
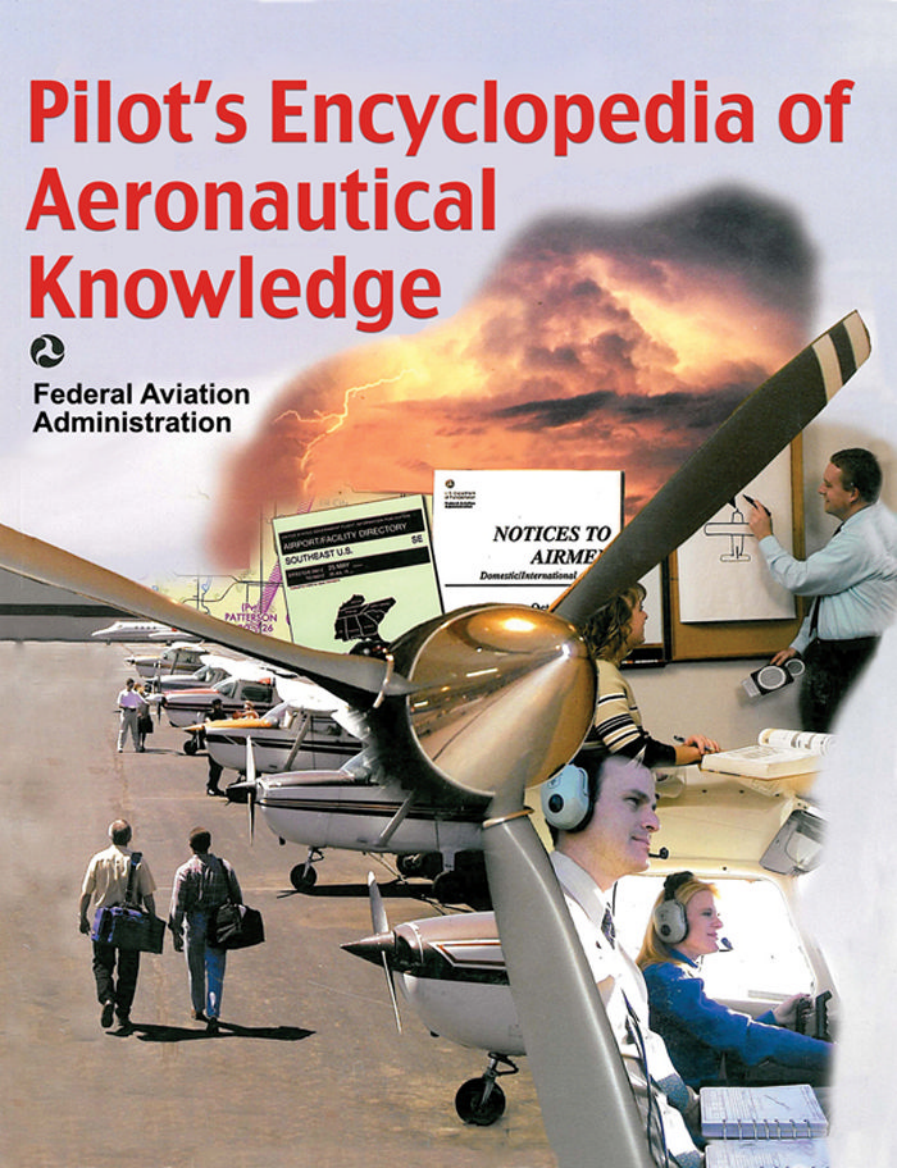


# Pilot's Encyclopedia of Aeronautical Knowledge

 Federal Aviation Administration



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# **PILOT'S ENCYCLOPEDIA OF AERONAUTICAL KNOWLEDGE**

**Federal Aviation Administration**



Skyhorse Publishing

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## PREFACE

The *Pilot's Encyclopedia of Aeronautical Knowledge* provides basic knowledge that is essential for pilots. This handbook introduces pilots to the broad spectrum of knowledge that will be needed as they progress in their pilot training. Except for the Code of Federal Regulations pertinent to civil aviation, most of the knowledge areas applicable to pilot certification are presented. This handbook is useful to beginning pilots, as well as those pursuing more advanced pilot certificates.

Occasionally, the word "must" or similar language is used where the desired action is deemed critical. The use of such language is not intended to add to, interpret, or relieve a duty imposed by Title 14 of the Code of Federal Regulations (14 CFR).

It is essential for persons using this handbook to also become familiar with and apply the pertinent parts of 14 CFR and the *Aeronautical Information Manual* (AIM).

The current Flight Standards Service airman training and testing material and subject matter knowledge codes for all airman certificates and ratings can be obtained from the Flight Standards Service Web site at <http://av-info.faa.gov>.

This handbook supersedes Advisory Circular (AC) 61-23C, Pilot's Handbook of Aeronautical Knowledge, dated 1997.

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AC 00-2, Advisory Circular Checklist, transmits the current status of FAA advisory circulars and other flight information and publications. This checklist is available via the Internet at [http://www.faa.gov/aba/html\\_policies/ac00\\_2.html](http://www.faa.gov/aba/html_policies/ac00_2.html).



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# Chapter 1



## Aircraft Structure

According to the current Title 14 of the Code of Federal Regulations (14 CFR) part 1, Definitions and Abbreviations, an **aircraft** is a device that is used, or intended to be used, for flight. Categories of aircraft for certification of airmen include airplane, rotorcraft, lighter-than-air, powered-lift, and glider. Part 1 also defines **airplane** as an engine-driven, fixed-wing aircraft heavier than air that is supported in flight by the dynamic reaction of air against its wings. This chapter

**Aircraft**—A device that is used for flight in the air.

**Airplane**—An engine-driven, fixed-wing aircraft heavier than air that is supported in flight by the dynamic reaction of air against its wings.

provides a brief introduction to the airplane and its major components.

### MAJOR COMPONENTS

Although airplanes are designed for a variety of purposes, most of them have the same major components. The overall characteristics are largely determined by the original design objectives. Most airplane structures include a fuselage, wings, an empennage, landing gear, and a powerplant. [Figure 1-1]

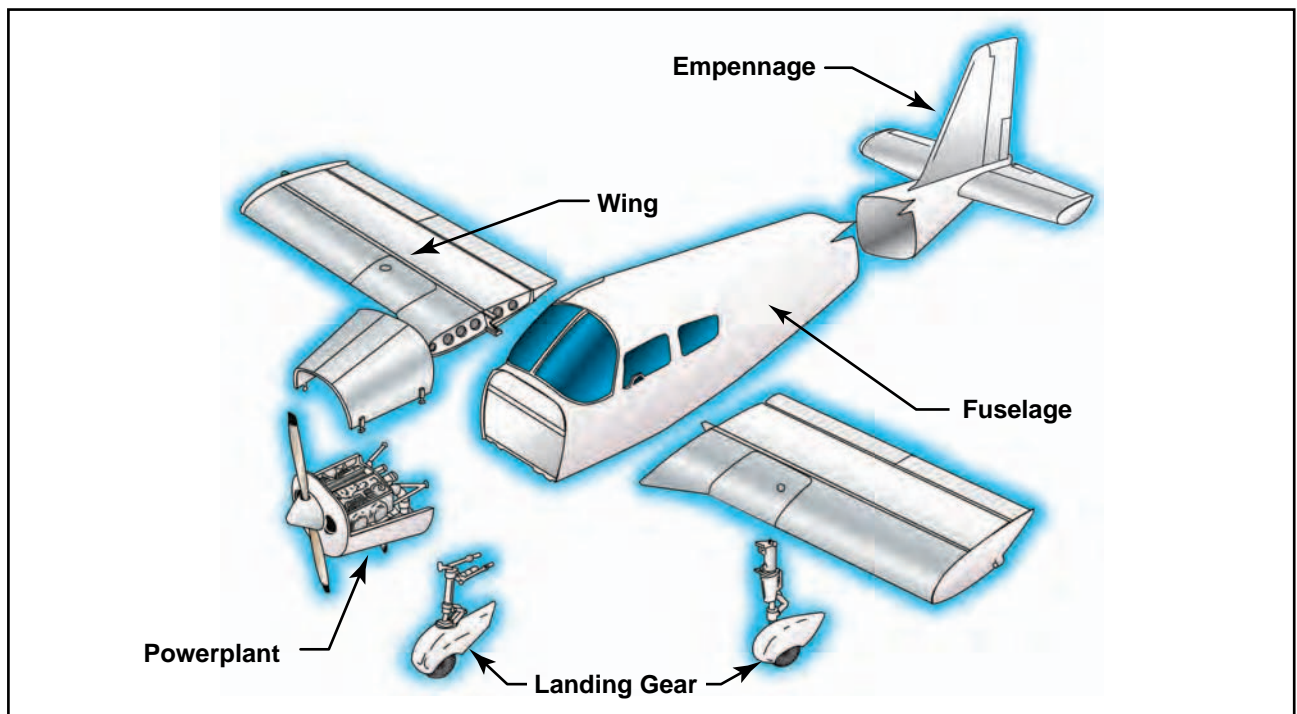


Figure 1-1. Airplane components.

## FUSELAGE

The fuselage includes the cabin and/or cockpit, which contains seats for the occupants and the controls for the airplane. In addition, the fuselage may also provide room for cargo and attachment points for the other major airplane components. Some aircraft utilize an open **truss** structure. The truss-type fuselage is constructed of steel or aluminum tubing. Strength and rigidity is achieved by welding the tubing together into a series of triangular shapes, called trusses. [Figure 1-2]

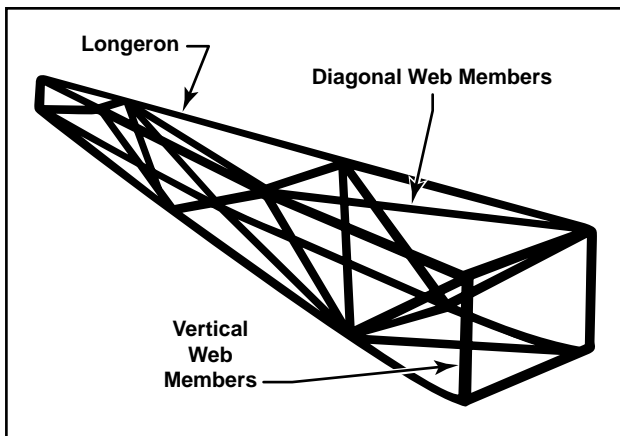


Figure 1-2. The Warren truss.

Construction of the Warren truss features longerons, as well as diagonal and vertical web members. To reduce weight, small airplanes generally utilize aluminum alloy tubing, which may be riveted or bolted into one piece with cross-bracing members.

As technology progressed, aircraft designers began to enclose the truss members to streamline the airplane and improve performance. This was originally accomplished with cloth fabric, which eventually gave way to lightweight metals such as aluminum. In some cases, the outside skin can support all or a major portion of the flight loads. Most modern aircraft use a form of this stressed skin structure known as monocoque or semi-monocoque construction.

The **monocoque** design uses stressed skin to support almost all imposed loads. This structure can be very strong but cannot tolerate dents or deformation of the surface. This characteristic is easily demonstrated by a thin aluminum beverage can. You can exert considerable force to the ends of the can without causing any damage.

**Truss**—A fuselage design made up of supporting structural members that resist deformation by applied loads.

**Monocoque**—A shell-like fuselage design in which the stressed outer skin is used to support the majority of imposed stresses. Monocoque fuselage design may include bulkheads but not stringers.

However, if the side of the can is dented only slightly, the can will collapse easily. The true monocoque construction mainly consists of the skin, formers, and bulkheads. The formers and bulkheads provide shape for the fuselage. [Figure 1-3]

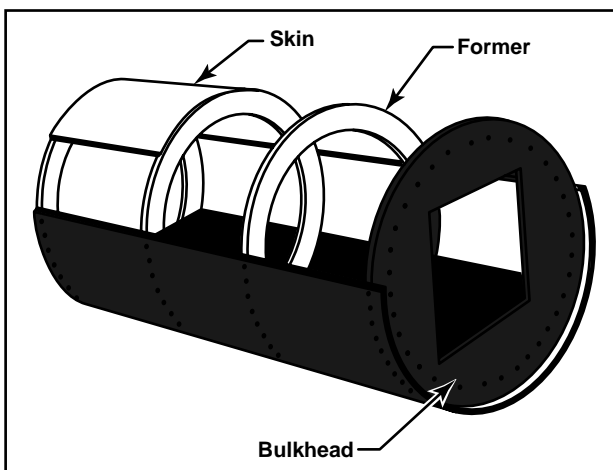


Figure 1-3. Monocoque fuselage design.

Since no bracing members are present, the skin must be strong enough to keep the fuselage rigid. Thus, a significant problem involved in monocoque construction is maintaining enough strength while keeping the weight within allowable limits. Due to the limitations of the monocoque design, a semi-monocoque structure is used on many of today's aircraft.

The **semi-monocoque** system uses a substructure to which the airplane's skin is attached. The substructure, which consists of bulkheads and/or formers of various sizes and stringers, reinforces the stressed skin by taking some of the bending stress from the fuselage. The main section of the fuselage also includes wing attachment points and a firewall. [Figure 1-4]

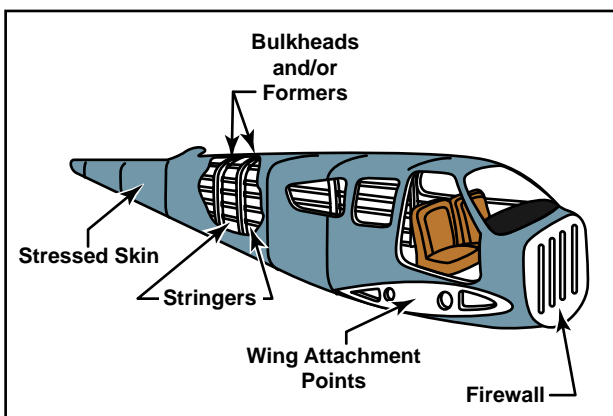


Figure 1-4. Semi-monocoque construction.

**Semi-Monocoque**—A fuselage design that includes a substructure of bulkheads and/or formers, along with stringers, to support flight loads and stresses imposed on the fuselage.

On single-engine airplanes, the engine is usually attached to the front of the fuselage. There is a fireproof partition between the rear of the engine and the cockpit or cabin to protect the pilot and passengers from accidental engine fires. This partition is called a firewall and is usually made of heat-resistant material such as stainless steel.

## WINGS

The wings are **airfoils** attached to each side of the fuselage and are the main lifting surfaces that support the airplane in flight. There are numerous wing designs, sizes, and shapes used by the various manufacturers. Each fulfills a certain need with respect to the expected performance for the particular airplane. How the wing produces lift is explained in subsequent chapters.

Wings may be attached at the top, middle, or lower portion of the fuselage. These designs are referred to as high-, mid-, and low-wing, respectively. The number of wings can also vary. Airplanes with a single set of wings are referred to as **monoplanes**, while those with two sets are called **biplanes**. [Figure 1-5]

Many high-wing airplanes have external braces, or wing struts, which transmit the flight and landing loads

**Airfoil**—An airfoil is any surface, such as a wing, propeller, rudder, or even a trim tab, which provides aerodynamic force when it interacts with a moving stream of air.

**Monoplane**—An airplane that has only one main lifting surface or wing, usually divided into two parts by the fuselage.

**Biplane**—An airplane that has two main airfoil surfaces or wings on each side of the fuselage, one placed above the other.

through the struts to the main fuselage structure. Since the wing struts are usually attached approximately halfway out on the wing, this type of wing structure is called semi-cantilever. A few high-wing and most low-wing airplanes have a full cantilever wing designed to carry the loads without external struts.



Figure 1-5. Monoplane and biplane.

The principal structural parts of the wing are spars, ribs, and stringers. [Figure 1-6] These are reinforced by

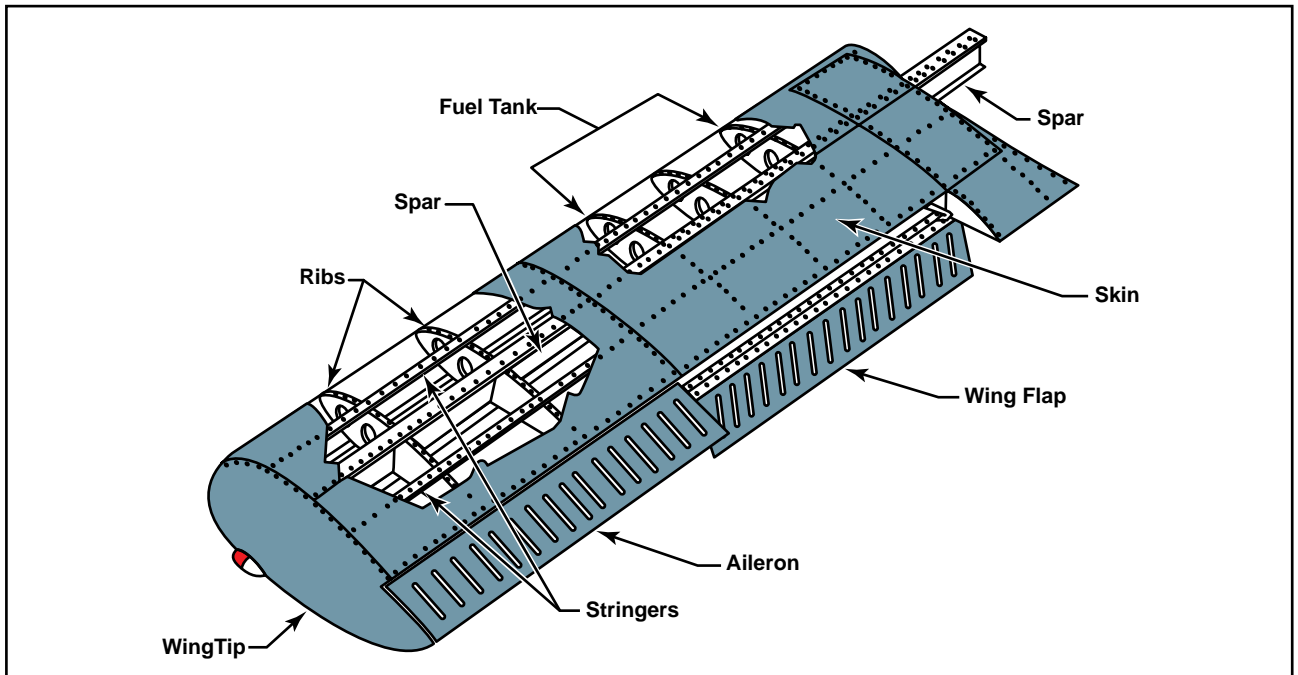


Figure 1-6. Wing components.

trusses, I-beams, tubing, or other devices, including the skin. The wing ribs determine the shape and thickness of the wing (airfoil). In most modern airplanes, the fuel tanks either are an integral part of the wing's structure, or consist of flexible containers mounted inside of the wing.

Attached to the rear, or trailing, edges of the wings are two types of control surfaces referred to as ailerons and flaps. Ailerons extend from about the midpoint of each wing outward toward the tip and move in opposite directions to create aerodynamic forces that cause the airplane to roll. Flaps extend outward from the fuselage to near the midpoint of each wing. The flaps are normally flush with the wing's surface during cruising flight. When extended, the flaps move simultaneously downward to increase the lifting force of the wing for takeoffs and landings.

### EMPENNAGE

The correct name for the tail section of an airplane is empennage. The **empennage** includes the entire tail group, consisting of fixed surfaces such as the vertical stabilizer and the horizontal stabilizer. The movable surfaces include the rudder, the elevator, and one or more trim tabs. [Figure 1-7]

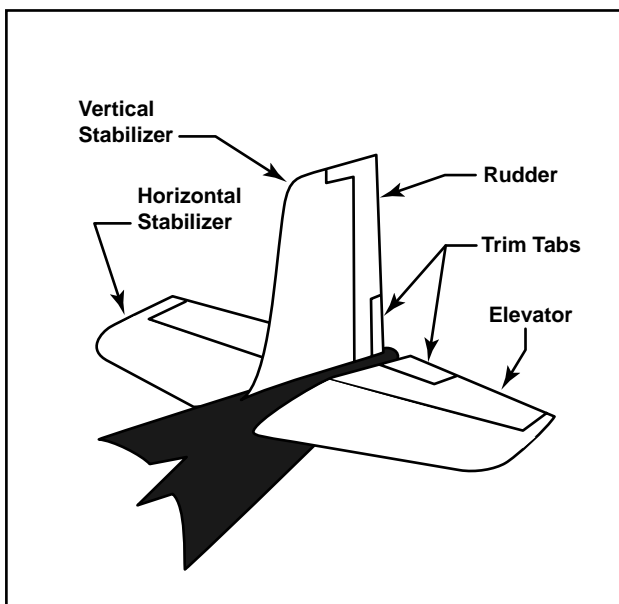


Figure 1-7. Empennage components.

**Empennage**—The section of the airplane that consists of the vertical stabilizer, the horizontal stabilizer, and the associated control surfaces.

A second type of empennage design does not require an elevator. Instead, it incorporates a one-piece horizontal stabilizer that pivots from a central hinge point. This type of design is called a stabilator, and is moved using the control wheel, just as you would the elevator. For example, when you pull back on the control wheel, the stabilator pivots so the trailing edge moves up. This increases the aerodynamic tail load and causes the nose of the airplane to move up. Stabilators have an antiservo tab extending across their trailing edge. [Figure 1-8]

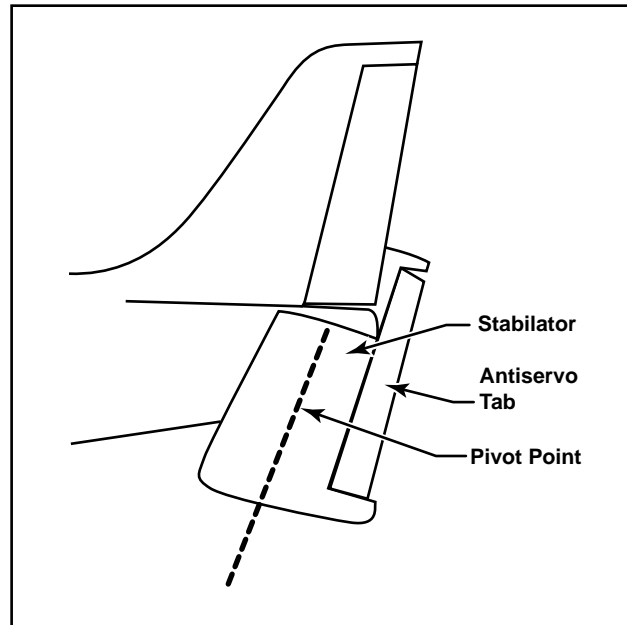


Figure 1-8. Stabilator components.

The antiservo tab moves in the same direction as the trailing edge of the stabilator. The antiservo tab also functions as a trim tab to relieve control pressures and help maintain the stabilator in the desired position.

The rudder is attached to the back of the vertical stabilizer. During flight, it is used to move the airplane's nose left and right. The rudder is used in combination with the ailerons for turns during flight. The elevator, which is attached to the back of the horizontal stabilizer, is used to move the nose of the airplane up and down during flight.

Trim tabs are small, movable portions of the trailing edge of the control surface. These movable trim tabs, which are controlled from the cockpit, reduce control pressures. Trim tabs may be installed on the ailerons, the rudder, and/or the elevator.

### LANDING GEAR

The landing gear is the principle support of the airplane when parked, taxiing, taking off, or when landing. The

most common type of landing gear consists of wheels, but airplanes can also be equipped with floats for water operations, or skis for landing on snow. [Figure 1-9]



Figure 1-9. Landing gear.

The landing gear consists of three wheels—two main wheels and a third wheel positioned either at the front or rear of the airplane. Landing gear employing a rear-mounted wheel is called conventional landing gear. Airplanes with conventional landing gear are sometimes referred to as tailwheel airplanes. When the third wheel is located on the nose, it is called a nosewheel, and the design is referred to as a tricycle gear. A steerable nosewheel or tailwheel permits the airplane to be controlled throughout all operations while on the ground.

## THE POWERPLANT

The powerplant usually includes both the engine and the propeller. The primary function of the engine is to provide the power to turn the propeller. It also generates electrical power, provides a vacuum source for some flight instruments, and in most single-engine

airplanes, provides a source of heat for the pilot and passengers. The engine is covered by a cowling, or in the case of some airplanes, surrounded by a nacelle. The purpose of the cowling or nacelle is to streamline the flow of air around the engine and to help cool the engine by ducting air around the cylinders. The propeller, mounted on the front of the engine, translates the rotating force of the engine into a forward-acting force called thrust that helps move the airplane through the air. [Figure 1-10]

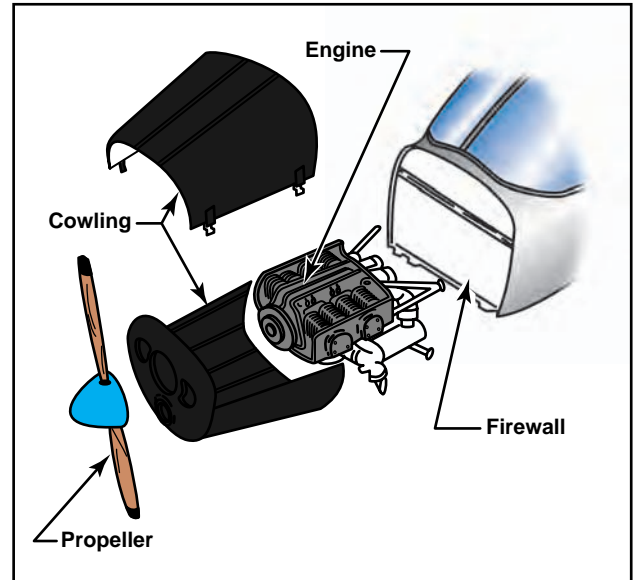


Figure 1-10. Engine compartment.

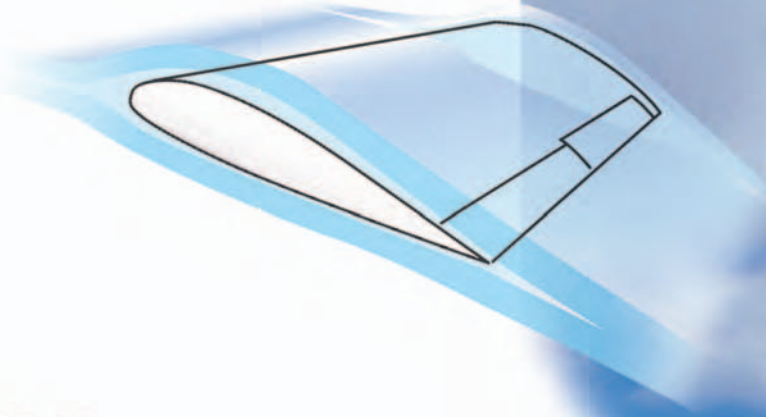
**Nacelle**—A streamlined enclosure on an aircraft in which an engine is mounted. On multiengine propeller-driven airplanes, the nacelle is normally mounted on the leading edge of the wing.





# Chapter 2

## Principles of Flight



This chapter discusses the fundamental physical laws governing the forces acting on an airplane in flight, and what effect these natural laws and forces have on the performance characteristics of airplanes. To competently control the airplane, the pilot must understand the principles involved and learn to utilize or counteract these natural forces.

Modern general aviation airplanes 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.

### **STRUCTURE OF THE ATMOSPHERE**

The atmosphere in which flight is conducted 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. However, air differs from land and water inasmuch as it is a mixture of gases. It has mass, weight, and indefinite shape.

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

The atmosphere is composed of 78 percent nitrogen, 21 percent oxygen, and 1 percent other gases, such as argon or helium. As some of these elements are heavier than others, there is a natural tendency of these heavier elements, such as oxygen, to settle to the surface of the earth, while the lighter elements are lifted up to the region of higher altitude. This explains why most of the oxygen is contained below 35,000 feet altitude.

Because air has mass and weight, it is a body, and as a body, it reacts to the scientific laws of bodies in the same manner as other gaseous bodies. This body of air resting upon the surface of the earth has weight and at sea level develops an average pressure of 14.7 pounds on each square inch of surface, or 29.92 inches of

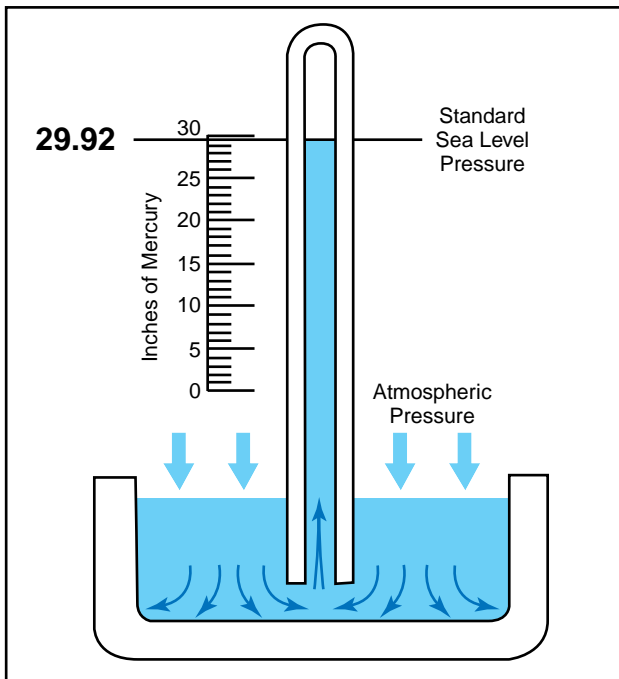


Figure 2-1. Standard sea level pressure.

mercury—but as its thickness is limited, the higher the altitude, the less air there is above. For this reason, the weight of the atmosphere at 18,000 feet is only one-half what it is at sea level. [Figure 2-1]

### ATMOSPHERIC PRESSURE

Though there are various kinds of pressure, this discussion is mainly concerned with atmospheric pressure. It is one of the basic factors in weather changes, helps to lift the airplane, and actuates some of the important flight instruments in the airplane. These instruments are the altimeter, the airspeed indicator, the rate-of-climb indicator, and the manifold pressure gauge.

Though air is very light, 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 on the human body by the weight of the atmosphere around it is approximately 14.7 lb./in. The density of air has significant effects on the airplane's capability. As air becomes less dense, it reduces (1) power because the engine takes in less air, (2) thrust because the propeller is less efficient in thin air, and (3) lift because the thin air exerts less force on the airfoils.

### EFFECTS OF PRESSURE ON DENSITY

Since air is a gas, it can be compressed or expanded. When 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. That is, the original column of air at a lower pressure contains a smaller mass of air. In other words, the density is decreased. In fact, density is directly proportional to pressure. If the pressure is doubled, the density is doubled, and if the pressure is lowered, so is the density. This statement is true, only at a constant temperature.

### EFFECT OF TEMPERATURE ON DENSITY

The effect of increasing the temperature of a substance is to decrease its density. Conversely, decreasing the temperature has the effect of increasing the density. Thus, the density of air varies inversely as the absolute temperature varies. 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, density can be expected to decrease with altitude.

### EFFECT OF HUMIDITY ON DENSITY

The preceding paragraphs have assumed that the air was perfectly dry. In reality, it is never completely dry. The small amount of water vapor 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 airplane. Water vapor is lighter than air; consequently, moist air is lighter than dry air. It is lightest or least dense when, in a given set of conditions, it contains the maximum amount of water vapor. The higher the temperature, the greater amount of water vapor the air can hold. When 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 necessarily must be less dense than the second. Pressure, temperature, and humidity have a great influence on airplane performance, because of their effect upon density.

## NEWTON'S LAWS OF MOTION AND FORCE

In the 17th century, a philosopher and mathematician, Sir Isaac Newton, propounded three basic laws of motion. It is certain that he did not have the airplane in mind when he did so, but almost everything known about motion goes back to his three simple laws. These laws, named after Newton, are as follows:

**Newton's first law** states, in part, that: A body at rest tends to remain at rest, and a body in motion tends to

remain moving at the same speed and in the same direction.

This simply means that, in nature, nothing starts or stops moving until some outside force causes it to do so. An airplane at rest on the ramp will remain at rest unless a force strong enough to overcome its inertia is applied. Once it is moving, however, 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.

**Newton's second law** implies that: 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.

What is being dealt with here are the factors involved in overcoming Newton's First Law of Inertia. It covers both changes in direction and speed, including starting up from rest (positive acceleration) and coming to a stop (negative acceleration, or deceleration).

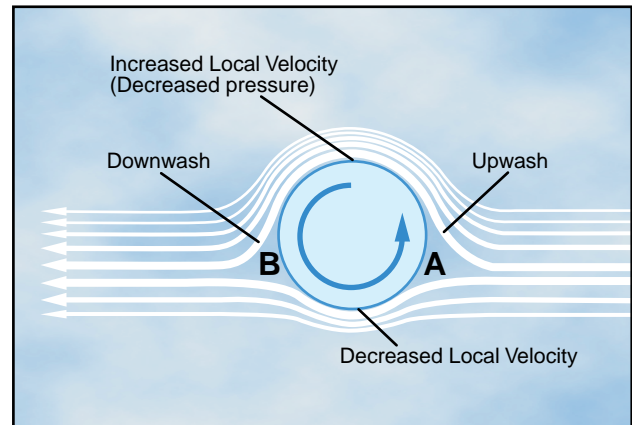
**Newton's third law** states that: Whenever one body exerts a force on another, the second body always exerts on the first, a force that is equal in magnitude but opposite in direction.

The recoil of a gun as it is fired is a graphic example of Newton's third law. The champion swimmer who pushes against the side of the pool during the turnaround, or the infant learning to walk—both would fail but for the phenomena expressed in this law. In an airplane, the propeller moves and pushes back the air; consequently, the air pushes the propeller (and thus the airplane) in the opposite direction—forward. In a jet airplane, the engine pushes a blast of hot gases backward; the force of equal and opposite reaction pushes against the engine and forces the airplane forward. The movement of all vehicles is a graphic illustration of Newton's third law.

## MAGNUS EFFECT

The explanation of lift can best be explained by looking at a cylinder rotating in an airstream. The local velocity near the cylinder is composed of the airstream velocity and the cylinder's rotational velocity, which decreases with distance from the cylinder. On a cylinder, which is rotating in such a way that the top surface area is rotating in the same direction as the airflow, the local velocity at the surface is high on top and low on the bottom.

As shown in figure 2-2, at point "A," a stagnation point exists where the airstream line that impinges on the surface splits; some air goes over and some under. Another stagnation point exists at "B," where the two

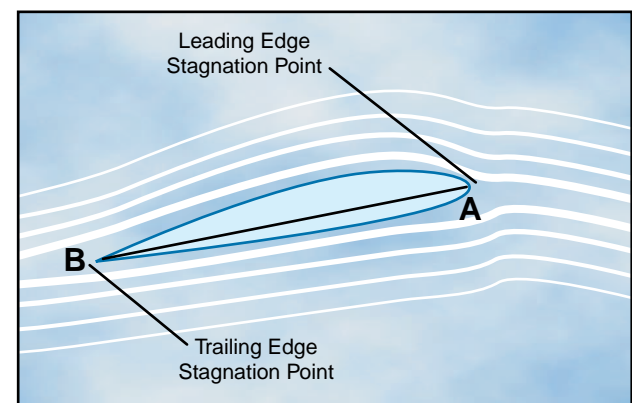


**Figure 2-2. Magnus Effect is a lifting force produced when a rotating cylinder produces a pressure differential. This is the same effect that makes a baseball curve or a golf ball slice.**

airstreams rejoin and resume at identical velocities. We now have upwash ahead of the rotating cylinder and downwash at the rear.

The difference in surface velocity accounts for a difference in pressure, with the pressure being lower on the top than the bottom. This low pressure area produces an upward force known as the "Magnus Effect." This mechanically induced circulation illustrates the relationship between circulation and lift.

An airfoil with a positive angle of attack develops air circulation as its sharp trailing edge forces the rear stagnation point to be aft of the trailing edge, while the front stagnation point is below the leading edge. [Figure 2-3]



**Figure 2-3. Air circulation around an airfoil occurs when the front stagnation point is below the leading edge and the aft stagnation point is beyond the trailing edge.**

## BERNOULLI'S PRINCIPLE OF PRESSURE

A half century after Sir Newton presented his laws, Mr. Daniel Bernoulli, a Swiss mathematician, explained how the pressure of a moving fluid (liquid or gas) varies with its speed of motion. Specifically,

he stated that an increase in the speed of movement or flow would cause a decrease in the fluid's pressure. This is exactly what happens to air passing over the curved top of the airplane wing.

An appropriate analogy can be made with water flowing through a garden hose. Water moving through a hose of constant diameter exerts a uniform pressure on the hose; but if the diameter of a section of the hose is increased or decreased, it is certain to change the pressure of the water at that point. Suppose the hose was pinched, thereby constricting the area through which the water flows. Assuming that the same volume of water flows through the constricted portion of the hose in the same period of time as before the hose was pinched, it follows that the speed of flow must increase at that point.

Therefore, if a portion of the hose is constricted, it not only increases the speed of the flow, but also decreases the pressure at that point. Like results could be achieved if streamlined solids (airfoils) were introduced at the same point in the hose. This same principle is the basis for the measurement of airspeed (fluid flow) and for analyzing the airfoil's ability to produce lift.

A practical application of Bernoulli's theorem is the venturi tube. The venturi tube has an air inlet which narrows to a throat (constricted point) and an outlet section which 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 2-4]

If air is recognized as a body and it is accepted that it must follow the above laws, one can begin to see how and why an airplane wing develops lift as it moves through the air.

## AIRFOIL DESIGN

In the sections devoted to Newton's and Bernoulli's discoveries, it has already been discussed in general

terms the question of how an airplane wing can sustain flight when the airplane is heavier than air. Perhaps the explanation can best be reduced to its most elementary concept by stating that lift (flight) is simply the result of fluid flow (air) about an airfoil—or in everyday language, the result of moving an airfoil (wing), by whatever means, through the air.

Since it is the airfoil which harnesses the force developed by its movement through the air, a discussion and explanation of this structure, as well as some of the material presented in previous discussions on Newton's and Bernoulli's laws, will be presented.

An airfoil 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 will be confined to the parts of an airplane that a pilot is most concerned with in flight—namely, the airfoils designed to produce lift. By looking at a typical airfoil profile, such as the cross section of a wing, one can see several obvious characteristics of design. [Figure 2-5] Notice that there is a difference in the curvatures of the upper and lower surfaces of the airfoil (the curvature is called camber). The camber of the upper surface is more pronounced than that of the lower surface, which is somewhat flat in most instances.

In figure 2-5, note that the two extremities of the airfoil profile also differ in appearance. The end which faces forward in flight is called the leading edge, and is rounded; while the other end, the trailing edge, is quite narrow and tapered.

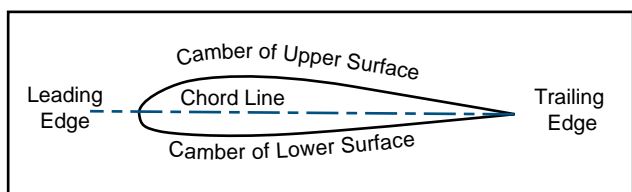


Figure 2-5. Typical airfoil section.

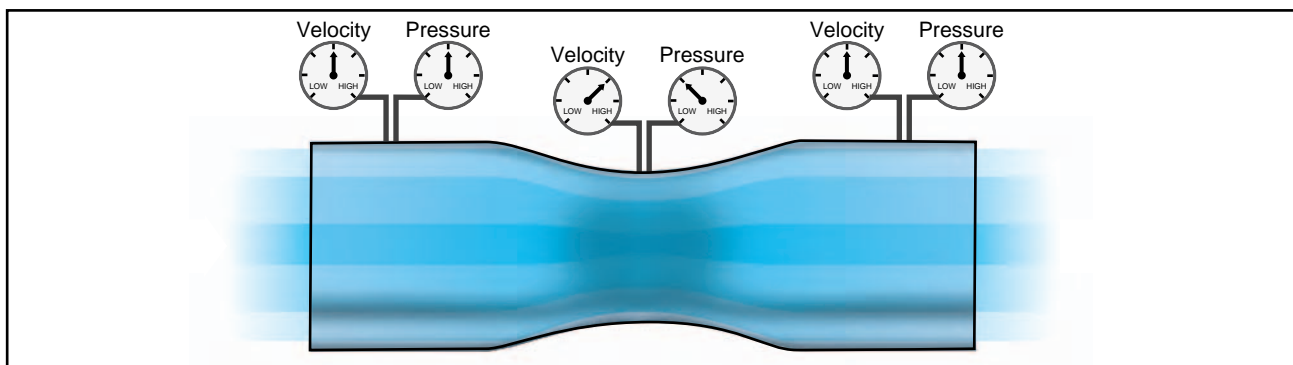


Figure 2-4. Air pressure decreases in a venturi.

A reference line often used in discussing the airfoil 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 contours.

The construction of the wing, so as to provide actions greater than its weight, is done by shaping the wing so that advantage can be taken of the air’s response to certain physical laws, and thus develop 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.

As the airstream strikes the relatively flat lower surface of the wing when inclined at a small angle to its direction of motion, the air is forced to rebound downward and therefore causes an upward reaction in positive lift, while at the same time airstream striking the upper curved section of the “leading edge” of the wing is deflected upward. In other words, a wing shaped to cause an action on the air, and forcing it downward, will provide an equal reaction from the air, forcing the wing upward. If a wing is constructed in such form that it will cause a lift force greater than the weight of the airplane, the airplane will fly.

However, if all the lift required were obtained merely from the deflection of air by the lower surface of the wing, an airplane would need only a flat wing like a kite. This, of course, is not the case at all; under certain conditions disturbed air currents circulating at the trailing edge of the wing could be so excessive as to make the airplane lose speed and lift. The balance of the lift needed to support the airplane comes from the flow of air above the wing. Herein lies the key to flight. The fact that most lift is the result of the airflow’s downwash from above the wing, must be thoroughly understood in order to continue further in the study of flight. It is neither accurate nor does it serve a useful purpose, however, to assign specific values to the percentage of lift generated by the upper surface of an airfoil versus that generated by the lower surface. These are not constant values and will vary, not only with flight conditions, but with different wing designs.

It should be understood that different airfoils have different flight characteristics. Many thousands of airfoils have been tested in wind tunnels and in actual flight, but no one airfoil has been found that satisfies every flight requirement. The weight, speed, and

purpose of each airplane dictate the shape of its airfoil. It was learned many years ago that the most efficient airfoil for producing the greatest lift was one that had a concave, or “scooped out” lower surface. Later it was also learned that as a fixed design, this type of airfoil sacrificed too much speed while producing lift and, therefore, was not suitable for high-speed flight. It is interesting to note, however, that through advanced progress in engineering, today’s high-speed jets can again take advantage of the concave airfoil’s high lift characteristics. Leading edge (Kreuger) flaps and trailing edge (Fowler) flaps, when extended from the basic wing structure, literally change the airfoil shape into the classic concave form, thereby generating much greater lift during slow flight conditions.

On the other hand, an airfoil that is perfectly streamlined and offers little wind resistance sometimes does not have enough lifting power to take the airplane off the ground. Thus, modern airplanes have airfoils which strike a medium between extremes in design, the shape varying according to the needs of the airplane for which it is designed. Figure 2-6 shows some of the more common airfoil sections.

## LOW PRESSURE ABOVE

In a wind tunnel or in flight, an airfoil is simply a streamlined object inserted into a moving stream of air. If the airfoil 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 airfoil were cut in half lengthwise, a form resembling the basic airfoil (wing) section would result. If the airfoil were then inclined so the airflow strikes it at an angle (angle of attack), the air molecules moving over the upper surface would be forced to move faster than would the molecules moving along the bottom of the airfoil, since the upper molecules must travel a greater distance due to the curvature of the upper surface. This increased velocity reduces the pressure above the airfoil.

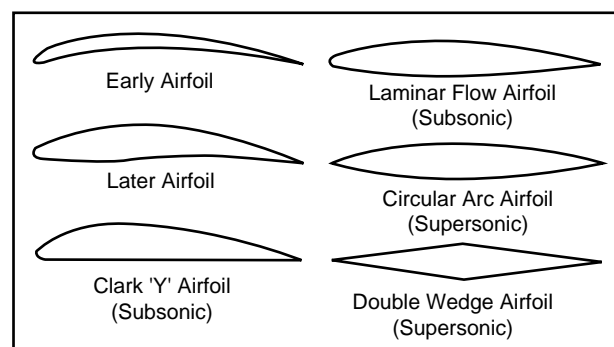


Figure 2-6. Airfoil designs.

Bernoulli's principle of pressure by itself does not explain the distribution of pressure over the upper surface of the airfoil. A discussion of the influence of momentum of the air as it flows in various curved paths near the airfoil will be presented. [Figure 2-7] Momentum is the resistance a moving body offers to having its direction or amount of motion changed. When a body is forced to move in a circular path, it offers resistance in the direction away from the center of the curved path. This is "centrifugal force." While the particles of air move in the curved path AB, centrifugal force tends to throw them in the direction of the arrows between A and B and hence, causes the air to exert more than normal pressure on the leading edge of the airfoil. But after the air particles pass B (the point of reversal of the curvature of the path) the centrifugal force tends to throw them in the direction of the arrows between B and C (causing reduced pressure on the airfoil). This effect is held until the particles reach C, the second point of reversal of curvature of the airflow. Again the centrifugal force is reversed and the particles may even tend to give slightly more than normal pressure on the trailing edge of the airfoil, as indicated by the short arrows between C and D.

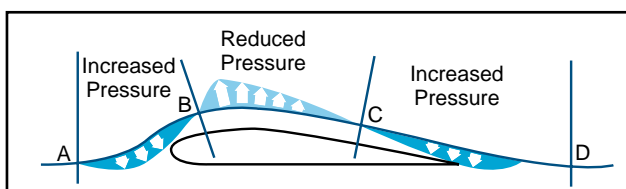


Figure 2-7. Momentum influences airflow over an airfoil.

Therefore, the air pressure on the upper surface of the airfoil is distributed so that the pressure is much greater on the leading edge than the surrounding atmospheric pressure, causing strong resistance to forward motion; but the air pressure is less than surrounding atmospheric pressure over a large portion of the top surface (B to C).

As seen in the application of Bernoulli's theorem to a venturi, the speedup of air on the top of an airfoil produces a drop in pressure. This lowered pressure is a component of total lift. It is a mistake, however, to assume that the pressure difference between the upper and lower surface of a wing alone accounts for the total lift force produced.

One must also bear in mind that associated with the lowered pressure is downwash; a downward backward flow from the top surface of the wing. As already seen from previous discussions relative to the dynamic action of the air as it strikes the lower surface of the wing, the reaction of this downward backward flow

results in an upward forward force on the wing. This same reaction applies to the flow of air over the top of the airfoil as well as to the bottom, and Newton's third law is again in the picture.

## HIGH PRESSURE BELOW

In the section dealing with Newton's laws as they apply to lift, it has already been discussed how a certain amount of lift is generated by pressure conditions underneath the wing. Because of the manner in which air flows underneath the wing, 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 has again reached a velocity equal to that on the upper surface. In conformance with Bernoulli's principles, where the airflow was slowed beneath the wing, a positive upward pressure was created against the wing; i.e., as the fluid speed decreases, the pressure must increase. In essence, this simply "accentuates the positive" since it increases the pressure differential between the upper and lower surface of the airfoil, and therefore increases total lift over that which would have resulted had there been no increase of pressure at the lower surface. Both Bernoulli's principle and Newton's laws are in operation whenever lift is being generated by an airfoil.

Fluid flow or airflow then, is the basis for flight in airplanes, and is a product of the velocity of the airplane. The velocity of the airplane is very important to the pilot since it affects the lift and drag forces of the airplane. The pilot uses the velocity (airspeed) to fly at a minimum glide angle, at maximum endurance, and for a number of other flight maneuvers. Airspeed is the velocity of the airplane relative to the air mass through which it is flying.

## PRESSURE DISTRIBUTION

From experiments conducted on wind tunnel models and on full size airplanes, 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 2-8 shows the pressure distribution along an airfoil at three different angles of attack. In general, at high angles of attack the

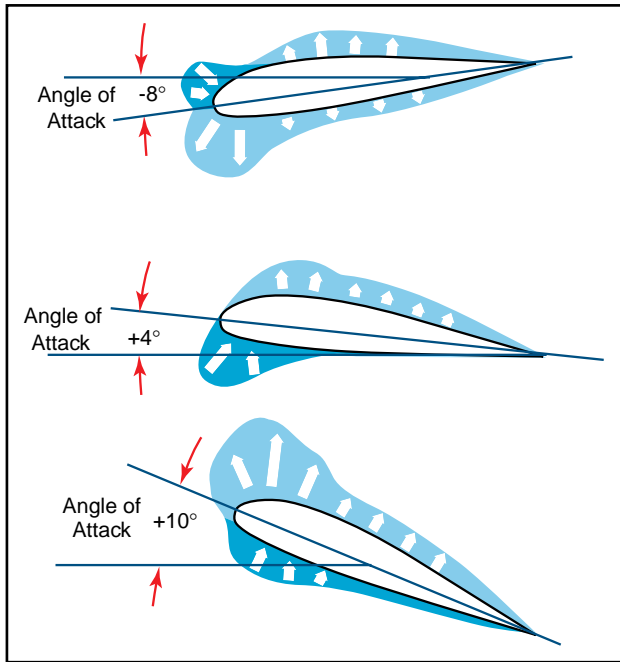


Figure 2-8. Pressure distribution on an airfoil.

center of pressure moves forward, while at low angles of attack the center of pressure moves aft. In the design of wing structures, this center of pressure travel is very important, since it affects the position of the airloads imposed on the wing structure in low angle-of-attack conditions and high angle-of-attack conditions. The airplane's aerodynamic balance and controllability are governed by changes in the center of pressure.

The center of pressure is determined through calculation and wind tunnel tests by varying the airfoil's angle of attack through normal operating extremes. As the angle of attack is changed, so are the various pressure distribution characteristics. [Figure 2-8] Positive (+) and negative (-) pressure forces are totaled for each angle of attack and the resultant force is obtained. The total resultant pressure is represented by the resultant force vector shown in figure 2-9.

The point of application of this force vector is termed the "center of pressure" (CP). For any given

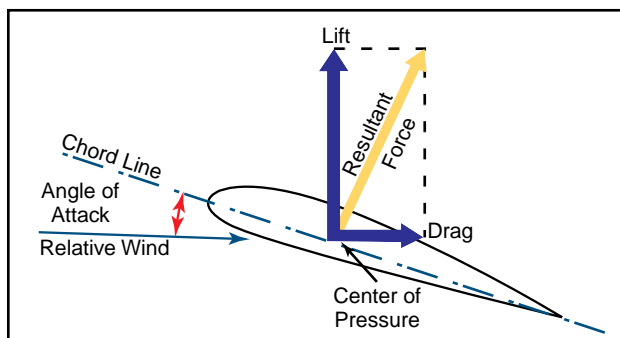


Figure 2-9. Force vectors on an airfoil.

angle of attack, the center of pressure is the point where the resultant force crosses the chord line. This point is expressed as a percentage of the chord of the airfoil. A center of pressure at 30 percent of a 60-inch chord would be 18 inches aft of the wing's leading edge. It would appear then that if the designer would place the wing so that its center of pressure was at the airplane's center of gravity, the airplane would always balance. The difficulty arises, however, that the location of the center of pressure changes with change in the airfoil's angle of attack. [Figure 2-10]

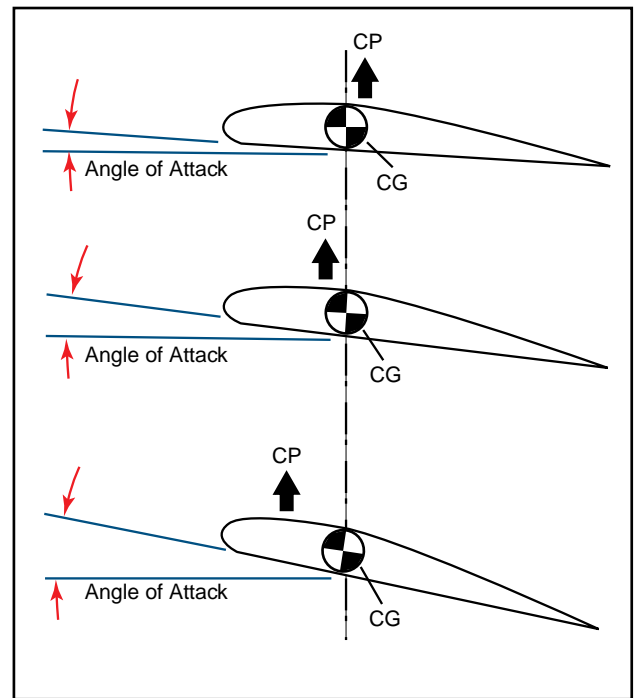


Figure 2-10. CP changes with an angle of attack.

In the airplane's normal range of flight attitudes, if the angle of attack is increased, the center of pressure moves forward; and if decreased, it moves rearward. Since the center of gravity is fixed at one point, it is evident that as the angle of attack increases, the center of lift (CL) moves ahead of the center of gravity, creating a force which tends to raise the nose of the airplane or tends to increase the angle of attack still more. On the other hand, if the angle of attack is decreased, the center of lift (CL) moves aft and tends to decrease the angle a greater amount. It is seen then, that the ordinary airfoil is inherently unstable, and that an auxiliary device, such as the horizontal tail surface, must be added to make the airplane balance longitudinally.

The balance of an airplane in flight depends, therefore, on the relative position of the center of gravity (CG) and the center of pressure (CP) of the airfoil. Experience has shown that an airplane with the center



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