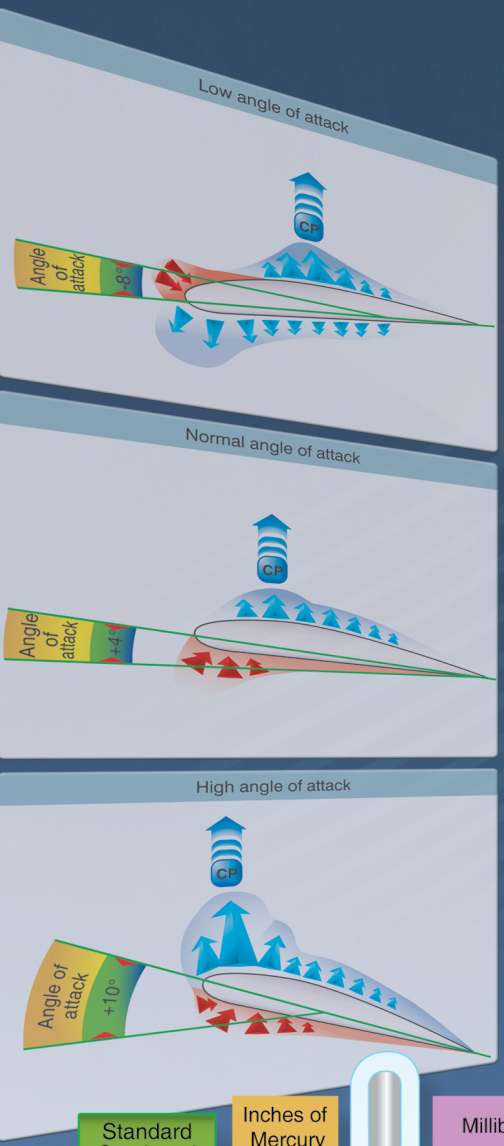
Chapter 4

Principles of Flight



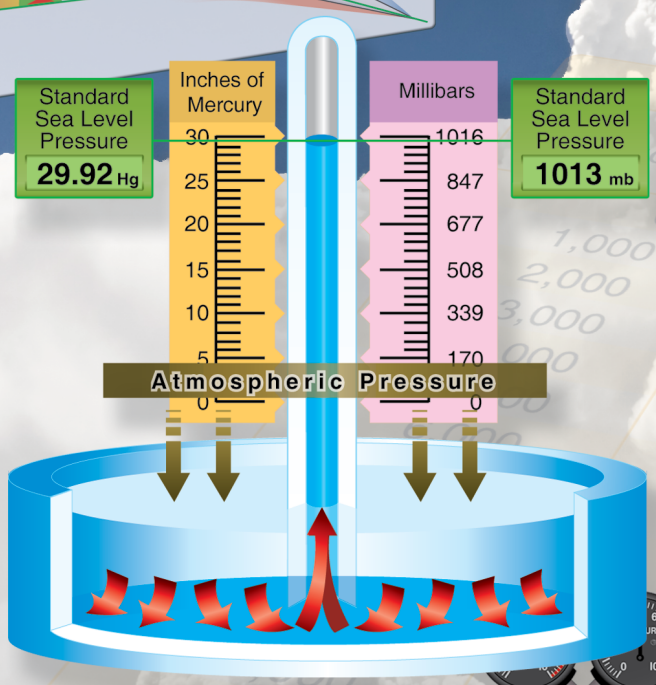
Introduction

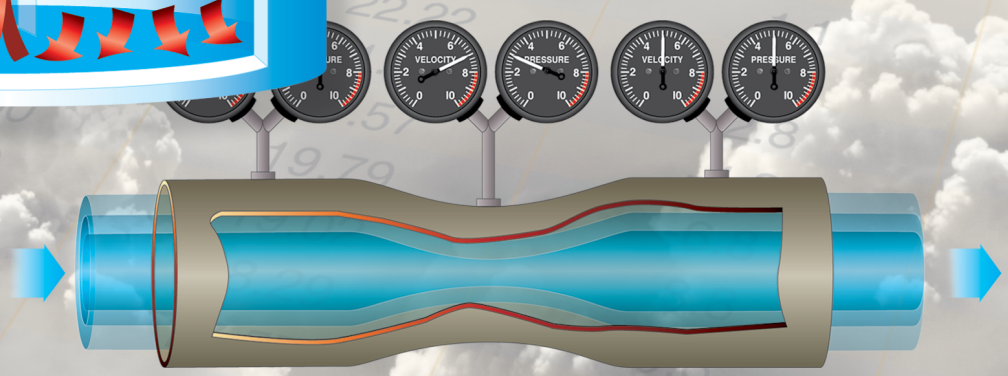
This chapter examines the fundamental physical laws governing the forces acting on an aircraft in flight, and what effect these natural laws and forces have on the performance characteristics of aircraft. To control an aircraft, be it an airplane, helicopter, glider, or balloon, the pilot must understand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





Air is a Fluid

When most people hear the word "fluid," they usually think of liquid. However, gasses, like air, are also fluids. Fluids take on the shape of their containers. Fluids generally do not resist deformation when even the smallest stress is applied, or they resist it only slightly. We call this slight resistance viscosity. Fluids also have the ability to flow. Just as a liquid flows and fills a container, air will expand to fill the available volume of its container. Both liquids and gasses display these unique fluid properties, even though they differ greatly in density. Understanding the fluid properties of air is essential to understanding the principles of flight.

Viscosity

Viscosity is the property of a fluid that causes it to resist flowing. The way individual molecules of the fluid tend to adhere, or stick, to each other determines how much a fluid resists flow. High-viscosity fluids are "thick" and resist flow; low-viscosity fluids are "thin" and flow easily. Air has a low viscosity and flows easily.

Using two liquids as an example, similar amounts of oil and water poured down two identical ramps will flow at different rates due to their different viscosity. The water seems to flow freely while the oil flows much more slowly.

As another example, different types of similar liquids will display different behaviors because of different viscosities. Grease is very viscous. Given time, grease will flow, even though the flow rate will be slow. Motor oil is less viscous than grease and flows much more easily, but it is more viscous and flows more slowly than gasoline.

All fluids are viscous and have a resistance to flow, whether or not we observe this resistance. We cannot easily observe the viscosity of air. However, since air is a fluid and has viscosity properties, it resists flow around any object to some extent.

Friction

Another factor at work when a fluid flows over or around an object is called friction. Friction is the resistance that one surface or object encounters when moving over another. Friction exists between any two materials that contact each other.

The effects of friction can be demonstrated using a similar example as before. If identical fluids are poured down two identical ramps, they flow in the same manner and at the same speed. If the surface of one ramp is rough, and the other smooth, 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 on a microscopic level and impede the flow of a fluid.

The surface of a wing, like any other surface, has a certain roughness at the microscopic level. The surface roughness causes resistance and slows the velocity of the air flowing over the wing. *[Figure 4-1]*

Molecules of air pass over the surface of the wing and actually adhere (stick, or cling) to the surface because of friction. Air molecules near the surface of the wing resist motion and have a relative velocity near zero. The roughness of the surface impedes their motion. The layer of molecules that adhere to the wing surface is referred to as the boundary layer.

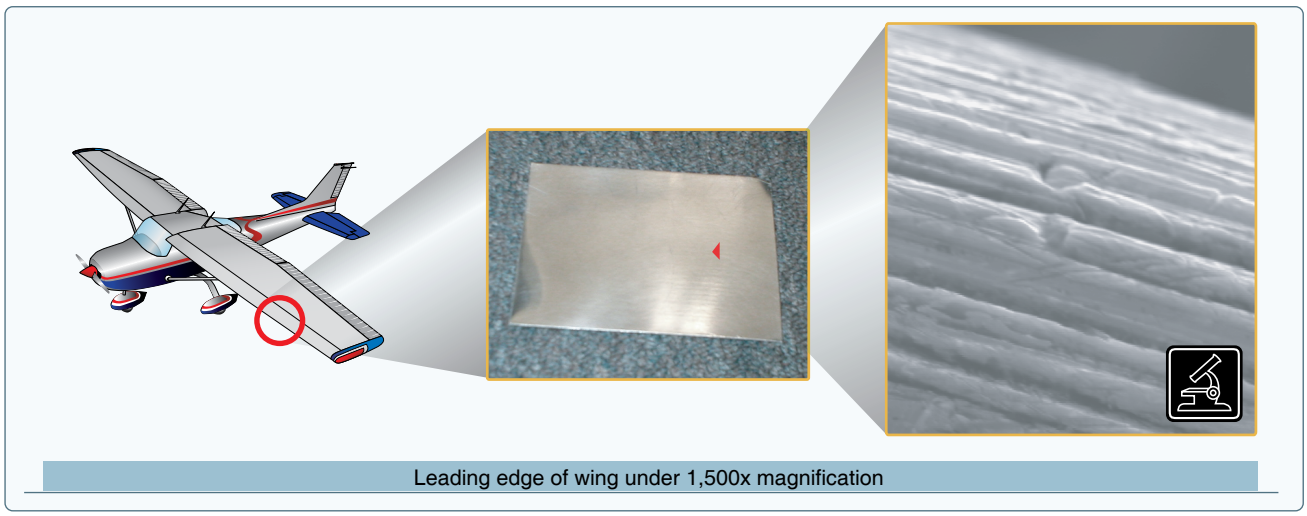


Figure 4-1. *Microscopic surface of a wing.*

Once the boundary layer of the air adheres to the wing by friction, further resistance to the airflow is caused by the viscosity, the tendency of the air to stick to itself. When these two forces act together to resist airflow over a wing, it is called drag.

Pressure

Pressure is the force applied in a perpendicular direction to the surface of an object. Often, pressure is measured in pounds of force exerted per square inch of an object, or PSI. An object completely immersed in a fluid will feel pressure uniformly around the entire surface of the object. If the pressure on one surface of the object becomes less than the pressure exerted on the other surfaces, the object will move in the direction of the lower pressure.

Atmospheric Pressure

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.

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 air is a fluid substance, this force is exerted equally in all directions. 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 millibars (mb). The thickness of the atmosphere 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.

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 59 °F or 15 °C and a surface pressure of 29.92 inches of mercury ("Hg) or 1,013.2 mb. *[Figure 4-2]*

A standard temperature lapse rate is when the temperature decreases at the rate of approximately 3.5 °F or 2 °C per thousand feet up to 36,000 feet, which is approximately –65 °F or –55 °C. Above this point, the temperature is considered constant up to 80,000 feet. A standard pressure lapse rate is when pressure decreases at a rate of approximately 1 "Hg per 1,000 feet of altitude gain to 10,000 feet. *[Figure 4-3]* 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 nonstandard temperature and pressure.

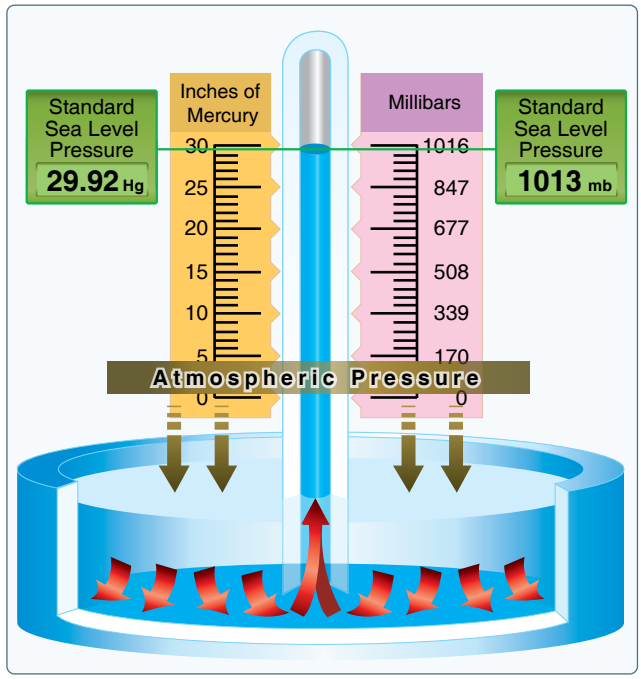


Figure 4-2. *Standard sea level pressure.*

Standard Atmosphere			
Altitude (ft)	Pressure (Hg)	Temperature	
		(°C)	(°F)
0	29.92	15.0	59.0
1,000	28.86	13.0	55.4
2,000	27.82	11.0	51.9
3,000	26.82	9.1	48.3
4,000	25.84	7.1	44.7
5,000	24.89	5.1	41.2
6,000	23.98	3.1	37.6
7,000	23.09	1.1	34.0
8,000	22.22	-0.9	30.5
9,000	21.38	-2.8	26.9
10,000	20.57	-4.8	23.3
11,000	19.79	-6.8	19.8
12,000	19.02	-8.8	16.2
13,000	18.29	-10.8	12.6
14,000	17.57	-12.7	9.1
15,000	16.88	-14.7	5.5
16,000	16.21	-16.7	1.9
17,000	15.56	-18.7	-1.6
18,000	14.94	-20.7	-5.2
19,000	14.33	-22.6	-8.8
20,000	13.74	-24.6	-12.3

Figure 4-3. *Properties of standard atmosphere.*

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 properly account for the nonstandard atmosphere, certain related terms must be defined.

Pressure Altitude

Pressure altitude is the height above a standard datum plane (SDP), which is a theoretical level where the weight of the atmosphere is 29.92 "Hg (1,013.2 mb) as measured by a barometer. An altimeter is essentially a sensitive barometer calibrated to indicate altitude in the standard atmosphere. If the altimeter is set for 29.92 "Hg SDP, 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 airplane performance, as well as for assigning flight levels to airplanes operating at or above 18,000 feet.

The pressure altitude can be determined by one of the following methods:

1. Setting the barometric scale of the altimeter to 29.92 and reading the indicated altitude
2. Applying a correction factor to the indicated altitude according to the reported altimeter setting

Density Altitude

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 performance 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 airfoils

Density altitude is pressure altitude corrected for nonstandard temperature. As the density of the air increases (lower density altitude), aircraft performance increases; conversely as air density decreases (higher density altitude), aircraft performance 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.

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 altimeter indications. Under conditions higher or lower than standard, these levels cannot be determined directly from the altimeter.

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 temperatures 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 of the aircraft, it will perform as though it were operating at an altitude equal to the existing density altitude.

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 atmospheric pressure, low temperatures, and low humidity are more indicative of low density altitude.

Effect 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. 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

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, a fairly rapid drop in pressure as altitude increases usually has a dominating effect. Hence, pilots can expect the density to decrease with altitude.

Effect of Humidity (Moisture) on Density

The preceding paragraphs refer to air that is 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 aircraft. Water vapor 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 vapor.

Humidity, also called relative humidity, refers to the amount of water vapor contained in the atmosphere and is expressed as a percentage of the maximum amount of water vapor the air can hold. This amount varies with temperature. Warm air holds more water vapor, while cold air holds less. Perfectly dry air that contains no water vapor has a relative humidity of zero percent, while saturated air, which cannot hold any more water vapor, 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 is a contributing factor.

As temperature increases, the air can hold greater amounts of water vapor. 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 must be less dense than the second. Pressure, temperature, and humidity have a great influence on aircraft performance because of their effect upon density. There are no rules of thumb that can be easily applied, but the affect of humidity can be determined using several online formulas. In the first example, the pressure is needed at the altitude for which density altitude is being sought. Using *Figure 4-2,* select the barometric pressure closest to the associated altitude. As an example, the pressure at 8,000 feet is 22.22 "Hg. Using the National Oceanic and Atmospheric Administration (NOAA) website (www.srh.noaa.gov/epz/?n=wxcalc_densityaltitude) for density altitude, enter the 22.22 for 8,000 feet in the station pressure window. Enter a temperature of 80° and a dew point of 75°. The result is a density altitude of 11,564 feet. With no humidity, the density altitude would be almost 500 feet lower.

Another website (www.wahiduddin.net/calc/density_altitude.htm) provides a more straight forward method of determining the effects of humidity on density altitude without using additional interpretive charts. In any case, the effects of humidity on density altitude include a decrease in overall performance in high humidity conditions.

Theories in the Production of Lift

In order to achieve flight in a machine that is heavier than air, there are several obstacles we must overcome. One of those obstacles, discussed previously, is the resistance to movement called drag. The most challenging obstacle to overcome in aviation, however, is the force of gravity. A wing moving through air generates the force called lift, also previously discussed. Lift from the wing that is greater than the force of gravity, directed opposite to the direction of gravity, enables an aircraft to fly. Generating this force called lift is based on some important principles, Newton's basic laws of motion, and Bernoulli's principle of differential pressure.

Newton's Basic Laws of Motion

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

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 human understanding, many philosophers, mathematicians, natural scientists, and inventors spent their lives unlocking the secrets of the universe. One of the most well-known was Sir Isaac Newton, who not only formulated the law of universal gravitation, but also described the three basic laws of motion.

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."

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.

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

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).

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

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.

Bernoulli's Principle of Differential Pressure

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 airplane 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. The mass of air entering the tube must exactly equal the mass exiting the tube. At the constriction, the speed must increase to allow the same amount of air to pass in the same amount of time as in all other parts of the tube. When the air speeds up, the pressure also decreases. Past the constriction, the airflow slows and the pressure increases. *[Figure 4-4]*

Since air is recognized as a body, and it is understood that air will follow the above laws, one can begin to see how and why an airplane 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.

Although Newton, 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.

Airfoil Design

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 is confined to the parts of an aircraft 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 4-5]* Notice that there is a difference in the curvatures (called cambers) of the upper and lower surfaces of the airfoil. 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 airfoil profile also differ in appearance. The rounded end, which faces forward in flight, is called the leading edge; the other end, the trailing edge, is quite narrow and tapered.

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

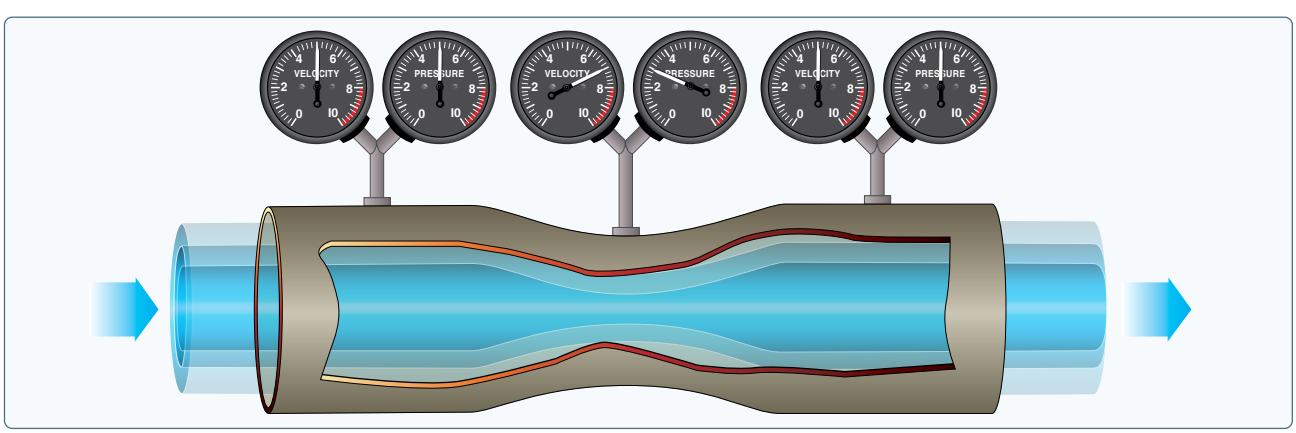


Figure 4-4. *Air pressure decreases in a venturi tube.*

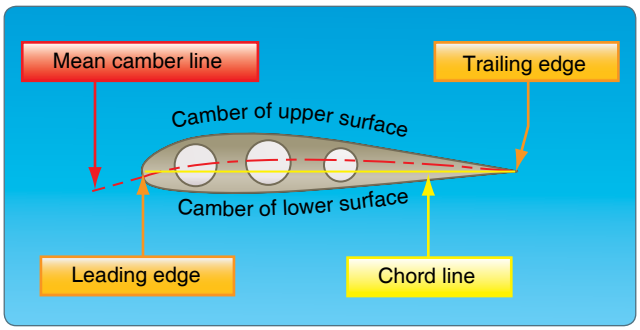


Figure 4-5. *Typical airfoil section.*

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 airfoil 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.

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 airfoil is shaped to cause an action on the air, and forces air downward, which provides an equal reaction from the air, forcing the airfoil upward. If a wing is constructed in such form 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.

It is neither accurate nor useful 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. They vary, not only with flight conditions, but also with different wing designs.

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 aircraft dictate the shape of its airfoil. The most efficient airfoil for producing the greatest lift is one that has a concave or "scooped out" lower surface. As a fixed design, this type of airfoil 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 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 that strike a medium between extremes in design. The shape varies according to the needs of the airplane for which it is designed. *Figure 4-6* shows some of the more common airfoil designs.

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, the air moving over the upper surface would be forced to move faster than the air moving along the bottom of the airfoil. This increased velocity reduces the pressure above the airfoil.

Applying Bernoulli's Principle of Pressure, the increase in the speed of the air across the top of an airfoil produces a

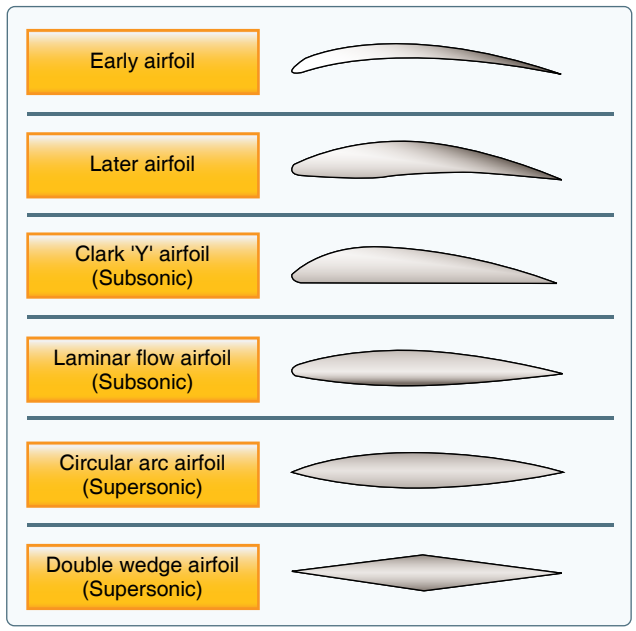


Figure 4-6. *Airfoil designs.*

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.

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

High Pressure Below

A certain amount of lift is generated by pressure conditions underneath the airfoil. Because of the manner in which air flows underneath the airfoil, a positive pressure results, particularly at higher angles of attack. However, 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 airfoil, 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 airfoil increases, total lift increases. Both Bernoulli's Principle and Newton's Laws are in operation whenever lift is being generated by an airfoil.

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 (AOA), 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 4-7* shows the pressure distribution along an airfoil at three different angles of attack. The average of the pressure variation for any given AOA is referred to as the center 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 airplane's aerodynamic balance and controllability are governed by changes in the CP.

Airfoil Behavior

Although specific examples can be cited in which each of the principles predict and contribute to the formation of lift,

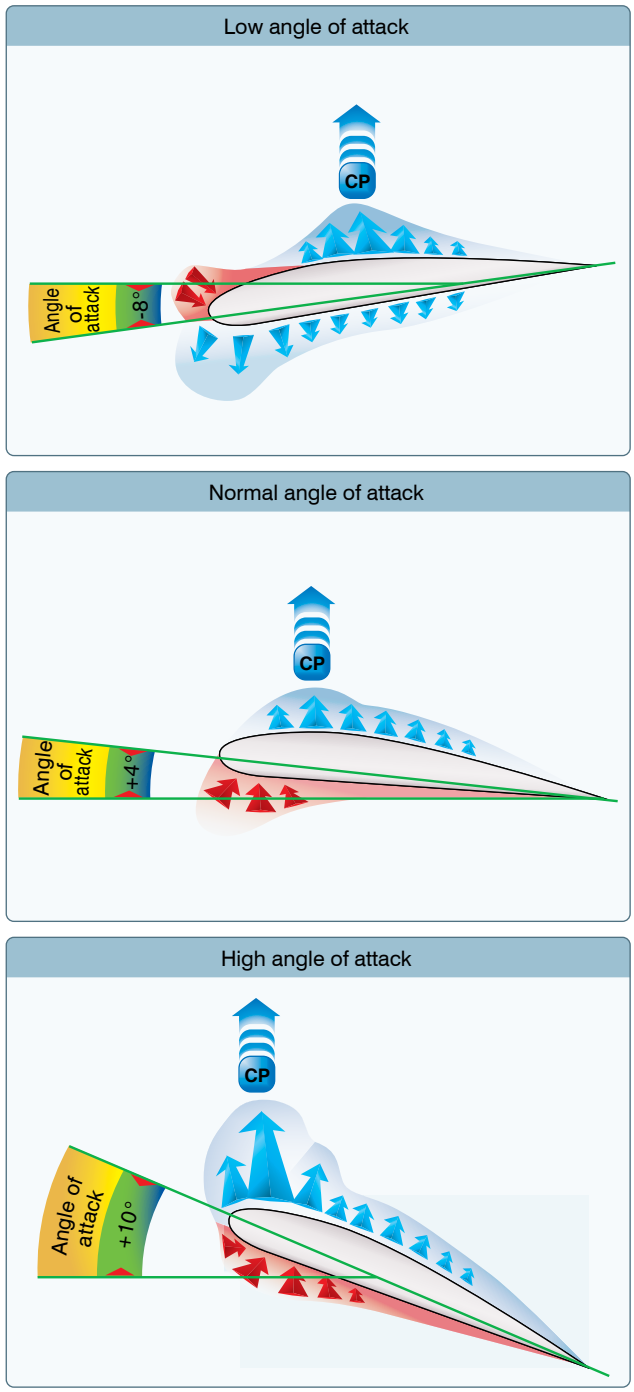


Figure 4-7. *Pressure distribution on an airfoil and CP changes with AOA.*

lift is a complex subject. The production of lift is much more complex than a simple differential pressure between upper and lower airfoil surfaces. In fact, many lifting airfoils do not have an upper surface longer than the bottom, as in the case of symmetrical airfoils. 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 only difference is the relationship of the airfoil with the oncoming airstream (angle). A paper airplane, which is simply a flat plate, has a bottom and top exactly the same shape and length. Yet, these airfoils do produce lift, and "flow turning" is partly (or fully) responsible for creating lift.

As an airfoil moves through air, the airfoil is inclined against the airflow, producing a different flow caused by the airfoil'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

To this point, the discussion has centered on the flow across the upper and lower surfaces of an airfoil. While most of the lift is produced by these two dimensions, a third dimension, the tip of the airfoil also has an aerodynamic effect. The high-pressure area on the bottom of an airfoil pushes around the tip to the low-pressure area on the top. *[Figure 4-8]* This action creates a rotating flow called a tip vortex. The vortex flows behind the airfoil creating a downwash that extends back to the trailing edge of the airfoil. This downwash results in an overall reduction in lift for the affected portion of the airfoil. Manufacturers have developed different methods to counteract this action. Winglets can be added to the tip of an airfoil to reduce this flow. The winglets act as a dam preventing the vortex from forming. Winglets can be on the top or bottom of the airfoil. Another method of countering the flow is to taper the airfoil tip, reducing the pressure differential and smoothing the airflow around the tip.

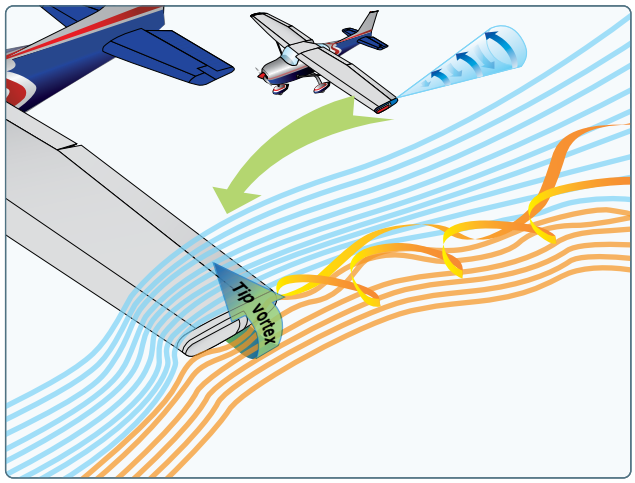


Figure 4-8. *Tip vortex.*

Chapter Summary

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. For additional information on the principles discussed in this chapter, visit the National Aeronautics and Space Administration (NASA) Beginner's Guide to Aerodynamics at www.grc.nasa.gov/www/k-12/airplane/bga.html.