps are the most common high-lift devices used on aircraft. These surfaces, which are attached to the trailing edge of the wing, increase both lift and induced drag for any given AOA. Flaps allow a compromise between high cruising speed and low landing speed, because they may be extended when needed, and retracted into the wing's structure when not needed. There are four common types of flaps: plain, split, slotted, and Fowler flaps. [Figure 1.80]

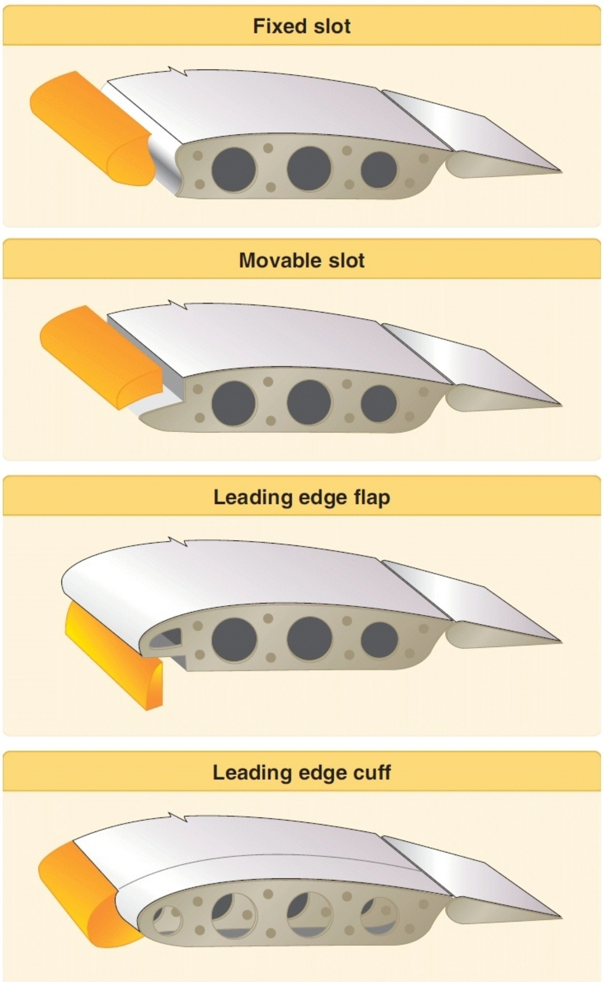


Figure 1.81 Leading edge high lift devices

351. The plain flap is the simplest of the four types. It increases the aerofoil camber, resulting in a significant increase in the coefficient of lift (CL) at a given AOA. At the same time, it greatly increases drag and moves the centre of pressure (CP) aft on the aerofoil, resulting in a nose-down pitching moment.

352. The split flap is deflected from the lower surface of the aerofoil and produces a slightly greater increase in lift than the plain flap. More drag is created because of the turbulent air pattern produced behind the aerofoil. W hen fully extended, both plain and split flaps produce high drag with little additional lift. The most popular flap on aircraft today is the slotted flap. Variations of this design are used for small aircraft, as well as for large ones. Slotted flaps increase the lift coefficient significantly more than plain or split flaps. On small aircraft, the hinge is located below the lower surface of the flap, and when the flap is lowered, a duct forms between the flap well in the wing and the leading edge of the flap. W hen the slotted flap is lowered, high energy air from the lower surface is ducted to the flap's upper surface. The high energy air from the slot accelerates the upper surface boundary layer and delays airflow separation, providing a higher C_{L}. Thus, the slotted flap produces much greater increases in maximum coefficient of lift (C_{L-MAX}) than the plain or split flap. W hile there are many types of slotted flaps, large aircraft often have double- and even triple-slotted flaps. These allow the maximum increase in drag without the airflow over the flaps separating and destroying the lift they produce.

353. Fowler flaps are a type of slotted flap. This flap design not only changes the camber of the wing, it also increases the wing area. Instead of rotating down on a hinge, it slides backwards on tracks. In the first portion of its extension, it increases the drag very little, but increases the lift a great deal as it increases both the area and camber. As the extension continues, the flap deflects downward. During the last portion of its travel, the flap increases the drag with little additional increase in lift.

354. Fixed slots direct airflow to the upper wing surface and delay airflow separation at higher angles of attack. The slot does not increase the wing camber, but allows a higher maximum CL because the stall is delayed until the wing reaches a greater AOA.

355. Movable slats consist of leading edge segments, which move on tracks. At low angles of attack, each slat is held flush against the wing's leading edge by the high pressure that forms at the wing's leading edge. As the AOA increases, the high pressure area moves aft below the lower surface of the wing, allowing the slats to move forward. Some slats, however, are pilot operated and can be deployed at any AOA. Opening a slat allows the air below the wing to flow over the wing's upper surface, delaying airflow separation.

356. Leading edge flaps, like trailing edge flaps, are

used to increase both $C_{L\text{-}MAX}$ and the camber of the wings. This type of leading edge device is frequently used in conjunction with trailing edge flaps and can reduce the nose-down pitching movement produced by the latter. As is true with trailing edge flaps, a small increment of leading edge flaps increases lift to a much greater extent than drag. As greater amounts of flaps are extended, drag increases at a greater rate than lift.

357. Leading edge cuffs, like leading edge flaps and trailing edge flaps are used to increase both CL-MAX and the camber of the wings. Unlike leading edge flaps and trailing edge flaps, leading edge cuffs are fixed aerodynamic devices. In most cases leading edge cuffs extend the leading edge down and forward. This causes the airflow to attach better to the upper surface of the wing at higher angles of attack, thus lowering an aircraft's stall speed. The fixed nature of leading edge cuffs extracts a penalty in maximum cruise airspeed, but recent advances in design and technology have reduced this penalty.

Spoilers

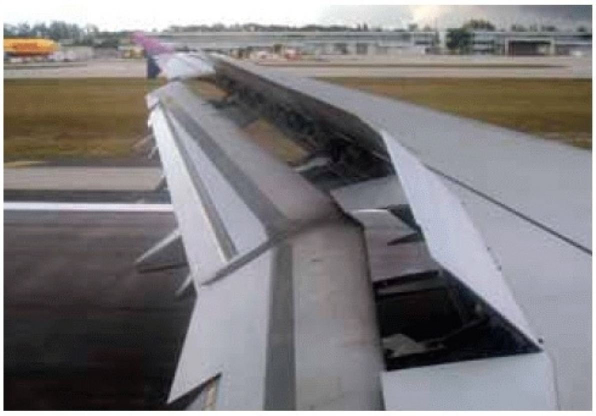


Figure 1.82 Spoilers reduce lift and increase drag during descent and landing

358. Found on many gliders and some aircraft, high drag devices called spoilers are deployed from the wings to spoil the smooth airflow, reducing lift and increasing drag. On gliders, spoilers are most often used to control rate of descent for accurate landings. On other aircraft, spoilers are often used for roll control, an advantage of which is the elimination of adverse yaw. To turn right, for example, the spoiler on the right wing is raised, destroying some of the lift and creating more drag on the right. The right wing drops, and the aircraft banks and yaws to the right. Deploying spoilers on both wings at the same time allows the aircraft to descend without gaining speed. Spoilers are also deployed to help reduce ground roll after landing. By destroying lift, they transfer weight to the wheels, improving braking effectiveness. [Figure 1.83]

Trim Systems

359. Although an aircraft can be operated throughout a wide range of attitudes, airspeeds, and power settings, it can be designed to fly hands-off within only a very limited combination of these variables. Trim systems are used to relieve the pilot of the need to maintain constant pressure on the flight controls, and usually consist of flight deck controls and small hinged devices attached to the trailing edge of one or more of the primary flight control surfaces. Designed to help minimize a pilot's workload, trim systems aerodynamically assist movement and position of the flight control surface to which they are attached. Common types of trim systems include trim tabs, balance tabs, anti-servo tabs, ground adjustable tabs, and an adjustable stabilizer.

Trim Tabs

359. The most common installation on small aircraft is a single trim tab attached to the trailing edge of the elevator. Most trim tabs are manually operated by a small, vertically mounted control wheel. However, a trim crank may be found in some aircraft. The flight deck control includes a trim tab position indicator. Placing the trim control in the full nose-down position moves the trim tab to its full up position. W ith the trim tab up and into the airstream, the airflow over the horizontal tail surface tends to force the trailing edge of the elevator down. This causes the tail of the aeroplane to move up, and the nose to move down. [Figure 1.83]

360. If the trim tab is set to the full nose-up position, the tab moves to its full down position. In this case, the air flowing under the horizontal tail surface hits the tab and forces the trailing edge of the elevator up, reducing the elevator's AOA. This causes the tail of the aeroplane to move down, and the nose to move up.

362. In spite of the opposing directional movement of the trim tab and the elevator, control of trim is natural to a pilot. If the pilot needs to exert constant back pressure on a control column, the need for nose-up trim is indicated. The normal trim procedure is to

continue trimming until the aircraft is balanced and the nose-heavy condition is no longer apparent. Pilots normally establish the desired power, pitch attitude, and configuration first, and then trim the aircraft to relieve control pressures that may exist for that flight condition. Any time power, pitch attitude, or configuration is changed, expect that re-trimming will be necessary to relieve the control pressures for the new flight condition.

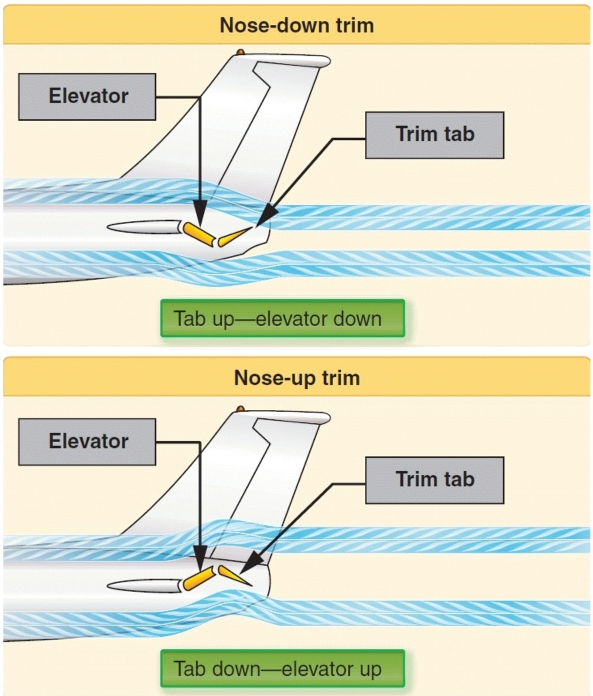


Figure 1.83 The movement of the elevator is opposite to the direction of movement of the elevator trim tab

Balance Tabs

363. The control forces may be excessively high in some aircraft, and, in order to decrease them, the manufacturer may use balance tabs. They look like trim tabs and are hinged in approximately the same places as trim tabs. The essential difference between the two is that the balancing tab is coupled to the control surface rod so that when the primary control surface is moved in any direction, the tab automatically moves in the opposite direction. The airflow striking the tab counterbalances some of the air pressure against the primary control surface, and enables the pilot to move more easily and hold the control surface in position.

364. If the linkage between the balance tab and the fixed surface is adjustable from the flight deck, the tab acts as a combination trim and balance tab that can be adjusted to any desired deflection.

Anti-servo Tabs

365. Anti-servo tabs work in the same manner as balance tabs except, instead of moving in the opposite direction, they move in the same direction as the trailing edge of the stabilator. In addition to decreasing the sensitivity of the stabilator, an anti-servo tab also functions as a trim device to relieve control pressure and maintain the stabilator in the desired position. The fixed end of the linkage is on the opposite side of the surface from the horn on the tab; when the trailing edge of the stabilator moves up, the linkage forces the trailing edge of the tab up. W hen the stabilator moves down, the tab also moves down. Conversely, trim tabs on elevators move opposite of the control surface. [Figure 1.84]

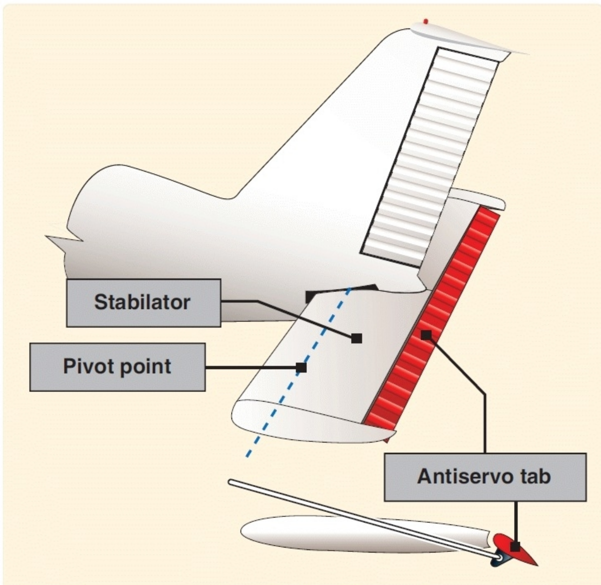


Figure 1.84 An anti-servo tab attempts to streamline the control surface and is used to make the stabilator less sensitive by opposing the force exerted by the pilot

Ground Adjustable Tabs

366. Many small aircraft have a nonmovable metal trim tab on the rudder. This tab is bent in one direction or the other while on the ground to apply a trim force to the rudder. The correct displacement is determined by trial and error. Usually, small adjustments are necessary until the aircraft no longer skids left or right during normal cruising flight. [Figure 1.85]

Figure 1.85 A ground adjustable tab is used on the rudder of many small aeroplanes to correct for a tendency to fly with the fuselage slightly misaligned with the relative wind

Adjustable Stabilizer

367. Rather than using a movable tab on the trailing edge of the elevator, some aircraft have an adjustable stabilizer. W ith this arrangement, linkages pivot the horizontal stabilizer about its rear spar. This is accomplished by use of a jackscrew mounted on the leading edge of the stabilator. [Figure 1.86]

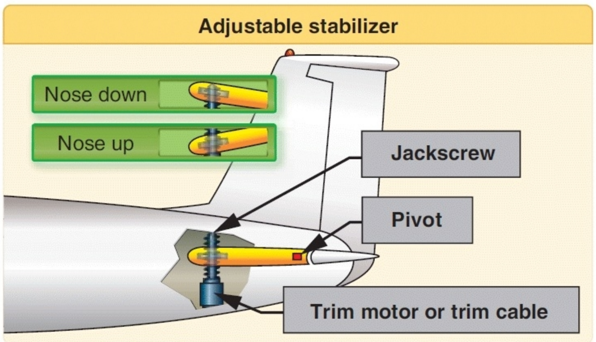


Figure 1.86 Some aeroplanes, including most jet transports, use an adjustable stabiliser to provide the required pitch trim

368. On small aircraft, the jackscrew is cable operated with a trim wheel or crank. On larger aircraft, it is motor driven. The trimming effect and flight deck indications for an adjustable stabilizer are similar to those of a trim tab.

Autopilot

369. Autopilot is an automatic flight control system that keeps an aircraft in level flight or on a set course. It can be directed by the pilot, or it may be coupled to a radio navigation signal. Autopilot reduces the physical and mental demands on a pilot and increases safety. The common features available on an autopilot are altitude and heading hold.

370. The simplest systems use gyroscopic attitude indicators and magnetic compasses to control servos connected to the flight control system. The number and location of these servos depends on the complexity of the system. For example, a single-axis autopilot controls the aircraft about the longitudinal axis and a servo actuates the ailerons. A three-axis autopilot controls the aircraft about the longitudinal, lateral, and vertical axes. Three different servos actuate ailerons, elevator, and rudder. More advanced systems often include a vertical speed and/or indicated airspeed hold mode. Advanced autopilot systems are coupled to navigational aids through a flight director.

371. The autopilot system also incorporates a disconnect safety feature to disengage the system automatically or manually. These autopilots work with inertial navigation systems, global positioning systems (GPS), and flight computers to control the aircraft. In fly-by-wire systems, the autopilot is an integrated com ponent.

372. Additionally, autopilots can be m anually overridden. Because autopilot systems differ widely in their operation, refer to the autopilot operating instructions in the Aeroplane Flight Manual (AFM) or the Pilot's Operating Handbook (POH).

Section Summary

373. Because flight control systems and aerodynamic characteristics vary greatly between aircraft, it is essential that a pilot become familiar with the primary and secondary flight control systems of the aircraft being flown. The primary source of this information is the AFM or the POH. Various manufacturer and owner group websites can also be a valuable source of additional information.

TYPICAL EXAM QUESTIONS

Once you have completed a subject, you will be required to sit an examination for that particular subject. This is done using an on-line computer generated examination paper. These exams are done at the Aviation Training Organization (ATO) where you are registered, and may not be done at any other ATO. Here are a few examples of the type of question you can expect, with explanations to assist you in choosing the correct answer.

1. After being disturbed from a trimmed attitude an aircraft returns to its original attitude without pilot input. This aircraft can be said to be:

   a. Positively unstable
   b. Possessing neutral stability
   c. Possessing positive stability
   d. Displaying divergent instability

Solution: In general terms, stability is positive when it tends to return the aircraft to the original state in this case the trimmed attitude. The element of stability that makes an aircraft tend to return back towards its original state is ‘static’ stability. The element of stability that damps out that movement until the aircraft has settled back at the original state is ‘dynamic’ stability. Option A would suggest that the aircraft would not return to it’s original position, and is therefore incorrect. Option B would suggest that the aircraft would continue oscillating without returning to its original position, and is also incorrect. Option D suggests that the aircraft would continue oscillating, but moving further away each time (divergent being the opposite of convergent) and is also incorrect. Option C suggests that the aircraft will return to its original position as is therefore correct.

2. At the stalling angle of attack:

   a. The maximum coefficient of lift is obtained
   b. The minimum coefficient of lift is obtained
   c. The maximum lift/ drag ratio is obtained
   d. The minimum coefficient of drag is obtained

Solution: As angle of attack increases, the value of coefficient of lift also increases, until it reaches its maximum value at around the stalling angle of attack, which excludes Option B. At this point the wing is producing the greatest coefficient of lift, but also a very high coefficient of drag, so this excludes both Options C and D. If angle of attack is increased beyond the stalling angle, coefficient of lift will reduce sharply. The correct answer is Option A.

3. In level flight an aircraft stalls at 60 knots. In a 60° angle of bank turn what would one expect the stalling speed to be?

   a. 60 knots
   b. 42 knots
   c. 62 knots
   d. 85 knots

Solution: Stalling speed increases by the square root of the load factor, and in a 60° angle of bank the aircraft is assumed to be experiencing a load factor of 2. Therefore, at a load factor of 2, stall speed is 1,41 x the ‘normal’ stall speed at a load factor of 1 (because the square root of 2 is 1.41). So, the stall speed in a 60° angle of bank turn is 1.41 x the wings level stall speed. 1.41 x 60 knots is 85 knots to the nearest knot, so Option D is correct.

Learn four things from each question. If you know why a particular statement is incorrect, you can find the correct answer by a process of elimination, even if you do not know the correct answer. Be careful when doing calculations. Your calculator only gives you digits, not units, so know what values you are working with.

Using your subject knowledge, find the correct answers to the following:

1. When air is flowing through the narrowest point of a venturi:

a. Airflow- speed will increase, static pressure will increase
b. Airflow speed will increase, static pressure will decrease
c. Airflow speed will decrease, static pressure will decrease
d. Airflow speed will decrease, static pressure will increase

2. Why is a propeller blade twisted along its length?

a. To reduce centrifugal stress
b. To reduce propeller torque
c. To maintain a constant angle of attack along the blade
d. To permit different RPM settings

3. In decreasing order of percentage, the major components of the atmosphere are:

a. Nitrogen; Oxygen; Water Vapour
b. Oxygen; Carbon Dioxide; Nitrogen
c. Oxygen; Water Vapour; Carbon Dioxide
d. Nitrogen; Carbon Dioxide; Oxygen

4. A slot or slat in the leading edge of a wing will:

a. Re-energise the airflow over the wing's upper surface, delaying airflow separation
b. Move the centre of gravity rearwards, thus reducing stall airspeed
c. Reduce drag at the cruise airspeed
d. Reduce lift at high angles of attack

5. A fixed 'bendable' trim tab, such as might be used on a rudder or aileron, is:

a. Set by the authority when the initial C of A is issued, and is not to be adjusted
b. Designed to be ground adjustable
c. Set by the manufacturer, and not to be adjusted by any other person or organisation
d. For training purposes only

6. Washout on an aeroplane wing means that there is a:

a. Reduction of angle of incidence from the wing root towards the wing tip
b. Reduction of angle of incidence from the wing tip towards the wing root
c. Tendency for the wing tips to stall first to increase stability in the stall and during slow flight
d. Increase in down-wash at the outer wing

The following questions may have more than one correct answer. Using the chapter notes see how many you can find.

1. In an aircraft which is spinning to the left the application of ailerons to the right:

2. Longitudinal dihedral is a design feature used as a method of improving stability:

3. Directional stability in an aeroplane is achieved:

4. W hen gliding into wind:

5. If only rudder is applied during straight and level flight the following will occur:

6. If the pressure of a parcel of air is kept constant and the:

7. The use of a Horn balance in an aeroplane:

8. The layer of air in contact with the surface of an aerofoil during flight is referred to as:

9. During a steady climb the arrangement of the four forces is such that:

10. A mass balance, extending ahead of the hinge line, is attached to the leading edge of a control surface in order to:

11. In order to maintain altitude during a turn:

12. The relationship between the four forces in level flight is that:

13. During a flapless approach to land the nose position of the aeroplane will, in relation to a normal approach with full flap, be:

14. The angle of attack of an aeroplane is defined as the angle:

15. Application of flaps during a turn will:

16. The stalling angle of attack of a particular aerofoil:

17. An anti-balance, or anti-servo, tab which is incorporated in a stabilator will:

18. A change in pitch will cause an aircraft to rotate around its:

19. During entry into a left hand turn from straight and level flight, rudder is normally applied in the same direction as ailerons in order to:

20. W hen climbing to clear obstacles in the takeoff path an aeroplane should climb:

21. An aircraft which has its CG too far aft would:

22. An increase in the angle of attack of an aerofoil will:

23. W hilst maintaining straight and level flight:

24. In order to maintain elevator control effectiveness, when loading an aeroplane it would be better to:

25. W hen climbing the maximum height gained in the shortest distance will be achieved:

26. Induced drag is created by:

27. If the temperature of a dry parcel of air is kept constant:

28. During a straight climb at a constant speed:

29. The total lift produced by the wings during a balanced level turn, must equal:

30. During a glide:

Quick Answers to questions with answer options

1	2	3	4	5	6
B	C	A	A	B	A

Full Explanations

1. At the narrowest point of a venturi, airflow speed increases and static pressure decreases. The faster the airflow speed, the lower the static pressure. This phenomenon is an example of 'Bernoulli's theorem', and is the essence of lift. Answer B.

2. Viewed from the side, the average aircraft propeller blade is 'twisted', so that the outer sections have a smaller blade angle than the inner. When the propeller blade is rotating, the outer sections travel through a greater distance than the inner in a given time, so they are travelling faster. If the blade angle was constant along its whole length, this would mean that the outer section would have a much greater angle of attack than the inner. For this reason, the outer sections of the blade have a reduced blade angle, so that when rotating all sections of the propeller blade have approximately the same angle of attack. Answer C.

3. The basic components of the 'dry' atmosphere are as follows: It is often overlooked that the 'dry' atmosphere does not exist outside the laboratory; and in the earth's atmosphere there is always a significant percentage of water vapour - usually in the order of 4%. Answer A.

4. A slot or slat in the wing's leading edge will allow a higher pressure air from beneath the wing to flow over the wing's upper surface. This airflow has the effect of adding energy, to the air blowing over the wing, thus encouraging the airflow, to follow the contours of the upper wing surface. Slots or slats mean that a wing can produce a greater maximum amount of lift, and attain a higher angle of attack than a 'clean' wing. Answer A.

5. Answer B. A bendable trim tab attached to a control surface is designed to be adjusted on the ground to achieve aerodynamic balance in the air. As such. its adjustment is for practical purposes a matter of trial and error, and it is recommended that the ground adjustment is done under the supervision of a licenced engineer. Answer B.

6. The angle of incidence is the angle between the wing's chordline and the fuselage. Washout is essentially a twist in the wing section, so that the angle of incidence at the wing root is greater than the angle of incidence at the wing tip. Washout means that the wing root flies at a greater angle of attack than the wing tip. This means that approaching the stall, the wing root is likely to reach the stalling angle of attack before the wing tip and so the inner wing will stall before the outer. The result is that the aircraft is less likely to roll, ie 'drop a wing', at the stall and the ailerons (nearer the wing tips) are more likely to remain effective near the stall. Answer A.

Some answer options to the short questions (remember there are many more possibilities):

1. may delay the spin recovery

2. about the lateral axis

3. through the vertical fin

4. the glide angle will increase
5. yaw followed by roll and a spiral dive
6. temperature is increased, the density will decrease
7. improves the aerodynamic balance of the controls
8. the boundary layer
9. thrust is greater than drag
10. prevent control flutter
11. the angle of attack must be increased
12. lift is equal to weight and thrust is equal to drag
13. higher
14. between the chord line and the relative airflow
15. decrease the stall speed
16. will remain constant irrespective of airspeed, bank angle or weight
17. move in the same direction as the control surface
18. lateral axis and centre of gravity
19. correct the adverse yaw created by lowering the aileron on the right wing
20. at the best angle of climb speed
21. be difficult to control in pitch
22. decrease the pressure above the wing and increase drag
23. the centre of pressure is located behind the centre of gravity
24. have a forward centre of gravity
25. by climbing at the best angle of climb speed
26. the lift produced by the wings
27. an increase in pressure will result in an increase in density
28. lift is less than weight
29. the vertical component of lift and the centripetal force
30. application of flap will reduce the best L/D ratio