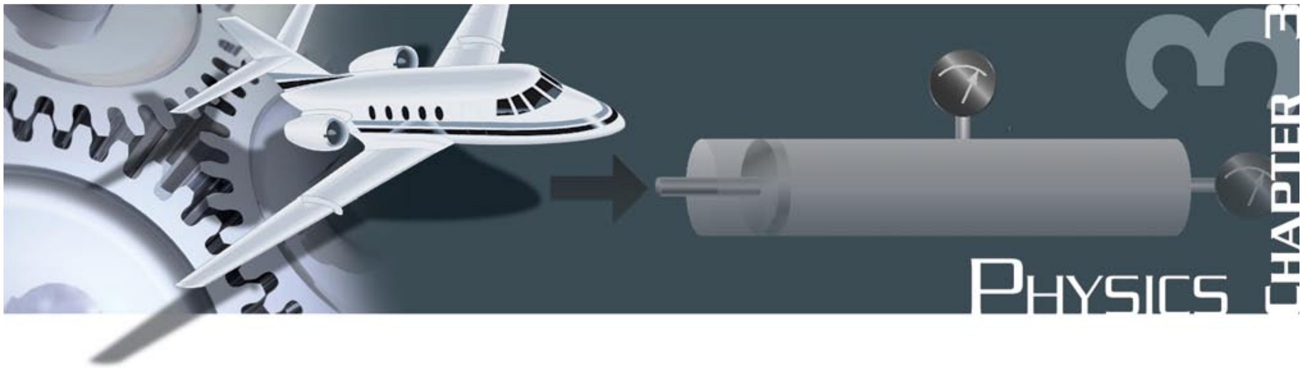

Physical science, or physics as it is most often called, is a very interesting and exciting topic. For the individual who likes technical things and is a hands-on type person, it is an invaluable tool. Physics allows us to explain how engines work, both piston and gas turbine; how airplanes and helicopters fly; and countless other things related to the field of aviation and aerospace. In addition to allowing us to explain the operation of the things around us, it also allows us to quantify them. For example, through the use of physics we can explain what the concept of thrust means for a jet engine, and then follow it up by mathematically calculating the pounds of thrust being created.

Physics is the term applied to that area of knowledge regarding the basic and fundamental nature of matter and energy. It does not attempt to determine why matter and energy behave as they do in their relation to physical phenomena, but rather how they behave. The people who maintain and repair aircraft should have a knowledge of basic physics, which is sometimes called the science of matter and energy.

Matter

Matter is the foundation or the building blocks for any discussion of physics. According to the dictionary, matter is what all things are made of; whatever occupies space, has mass, and is perceptible to the senses in some way. According to the Law of Conservation, matter cannot be created or destroyed, but it is possible to change its physical state. When liquid gasoline vaporizes and mixes with air, and then burns, it might seem that this piece of matter has disappeared and no longer exists. Although it no longer exists in the state of liquid gasoline, the matter still exists in the form of the gases given off by the burning fuel.

Characteristics of Matter

Mass and Weight

Mass is a measure of the quantity of matter in an object. In other words, how many molecules are in the object, or how many atoms, or to be more specific, how many protons, neutrons, and electrons. The mass of an object does not change regardless of where you take it in the universe, and it does not change with a change of state. The only way to change the mass of an object is to add or take away atoms. Mathematically, mass can be stated as follows:

$$\text{Mass} = \text{Weight} \div \text{Acceleration due to gravity}$$

The acceleration due to gravity here on earth is 32.2 feet per second per second (32.2 fps/s). An object weighing 32.2 pounds (lb) here on earth is said to have a mass of 1 slug. A slug is a quantity of mass that will accelerate at a rate of 1 ft/s^2 when a force of 1 pound is applied. In other words, under standard atmospheric conditions (gravity equal to 32.2) a mass of one slug is equal to 32.2 lb.

Weight is a measure of the pull of gravity acting on the mass of an object. The more mass an object has, the more it will weigh under the earth's force of gravity. Because it is not possible for the mass of an object to go away, the only way for an object to be weightless is for gravity to go away. We view astronauts on the space shuttle and it appears that they are weightless. Even though the shuttle is quite a few miles above the surface of the earth, the force of gravity has not gone away, and the astronauts are not weightless. The astronauts and the space shuttle are in a state of free fall, so relative to the shuttle the astronauts appear to be weightless. Mathematically, weight can be stated as follows:

$$\text{Weight} = \text{Mass} \times \text{Gravity}$$

Attraction

Attraction is the force acting mutually between particles of matter, tending to draw them together. Sir Isaac Newton called this the "Law of Universal Gravitation." He showed how each particle of matter attracts every other particle, how people are bound to the earth, and how the planets are attracted in the solar system.

Porosity

Porosity means having pores or spaces where smaller particles may fit when a mixture takes place. This is sometimes referred to as granular—consisting or appearing to consist of small grains or granules.

Impenetrability

Impenetrability means that no two objects can occupy the same place at the same time. Thus, two portions of matter cannot at the same time occupy the same space.

Density

The density of a substance is its weight per unit volume. The unit volume selected for use in the English system of measurement is 1 cubic foot (ft^3). In the metric system, it is 1 cubic centimeter (cm^3). Therefore, density is expressed in pounds per cubic foot ($^{lb}/_{ft^3}$) or in grams per cubic centimeter ($^{g}/_{cm^3}$).

To find the density of a substance, its weight and volume must be known. Its weight is then divided by its volume to find the weight per unit volume. For example, the liquid which fills a certain container weighs 1,497.6 lb. The container is 4 ft long, 3 ft wide, and 2 ft deep. Its volume is 24 ft^3 (4 ft × 3 ft × 2 ft). If 24 ft^3 of liquid weighs 1,497.6 lb, then 1 ft^3 weighs 1,497.6 ÷ 24, or 62.4 lb. Therefore, the density of the liquid is 62.4 lb/ft^3. This is the density of water at 4°C (Centigrade) and is usually used as the standard for comparing densities of other substances. In the metric system, the density of water is $^{1g}/_{cm^3}$. The standard temperature of 4°C is used when measuring the density of liquids and solids. Changes in temperature will not change the weight of a substance, but will change the volume of the substance by expansion or contraction, thus changing its weight per unit volume.

The procedure for finding density applies to all substances; however, it is necessary to consider the pressure when finding the density of gases. Pressure is more critical when measuring the density of gases than it is for other substances. The density of a gas increases in direct proportion to the pressure exerted on it. Standard conditions for the measurement of the densities of gases have been established at 0°C for temperature and a pressure of 76 cm of mercury (Hg). (This is the average pressure of the atmosphere at sea level.) Density is computed based on these conditions for all gases.

Specific Gravity

It is often necessary to compare the density of one substance with that of another. For this purpose, a standard is needed. Water is the standard that physicists have chosen to use when comparing the densities of all liquids and solids. For gases, air is most commonly used. However, hydrogen is sometimes used as a standard for gases. In physics, the word "specific" implies a ratio. Thus, specific gravity is calculated by comparing the weight of a definite volume of the given substance with the weight of an equal volume of water. The terms "specific weight" or "specific density" are sometimes used to express this ratio.

The following formulas are used to find the specific gravity of liquids and solids.

$$\text{Specific Gravity} = \frac{\text{Weight of the substance}}{\text{Weight of an equal volume of water}}$$

OR

$$\text{Specific Gravity} = \frac{\text{Density of the substance}}{\text{Density of water}}$$

The same formulas are used to find the density of gases by substituting air or hydrogen for water.

Specific gravity is not expressed in units, but as pure numbers. For example, if a certain hydraulic fluid has a specific gravity of 0.8, 1 ft^3 of the liquid weighs 0.8 times as much as 1 ft^3 of water: 62.4 times 0.8, or 49.92 lb.

Specific gravity and density are independent of the size of the sample under consideration and depend only upon the substance of which it is made. See Figure 3-1 for typical values of specific gravity for various substances.

A device called a hydrometer is used for measuring specific gravity of liquids. This device consists of a tubular glass float contained in a larger glass tube. [Figure 3-2] The larger glass tube provides the container for the liquid. A rubber suction bulb draws the liquid up into the container. There must be enough liquid to raise the float and prevent it from touching the bottom. The float is weighted and has a vertically graduated scale. To determine specific gravity, the scale is read at the surface of the liquid in which the float is immersed. An indication of 1000 is read when the float is immersed in pure water. When immersed in a liquid of greater density, the float rises, indicating a greater specific gravity. For liquids of lesser density the float sinks, indicating a lower specific gravity.

An example of the use of the hydrometer is to determine the specific gravity of the electrolyte (battery

Liquid	Specific Gravity	Solid	Specific Gravity	Gas	Specific Gravity
Gasoline	0.72	Ice	0.917	Hydrogen	0.0695
Jet Fuel Jp-4	0.785	Aluminum	2.7	Helium	0.138
Ethyl Alcohol	0.789	Titanium	4.4	Acetylene	0.898
Jet Fuel Jp-5	0.82	Zinc	7.1	Nitrogen	0.967
Kerosene	0.82	Iron	7.9	Air	1.000
Lube Oil	0.89	Brass	8.4	Oxygen	1.105
Synthetic Oil	0.928	Copper	8.9	Carbon Dioxide	1.528
Water	1.000	Lead	11.4		
Sulfuric Acid	1.84	Gold	19.3		
Mercury	13.6	Platinum	21.5		

Figure 3-1. Specific gravity of various substances.

liquid) in an aircraft battery. When a battery is discharged, the calibrated float immersed in the electrolyte will indicate approximately 1150. The indication of a charged battery is between 1275 and 1310. The values 1150, 1275, and 1310 actually represent 1.150, 1.275, and 1.310. The electrolyte in a discharged battery is 1.15 times denser than water, and in a charged battery 1.275 to 1.31 times denser than water.

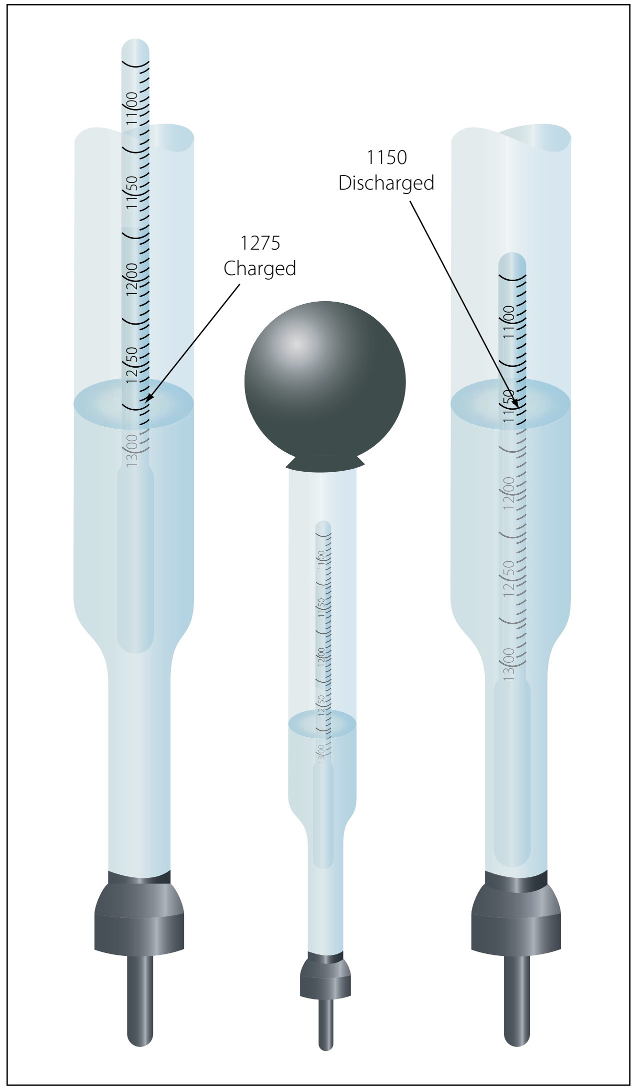

Figure 3-2. Hydrometer for checking battery specific gravity.

Energy

Energy is typically defined as something that gives us the capacity to perform work. As individuals, saying that we feel full of energy is probably indicating that we can perform a lot of work. Energy can be classified as one of two types: either potential or kinetic.

Potential Energy

Potential energy is defined as being energy at rest, or energy that is stored. Potential energy may be classified into three groups: (1) that due to position, (2) that due to distortion of an elastic body, and (3) that which produces work through chemical action. Water in an elevated reservoir, and an airplane raised off the ground sitting on jacks are examples of the first group; a stretched bungee chord on a Piper Tri-Pacer or compressed spring are examples of the second group; and energy in aviation gasoline, food, and storage batteries are examples of the third group.

To calculate the potential energy of an object due to its position, as in height, the following formula is used:

$$\text{Potential Energy} = \text{Weight} \times \text{Height}$$

A calculation based on this formula will produce an answer that has units of foot-pounds (ft-lb) or inch-pounds (in-lb), which are the same units that apply to work. Work, which is covered later in this chapter, is described as a force being applied over a measured distance, with the force being pounds and the distance being feet or inches. It can be seen that potential energy and work have a lot in common.

Example: *A Boeing 747 weighing 450,000 pounds needs to be raised 4 feet in the air so maintenance can be done on the landing gear. How much potential energy does the airplane possess because of this raised position?*

$$\text{Potential Energy} = \text{Weight} \times \text{Height}$$
$$PE = 450{,}000 \text{ lb} \times 4 \text{ ft}$$
$$PE = 1{,}800{,}000 \text{ ft-lb}$$

As mentioned previously, aviation gasoline possesses potential energy because of its chemical nature. Gasoline has the potential to release heat energy, based on its British thermal unit (BTU) content. One pound of aviation gas contains 18,900 BTU of heat energy, and each BTU is capable of 778 ft-lb of work. So if we multiply 778 by 18,900, we find that one pound of aviation gas is capable of 14,704,200 ft-lb of work. Imagine the potential energy in the completely serviced fuel tanks of an airplane.

Kinetic Energy

Kinetic energy is defined as being energy in motion. An airplane rolling down the runway or a rotating flywheel on an engine are both examples of kinetic energy. Kinetic energy has the same units as potential energy, namely foot-pounds or inch-pounds. To calculate the kinetic energy for something in motion, the following formula is used:

$$\text{Kinetic Energy} = \tfrac{1}{2} \text{ Mass} \times \text{Velocity}^2$$

To use the formula, we will show the mass as weight ÷ gravity and the velocity of the object will be in feet per second. This is necessary to end up with units in foot-pounds.

Example: *A Boeing 777 weighing 600,000 lb is moving down the runway on its takeoff roll with a velocity of 200 fps. How many foot-pounds of kinetic energy does the airplane possess? [Figure 3-3]*

$$\text{Kinetic Energy} = \tfrac{1}{2} \text{ Mass} \times \text{Velocity}^2$$
$$\text{Kinetic Energy} = \tfrac{1}{2} \times 600{,}000 \div 32.2 \times 200^2$$
$$KE = 372{,}670{,}000 \text{ ft-lb}$$

Force, Work, Power, and Torque

Force

Before the concept of work, power, or torque can be discussed, we must understand what force means. According to the dictionary, force is the intensity of an impetus, or the intensity of an input. For example, if we apply a force to an object, the tendency will be

Figure 3-3. Kinetic energy (Boeing 777 taking off).

for the object to move. Another way to look at it is that for work, power, or torque to exist, there has to be a force that initiates the process.

The unit for force in the English system of measurement is pounds, and in the metric system it is newtons. One pound of force is equal to 4.448 newtons. When we calculate the thrust of a turbine engine, we use the formula "Force = Mass × Acceleration," and the thrust of the engine is expressed in pounds. The GE90-115 turbofan engine (powerplant for the Boeing 777-300), for example, has 115,000 pounds of thrust.

Work

The study of machines, both simple and complex, is in one sense a study of the energy of mechanical work. This is true because all machines transfer input energy, or the work done on the machine, to output energy, or the work done by the machine.

Work, in the mechanical sense of the term, is done when a resistance is overcome by a force acting through a measurable distance. Two factors are involved: (1) force and (2) movement through a distance. As an example, suppose a small aircraft is stuck in the snow. Two men push against it for a period of time, but the aircraft does not move. According to the technical definition, no work was done in pushing against the aircraft. By definition, work is accomplished only when an object is displaced some distance against a resistive force. To calculate work, the following formula is used:

$$\text{Work} = \text{Force (F)} \times \text{distance (d)}$$

In the English system, the force will be identified in pounds and the distance either in feet or inches, so the units will be foot-pounds or inch-pounds. Notice

Figure 3-4. Airbus A-320 being jacked.

these are the same units that were used for potential and kinetic energy.

In the metric system, the force is identified in newtons (N) and the distance in meters, with the resultant units being joules. One pound of force is equal to 4.448 N and one meter is equal to 3.28 feet. One joule is equal to 1.36 ft-lb.

Example: *How much work is accomplished by jacking a 150,000-lb Airbus A-320 airplane a vertical height of 3 ft? [Figure 3-4]*

$$\begin{aligned} \text{Work} &= \text{Force} \times \text{Distance} \\ &= 150{,}000 \text{ lb} \times 4 \text{ ft} \\ &= 600{,}000 \text{ ft-lb} \end{aligned}$$

Example: *How much work is accomplished when a tow tractor is hooked up to a tow bar and a Boeing 737-800 airplane weighing 130,000 lb is pushed 80 ft into the hangar? The force on the tow bar is 5,000 lb.*

$$\begin{aligned} \text{Work} &= \text{Force} \times \text{Distance} \\ &= 5{,}000 \text{ lb} \times 80 \text{ ft} \\ &= 400{,}000 \text{ ft-lb} \end{aligned}$$

In this last example, notice the force does not equal the weight of the airplane. This is because the airplane is being moved horizontally and not lifted vertically. In virtually all cases, it takes less work to move something horizontally than it does to lift it vertically. Most people can push their car a short distance if it runs out of gas, but they cannot get under their car and lift it off the ground.

Friction and Work

In calculating work done, the actual resistance overcome is measured. This is not necessarily the weight of the object being moved. [Figure 3-5] A 900-lb load is being pulled a distance of 200 ft. This does not mean that the work done (force × distance) is 180,000 ft-lb (900 lb × 200 ft). This is because the person pulling the load is not working against the total weight of the load, but rather against the rolling friction of the cart, which may be no more than 90 lb.

Friction is an important aspect of work. Without friction it would be impossible to walk. One would have to shove oneself from place to place, and would have to bump against some obstacle to stop at a destination. Yet friction is a liability as well as an asset, and

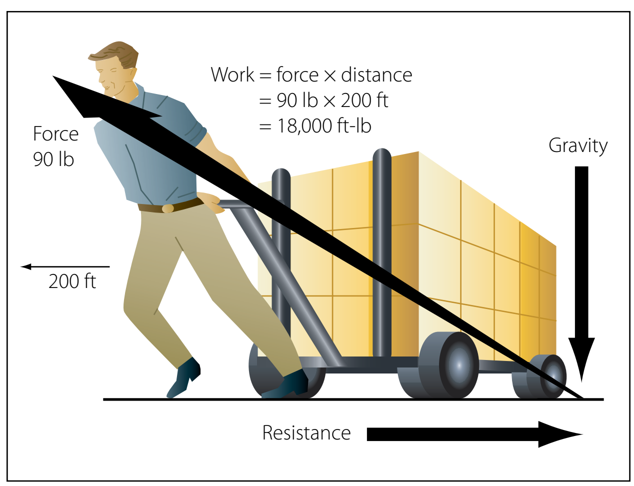

Figure 3-5. The effect of friction on work.

requires consideration when dealing with any moving mechanism.

In experiments relating to friction, measurement of the applied forces reveals that there are three kinds of friction. One force is required to start a body moving, while another is required to keep the body moving at constant speed. Also, after a body is in motion, a definitely larger force is required to keep it sliding than to keep it rolling.

Thus, the three kinds of friction may be classified as: (1) starting (static) friction, (2) sliding friction, and (3) rolling friction.

Static Friction

When an attempt is made to slide a heavy object along a surface, the object must first be broken loose or started. Once in motion, it slides more easily. The "breaking loose" force is, of course, proportional to the weight of the body. The force necessary to start the body moving slowly is designated "F," and "F'" is the normal force pressing the body against the surface (usually its weight). Since the nature of the surfaces rubbing against each other is important, they must be considered. The nature of the surfaces is indicated by the coefficient of starting friction which is designated by the letter "k." This coefficient can be established for various materials and is often published in tabular form. Thus, when the load (weight of the object) is known, starting friction can be calculated by using the following formula:

$$F = kF'$$

For example, if the coefficient of sliding friction of a smooth iron block on a smooth, horizontal surface is 0.3, the force required to start a 10 lb block would be 3 lb; a 40-lb block, 12 lb.

Starting friction for objects equipped with wheels and roller bearings is much smaller than that for sliding objects. Nevertheless, a locomotive would have difficulty getting a long train of cars in motion all at one time. Therefore, the couples between the cars are purposely made to have a few inches of play. When starting the train, the engineer backs the engine until all the cars are pushed together. Then, with a quick start forward the first car is set in motion. This technique is employed to overcome the static friction of each wheel (as well as the inertia of each car). It would be impossible for the engine to start all of the cars at the same instant, for static friction, which is the resistance of being set in motion, would be greater than the force exerted by the engine. Once the cars are in motion, however, static friction is greatly reduced and a smaller force is required to keep the train in motion than was required to start it.

Sliding Friction

Sliding friction is the resistance to motion offered by an object sliding over a surface. It pertains to friction produced after the object has been set in motion, and is always less than starting friction. The amount of sliding resistance is dependent on the nature of the surface of the object, the surface over which it slides, and the normal force between the object and the surface. This resistive force may be computed by using the following formula.

$$F = mN$$

In the formula above, "F" is the resistive force due to friction expressed in pounds; "N" is the force exerted on or by the object perpendicular (normal) to the surface over which it slides; and "m" (mu) is the coefficient of sliding friction. On a horizontal surface, N is equal to the weight of the object in pounds. The area of the sliding object exposed to the sliding surface has no effect on the results. A block of wood, for example, will not slide any easier on one of the broad sides than it will on a narrow side, (assuming all sides have the same smoothness). Therefore, area does not enter into the equation above.

Rolling Friction

Resistance to motion is greatly reduced if an object is mounted on wheels or rollers. The force of friction for objects mounted on wheels or rollers is called rolling friction. This force may be computed by the same equation used in computing sliding friction, but the values of "m" will be much smaller. For example, the value of "m" for rubber tires on concrete or macadam is about 0.02. The value of "m" for roller bearings is very small, usually ranging from 0.001 to 0.003 and is often disregarded.

Example: *An aircraft with a gross weight of 79,600 lb is towed over a concrete ramp. What force must be exerted by the towing vehicle to keep the airplane rolling after once set in motion?*

$$\begin{aligned} F &= mN \\ &= 0.02 \text{ mu} \times 79{,}600 \text{ lb} \\ &= 1{,}592 \text{ lb} \end{aligned}$$

Power

The concept of power involves the previously discussed topic of work, which was a force being applied over a measured distance, but adds one more consideration — time. In other words, how long does it take to accomplish the work. If someone asked the average person if he or she could lift one million pounds 5 feet off the ground, the answer most assuredly would be no. This person would probably assume that he or she is to lift it all at once. What if he or she is given 365 days to lift it, and could lift small amounts of weight at a time? The work involved would be the same, regardless of how long it took to lift the weight, but the power required is different. If the weight is to be lifted in a shorter period of time, it will take more power. The formula for power is as follows:

Power = Force × distance ÷ time

The units for power will be foot-pounds per minute, foot-pounds per second, inch-pounds per minute or second, and possibly mile-pounds per hour. The units depend on how distance and time are measured.

Many years ago there was a desire to compare the power of the newly evolving steam engine to that of horses. People wanted to know how many horses the steam engine was equivalent to. Because of this, the value we currently know as one horsepower (hp) was developed, and it is equal to 550 foot-pounds per second (ft-lb/s). It was found that the average horse could lift a weight of 550 lb, one foot off the ground, in one second. The values we use today, in order to convert power to horsepower, are as follows:

1 hp = 550 ft-lb/s
1 hp = 33,000 ft-lb/min.
1 hp = 375 mile pounds per hour (mi-lb/hr)
1 hp = 746 watts (electricity conversion)

To convert power to horsepower, divide the power by the appropriate conversion based on the units being used.

Example: *What power would be needed, and also horsepower, to raise the GE-90 turbofan engine into position to install it on a Boeing 777-300 airplane? The engine weighs 19,000 lb, and it must be lifted 4 ft in 2 minutes.*

Power = Force × distance ÷ time
= 19,000 lb × 4 ft ÷ 2 min.
= 38,000 ft-lb/min.

Hp = 38,000 ft-lb/min. ÷ 33,000 ft-lb/min.
Hp = 1.15

The hoist that will be used to raise this engine into position will need to be powered by an electric motor because the average person will not be able to generate 1.15 hp in their arms for the necessary 2 minutes.

Torque

Torque is a very interesting concept and occurrence, and it is definitely something that needs to be discussed in conjunction with work and power. Whereas work is described as a force acting through a distance, torque is described as a force acting along a distance. Torque is something that creates twisting and tries to make something rotate.

If we push on an object with a force of 10 lb and it moves 10 inches in a straight line, we have done 100 in-lb of work. By comparison, if we have a wrench 10 inches long that is on a bolt, and we push down on it with a force of 10 lb, a torque of 100 lb-in is applied to the bolt. If the bolt was already tight and did not move as we pushed down on the wrench, the torque of 100 lb-in would still exist. The formula for torque is:

Torque = Force × distance

Even though the formula looks the same as the one for calculating work, recognize that the distance value in this formula is not the linear distance an object moves, but rather the distance along which the force is applied.

Notice that with torque nothing had to move, because the force is being applied along a distance and not through a distance. Notice also that although the units of work and torque appear to be the same, they are not. The units of work were inch-pounds and the units of torque were pound-inches, and that is what differentiates the two.

Torque is very important when thinking about how engines work, both piston engines and gas turbine engines. Both types of engines create torque in advance of being able to create work or power. With a piston engine, a force in pounds pushes down on the top of the piston and tries to make it move. The piston is attached to the connecting rod, which is attached to the crankshaft at an offset. That offset would be like the length of the wrench discussed earlier, and the force acting along that length is what creates torque. [Figure 3-6]

For the cylinder in Figure 3-6, there is a force of 500 lb pushing down on the top of the piston. The connecting rod attaches to the crankshaft at an offset distance of 4 in. The product of the force and the offset distance is the torque, in this case 2,000 lb-in.

In a turbine engine, the turbine blades at the back of the engine extract energy from the high velocity exhaust gases. The energy extracted becomes a force in pounds pushing on the turbine blades, which happen to be a certain number of inches from the center of the shaft they are trying to make rotate. The number of inches from the turbine blades to the center of the shaft would be like the length of the wrench discussed earlier.

Mathematically, there is a relationship between the horsepower of an engine and the torque of an engine. The formula that shows this relationship is as follows:

$$\text{Torque} = \text{Horsepower} \times 5{,}252 \div \text{rpm}$$

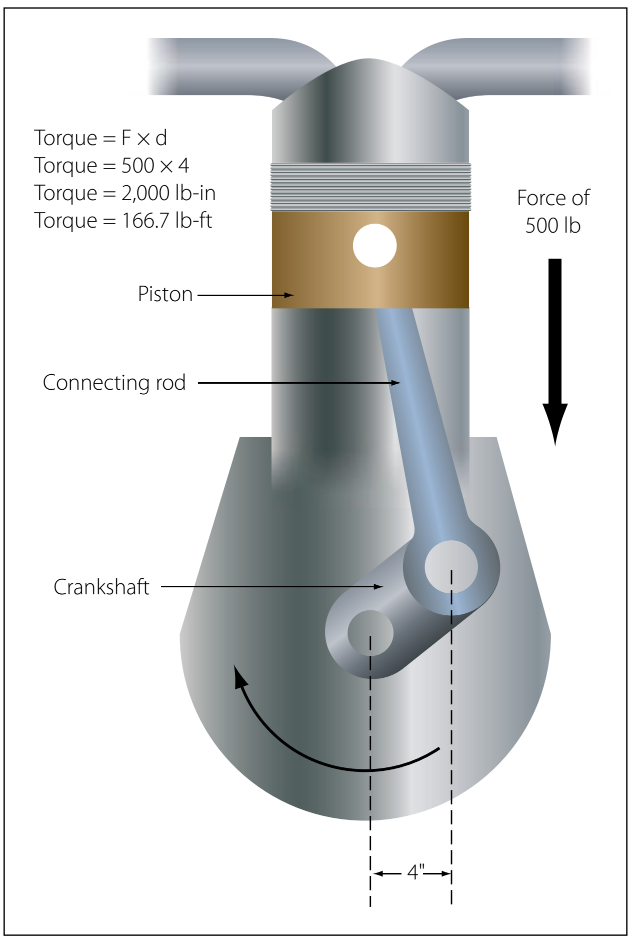

Figure 3-6. Piston engine and torque.

Example: *A Cessna 172R has a Lycoming IO-360 engine that creates 180 horsepower at 2,700 rpm. How many pound-feet of torque is the engine producing?*

$$\begin{aligned}\text{Torque} &= 180 \times 5{,}252 \div 2{,}700\\ &= 350 \text{ lb-ft}\end{aligned}$$

Simple Machines

A machine is any device with which work may be accomplished. In application, machines can be used for any of the following purposes, or combinations of these purposes.

1. Machines are used to transform energy, as in the case of a generator transforming mechanical energy into electrical energy.
2. Machines are used to transfer energy from one place to another, as in the examples of the connecting rods, crankshaft, and reduction gears transferring energy from an aircraft's engine to its propeller.
3. Machines are used to multiply force; for example, a system of pulleys may be used to lift a heavy load. The pulley system enables the load to be raised by exerting a force that is smaller than the weight of the load.
4. Machines can be used to multiply speed. A good example is the bicycle, by which speed can be gained by exerting a greater force.
5. Machines can be used to change the direction of a force. An example of this use is the flag hoist. A downward force on one side of the rope exerts an upward force on the other side, raising the flag toward the top of the pole.

There are only six simple machines. They are the lever, the pulley, the wheel and axle, the inclined plane, the screw, and the gear. Physicists, however, recognize only two basic principles in machines: the lever and the inclined plane. The pulley (block and tackle), the wheel and axle, and gears operate on the machine principle of the lever. The wedge and the screw use the principle of the inclined plane.

An understanding of the principles of simple machines provides a necessary foundation for the study of compound machines, which are combinations of two or more simple machines.

Mechanical Advantage of Machines

As identified in statements 3 and 4 under simple machines, a machine can be used to multiply force or to multiply speed. It cannot, however, multiply force and speed at the same time. In order to gain one, it must lose the other. To do otherwise would mean the machine has more power going out than coming in, and that is not possible.

In reference to machines, mechanical advantage is a comparison of the output force to the input force, or the output distance to the input distance. If there is a mechanical advantage in terms of force, there will be a fractional disadvantage in terms of distance. The following formulas can be used to calculate mechanical advantage.

Mechanical Advantage = Force Out ÷ Force In

Or

Mechanical Advantage = Distance Out ÷ Distance In

The Lever

The simplest machine, and perhaps the most familiar one, is the lever. A seesaw is a familiar example of a lever, with two people sitting on either end of a board and a pivoting point in the middle. There are three basic parts in all levers. They are the fulcrum "F," a force or effort "E," and a resistance "R." Shown in Figure 3-7 are the pivot point "F" (fulcrum), the effort "E" which is applied at a distance "L" from the fulcrum, and a resistance "R" which acts at a distance "l" from the fulcrum. Distances "L" and "l" are the lever arms.

The concept of torque was discussed earlier in this chapter, and torque is very much involved in the operation of a lever. When a person sits on one end of a seesaw, that person applies a downward force in pounds which acts along the distance to the center of the seesaw. This combination of force and distance creates torque, which tries to cause rotation.

First Class Lever

In the first class lever, the fulcrum is located between the effort and the resistance. As mentioned earlier, the seesaw is a good example of a lever, and it happens to be a first class lever. The amount of weight and the distance from the fulcrum can be varied to suit the need. Increasing the distance from the applied effort to the fulcrum, compared to the distance from the fulcrum to the weight being moved, increases the advantage provided by the lever. Crowbars, shears, and pliers are common examples of this class of lever. The proper balance of an airplane is also a good example, with the center of lift on the wing being the pivot point (fulcrum) and the weight fore and aft of this point being the effort and the resistance.

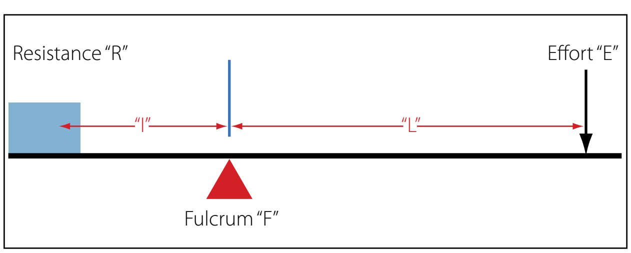

Figure 3-7. First class lever.

When calculating how much effort is required to lift a specific weight, or how much weight can be lifted by a specific effort, the following formula can be used.

Effort (E) × Effort Arm (L) = Resistance (R) × Resistance Arm (l)

What this formula really shows is the input torque (effort times effort arm) equals the output torque (resistance times resistance arm). This formula and concept apply to all three classes of levers, and to all simple machines in general.

Example: *A first class lever is to be used to lift a 500-lb weight. The distance from the weight to the fulcrum is 12 inches and from the fulcrum to the applied effort is 60 inches. How much force is required to lift the weight?*

Effort (E) × Effort Arm (L) = Resistance (R) × Resistance Arm (l)

E × 60 in = 500 lb × 12 in

E = 500 lb × 12 in ÷ 60 in

E = 100 lb

The mechanical advantage of the lever in this example would be:

Mechanical Advantage = Force Out ÷ Force In

= 500 lb ÷ 100 lb

= 5, or 5 to 1

An interesting thing to note with this example lever is if the applied effort moved down 10 inches, the weight on the other end would only move up 2 inches. The weight being lifted would only move one-fifth as far. The reason for this is the concept of work. Because a lever cannot have more work output than input, if it allows you to lift 5 times more weight, you will only move it $\frac{1}{5}$ as far as you move the effort.

Second Class Lever

The second class lever has the fulcrum at one end and the effort is applied at the other end. The resistance is somewhere between these points. A wheelbarrow is a good example of a second class lever, with the wheel at one end being the fulcrum, the handles at the opposite end being the applied effort, and the bucket

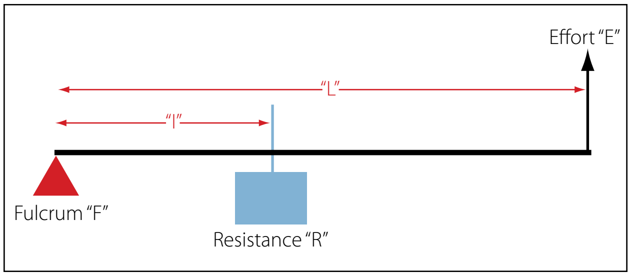

Figure 3-8. Second class lever.

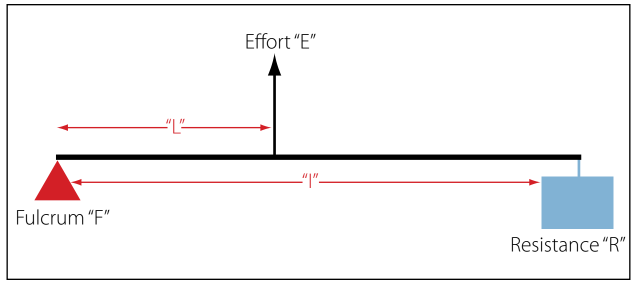

Figure 3-9. Third class lever.

in the middle being where the weight or resistance is placed. [Figure 3-8]

Both first and second class levers are commonly used to help in overcoming big resistances with a relatively small effort. The first class lever, however, is more versatile. Depending on how close or how far away the weight is placed from the fulcrum, the first class lever can be made to gain force or gain distance, but not both at the same time. The second class lever can only be made to gain force.

Example: *The distance from the center of the wheel to the handles on a wheelbarrow is 60 inches. The weight in the bucket is 18 inches from the center of the wheel. If 300 lb is placed in the bucket, how much force must be applied at the handles to lift the wheelbarrow?*

Effort (E) × Effort Arm (L) = Resistance (R) × Resistance Arm (l)
E × 60 inches = 300 lb × 18 in
E = 300 lb × 18 in ÷ 60 in
E = 90 lb

The mechanical advantage of the lever in this example would be:

Mechanical Advantage = Force Out ÷ Force In
= 300 lb ÷ 90 lb
= 3.33, or 3.33 to 1

Third Class Lever

There are occasions when it is desirable to speed up the movement of the resistance even though a large amount of effort must be used. Levers that help accomplish this are third class levers. As shown in Figure 3-9, the fulcrum is at one end of the lever and the weight or resistance to be overcome is at the other end, with the effort applied at some point between. Third class levers are easily recognized because the effort is applied between the fulcrum and the resistance. The retractable main landing gear on an airplane is a good example of a third class lever. The top of the landing gear, where it attaches to the airplane, is the pivot point. The wheel and brake assembly at the bottom of the landing gear is the resistance. The hydraulic actuator that makes the gear retract is attached somewhere in the middle, and that is the applied effort.

The Pulley

Pulleys are simple machines in the form of a wheel mounted on a fixed axis and supported by a frame. The wheel, or disk, is normally grooved to accommodate a rope. The wheel is sometimes referred to as a "sheave" (sometimes "sheaf"). The frame that supports the wheel is called a block. A block and tackle consists of a pair of blocks. Each block contains one or more pulleys and a rope connecting the pulley(s) of each block.

Single Fixed Pulley

A single fixed pulley is really a first class lever with equal arms. In Figure 3-10, the arm from point "R" to point "F" is equal to the arm from point "F" to point "E" (both distances being equal to the radius of the pulley). When a first class lever has equal arms, the mechanical advantage is 1. Thus, the force of the pull on the rope must be equal to the weight of the object being lifted. The only advantage of a single fixed pulley is to change the direction of the force, or pull on the rope.

Single Movable Pulley

A single pulley can be used to magnify the force exerted. In Figure 3-11, the pulley is movable, and both ropes extending up from the pulley are sharing in the support of the weight. This single movable pulley acts like a second class lever, with the effort arm (EF) being the diameter of the pulley and the resistance arm (FR) being the radius of the pulley. This type of pulley would have a mechanical advantage of two because the diameter of the pulley is double the radius of the pulley. In use, if someone pulled in 4 ft of the effort rope, the weight would only rise off the floor 2 ft. If the weight was 100 lb, the effort applied would only need to be 50 lb. With this type of pulley, the effort will always be one-half of the weight being lifted.

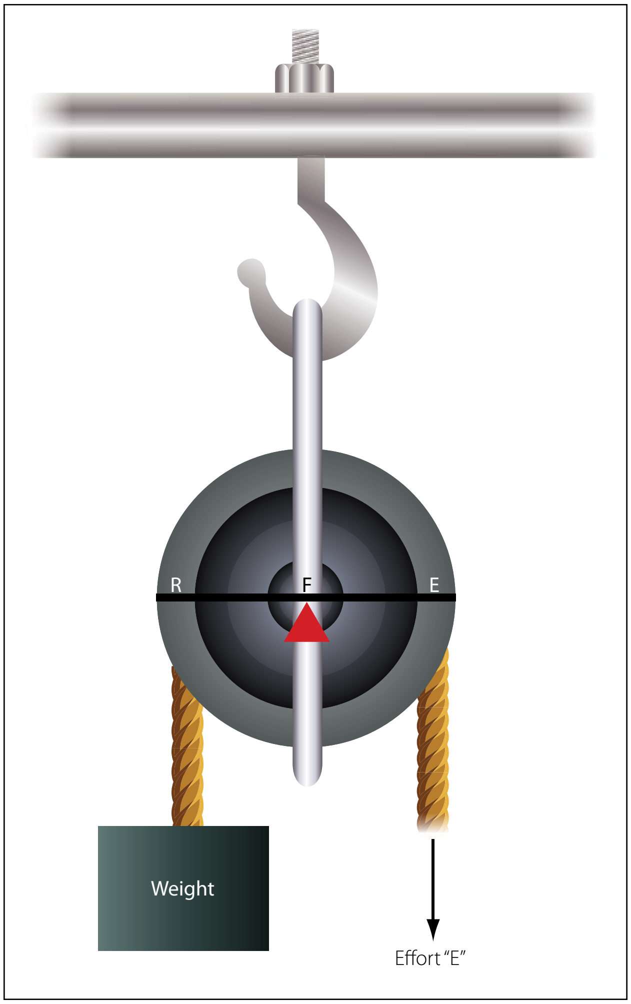

Figure 3-10. Single fixed pulley.

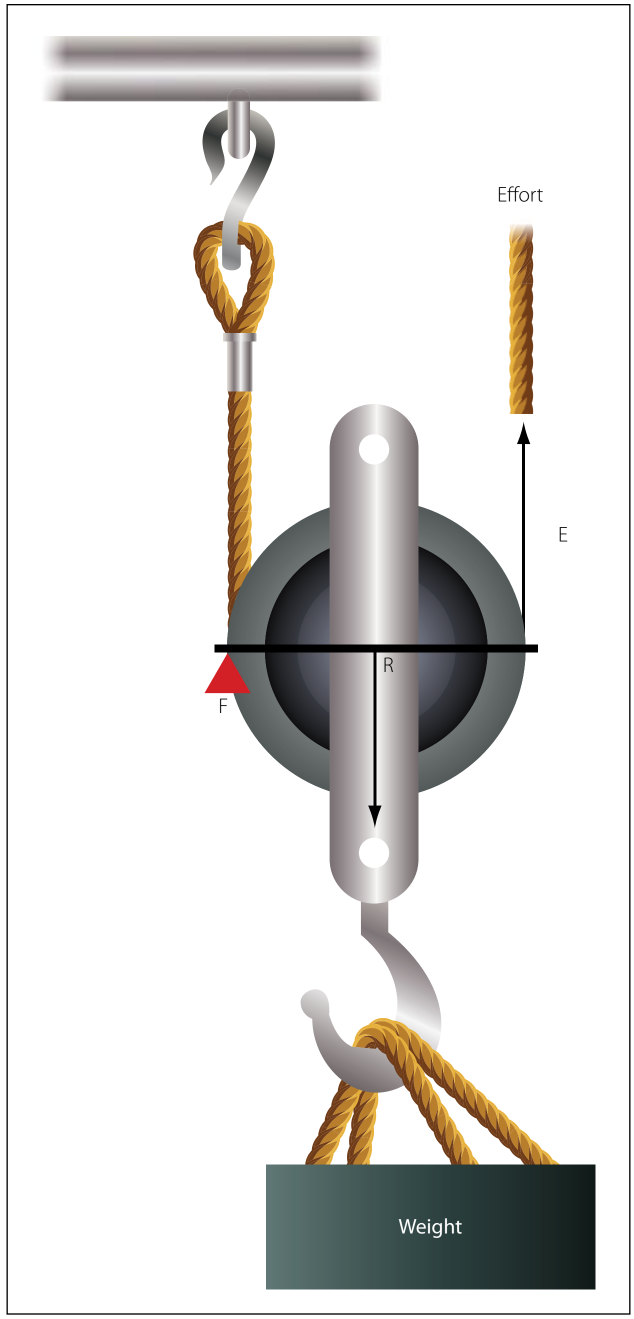

Figure 3-11. Single movable pulley.

Block and Tackle

A block and tackle is made up of multiple pulleys, some of them fixed and some movable. In Figure 3-12, the block and tackle is made up of four pulleys, the top two being fixed and the bottom two being movable. Viewing the figure from right to left, notice there are four ropes supporting the weight and a fifth rope where the effort is applied. The number of weight supporting ropes determines the mechanical advantage of a block and tackle, so in this case the mechanical advantage is four. If the weight was 200 lb, it would require a 50 lb effort to lift it.

The Gear

Two gears with teeth on their outer edges, as shown in Figure 3-13, act like a first class lever when one gear drives the other. The gear with the input force is called the drive gear, and the other is called the driven gear. The effort arm is the diameter of the driven gear, and the resistance arm is the diameter of the drive gear. Notice that the two gears turn in opposite directions (the bottom one clockwise and the top one counter-clockwise). The gear on top (yellow) is 9 inches in diameter and has 45 teeth, and the gear on the bottom (blue) is 12 inches in diameter and has 60 teeth.

Imagine that the blue gear is driving the yellow one (blue is the drive, yellow is the driven). The mechanical advantage in terms of force would be the effort arm divided by the resistance arm, or 9 ÷ 12, which is 0.75. This would actually be called a fractional disadvantage, because there would be less force out than force in.

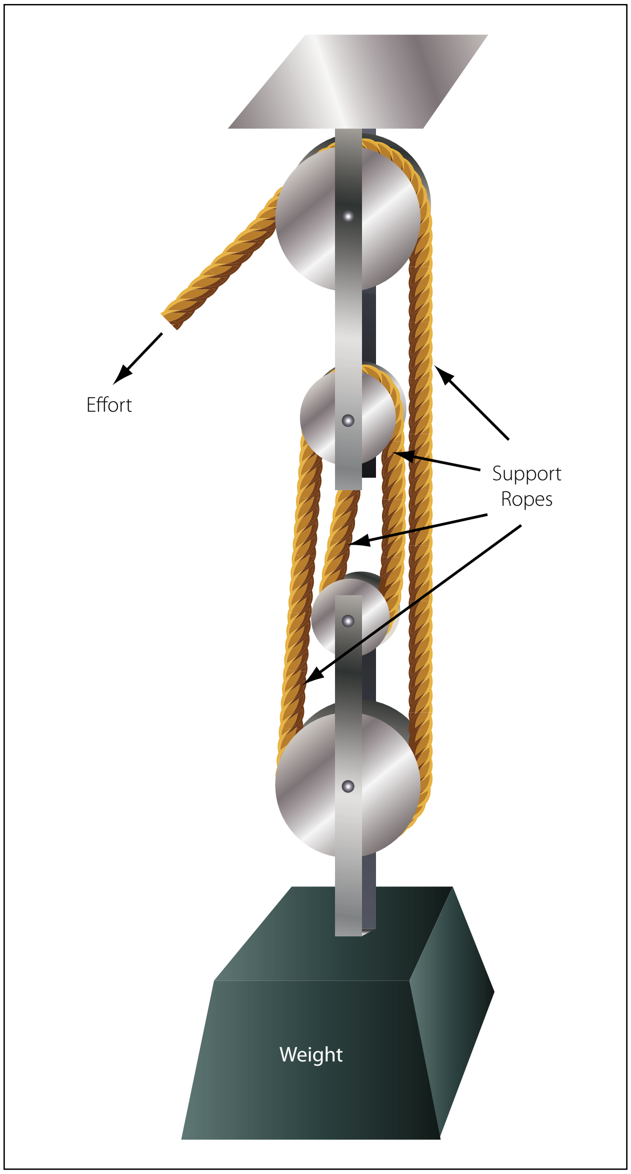

Figure 3-12. Block and tackle.

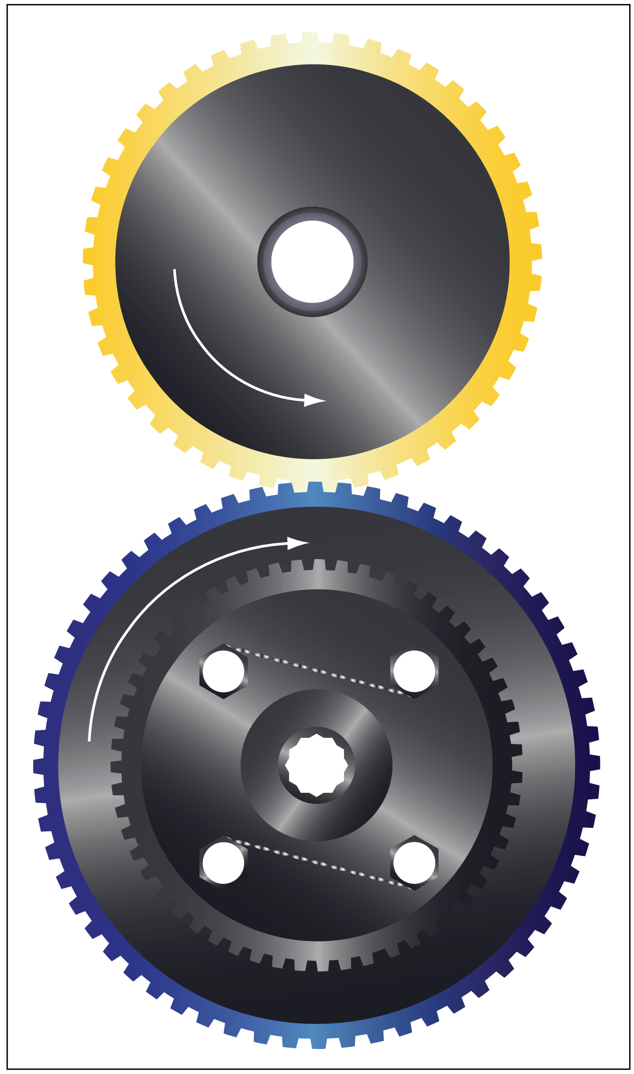

Figure 3-13. Spur gears.

The mechanical advantage in terms of distance (rpm in this case), would be 12 ÷ 9, or 1.33.

This analysis tells us that when a large gear drives a small one, the small one turns faster and has less available force. In order to be a force gaining machine, the small gear needs to turn the large one. When the terminology reduction gearbox is used, such as a propeller reduction gearbox, it means that there is more rpm going in than is coming out. The end result is an increase in force, and ultimately torque.

Bevel gears are used to change the plane of rotation, so that a shaft turning horizontally can make a vertical shaft rotate. The size of the gears and their number of teeth determine the mechanical advantage, and whether force is being increased or rpm is being increased. If each gear has the same number of teeth, there would be no change in force or rpm. [Figure 3-14]

The worm gear has an extremely high mechanical advantage. The input force goes into the spiral worm gear, which drives the spur gear. One complete revolution of the worm gear only makes the spur gear turn an amount equal to one tooth. The mechanical advantage is equal to the number of teeth on the spur gear, which in this case is 25. This is a force gaining machine, to the tune of 25 times more output force. [Figure 3-15]

The planetary sun gear system is typical of what would be found in a propeller reduction gearbox. The power output shaft of the engine would drive the sun gear in the middle, which rotates the planetary gears and ultimately the ring gear. In this example, the sun gear has 28 teeth, each planet gear has 22 teeth, and the ring gear has 82 teeth. To figure how much gear reduction is taking place, the number of teeth on the

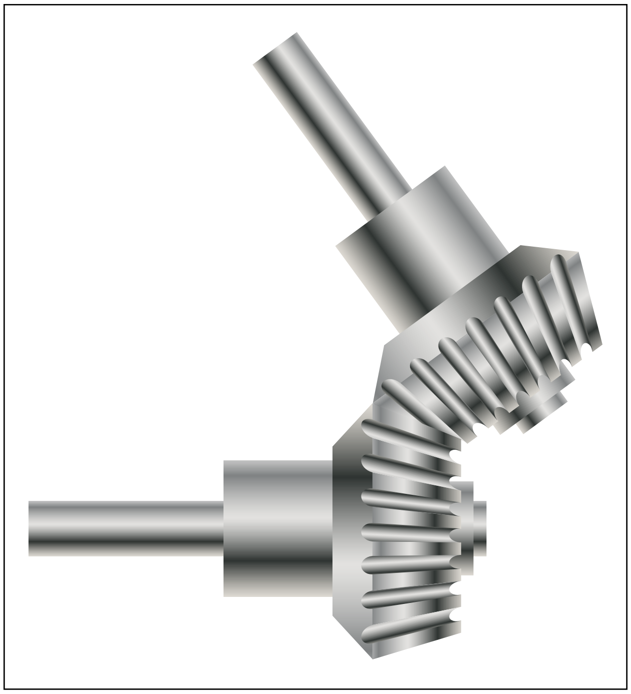

Figure 3-14. Bevel gears.

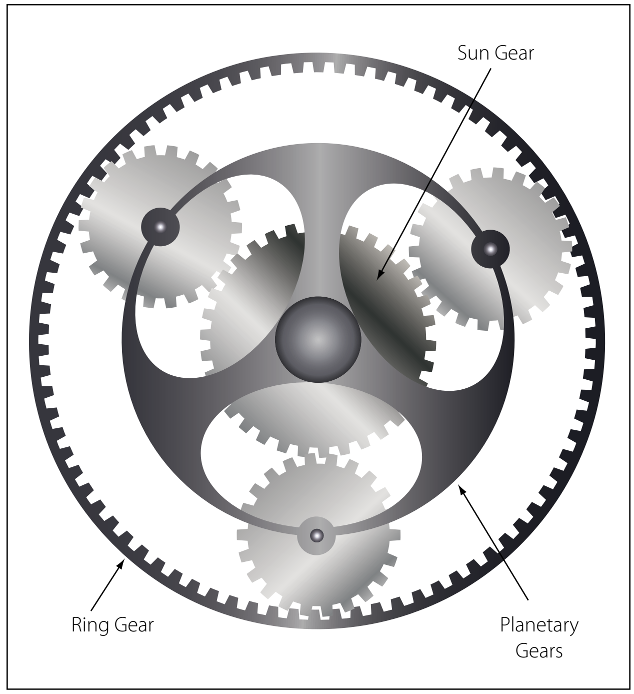

Figure 3-16. Planetary sun gear.

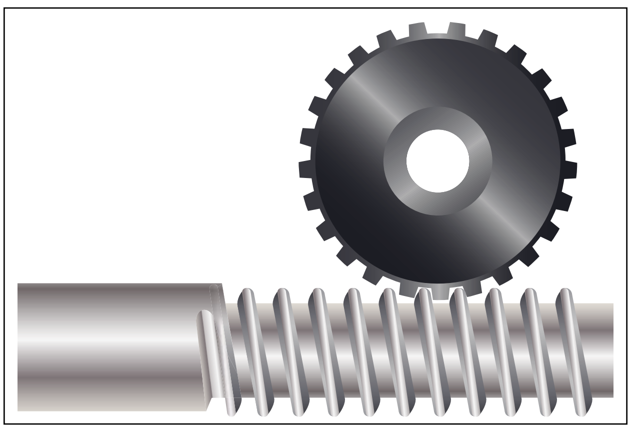

Figure 3-15. Worm gear.

ring gear is divided by the number of teeth on the sun gear. In this case, the gear reduction is 2.93, meaning the engine has an rpm 2.93 times greater than the propeller. [Figure 3-16]

Inclined Plane

The inclined plane is a simple machine that facilitates the raising or lowering of heavy objects by application of a small force over a relatively long distance. Some familiar examples of the inclined plane are mountain highways and a loading ramp on the back of a moving truck. When weighing a small airplane, like a Cessna 172, an inclined plane (ramp) can be used to get the airplane on the scales by pushing it, rather than jacking it. A ramp can be seen in Figure 3-17, where a Cessna 172 right main gear is sitting on an electronic scale. The airplane was pushed up the ramps to get it on the scales.

With an inclined plane, the length of the incline is the effort arm and the vertical height of the incline is the resistance arm. If the length of the incline is five times greater than the height, there will be a force advantage, or mechanical advantage, of five. The Cessna 172 in Figure 3-17 weighed 1,600 lb on the day of the weighing. The ramp it is sitting on is 6 inches tall (resistance

Figure 3-17. Ramp in use with a Cessna 172.

Figure 3-18. A bolt and nut as an inclined plane.

arm) and the length of the ramp is 24 inches (effort arm). To calculate the force needed to push the airplane up the ramps, use the same formula introduced earlier when levers were discussed, as follows:

Effort (E) × Effort Arm (L) = Resistance (R) × Resistance Arm (l)

$$E \times 24 \text{ in} = 1{,}600 \text{ lb} \times 6 \text{ in}$$
$$E = 1{,}600 \text{ lb} \times 6 \text{ in} \div 24 \text{ in}$$
$$E = 400 \text{ lb}$$

Bolts, screws, and wedges are also examples of devices that operate on the principle of the inclined plane. A bolt, for example, has a spiral thread that runs around its circumference. As the thread winds around the bolt's circumference, it moves a vertical distance equal to the space between the threads. The circumference of the bolt is the effort arm and the distance between the threads is the resistance arm. [Figure 3-18] Based on this analysis, it can be seen that a fine threaded bolt (more threads per inch) has a greater mechanical advantage than a coarse threaded bolt.

A chisel is a good example of a wedge. A chisel might be 8 inches long and only ½ inch wide, with a sharp tip and tapered sides. The 8-inch length is the effort arm and the ½-inch width is the resistance arm. This chisel would provide a force advantage (mechanical advantage) of 16.

Stress

Whenever a machine is in operation, be it a simple machine like a lever or a screw, or a more complex machine like an aircraft piston engine or a hydraulically operated landing gear, the parts and pieces of that machine will experience something called stress. Whenever an external force is applied to an object, like a weight pushing on the end of a lever, a reaction will occur inside the object which is known as stress. Stress is typically measured in pounds per square foot or pounds per square inch (psi).

An external force acting on an object causes the stress to manifest itself in one of five forms, or combination of those five. The five forms are tension, compression, torsion, bending, and shear.

Tension

Tension is a force that tries to pull an object apart. In the block and tackle system discussed earlier in this chapter, the upper block that housed the two fixed pulleys was secured to an overhead beam. The movable lower block and its two pulleys were hanging by ropes, and the weight was hanging below the entire assembly. The weight being lifted would cause the ropes and the blocks to be under tension. The weight is literally trying to pull the rope apart, and ultimately would cause the rope to break if the weight was too great.

Compression

Compression is a force that tries to crush an object. An excellent example of compression is when a sheet metal airplane is assembled using the fastener known as a rivet. The rivet passes through a hole drilled in the pieces of aluminum, and then a rivet gun on one side and a bucking bar on the other apply a force. This applied force tries to crush the rivet and makes it expand to fill the hole and securely hold the aluminum pieces together. [Figure 3-19]

Torsion

Torsion is the stress an object experiences when it is twisted, which is what happens when torque is applied to a shaft. Torsion is actually made up of two other stresses: tension and compression. When a shaft is twisted, tension is experienced at a diagonal to the shaft and compression acts 90 degrees to the tension. [Figure 3-20]

The turbine shaft on a turbofan engine, which connects to the compressor in order to drive it, is under a torsion stress. The turbine blades extract energy from the high velocity air as a force in pounds. This force in pounds acts along the length from the blades to the center of the shaft, and creates the torque that causes rotation. [Figure 3-21]

Bending

An airplane in flight experiences a bending force on the wing as aerodynamic lift tries to raise the wing. This force of lift actually causes the skin on the top of the

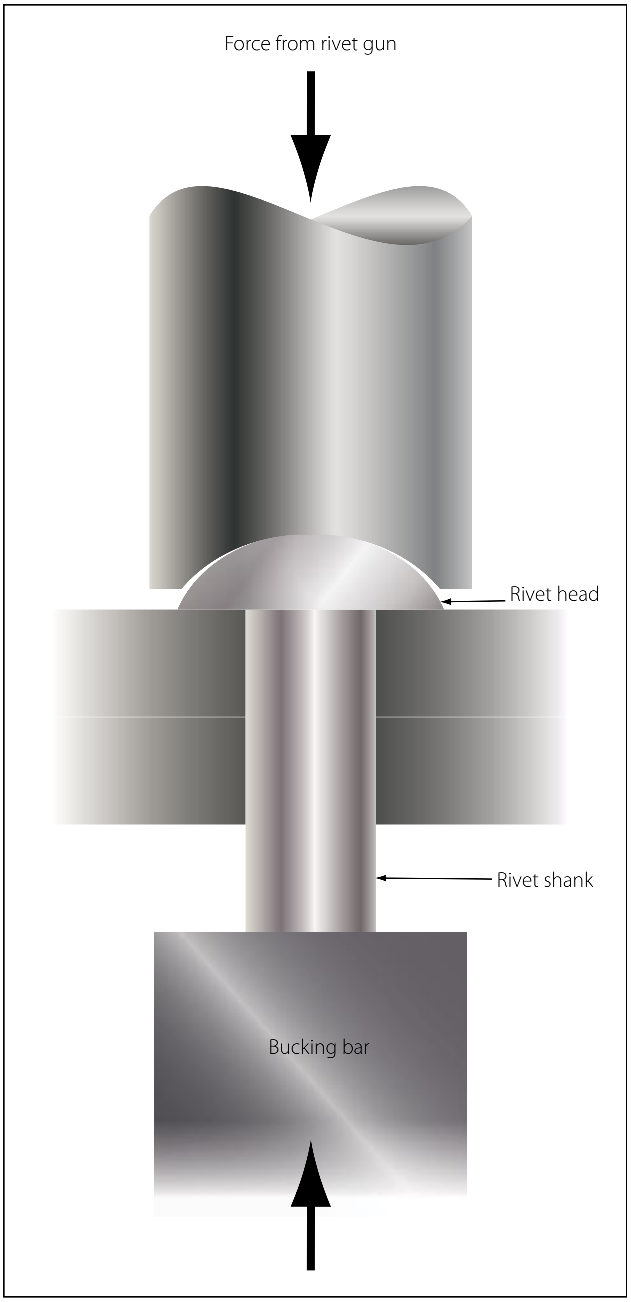

Figure 3-19. A rivet fastener and compression.

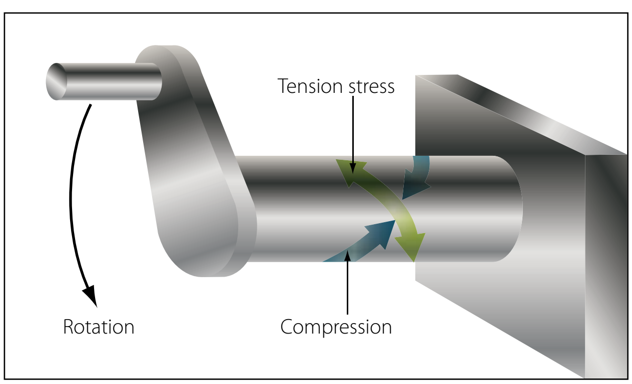

Figure 3-20. Torsion on a rotating shaft, made up of tension and compression.

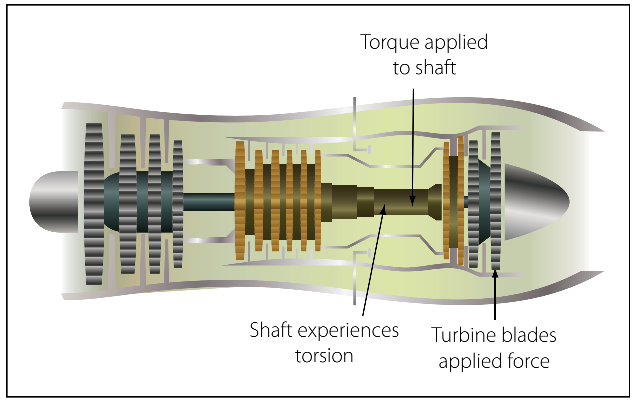

Figure 3-21. Turbofan engine, torque creating torsion in the shaft.

wing to compress and the skin on the bottom of the wing to be under tension. When the airplane is on the ground sitting on its landing gear, the force of gravity tries to bend the wing downward, subjecting the bottom of the wing to compression and the top of the wing to tension. [Figure 3-22] During the testing that occurs prior to FAA certification, an airplane manufacturer intentionally bends the wing up and down to make sure it can take the stress without failing.

Shear

When a shear stress is applied to an object, the force tries to cut or slice through, like a knife cutting through butter. A clevis bolt, which is often used to secure a cable to a part of the airframe, has a shear stress acting on it. As shown in Figure 3-23, a fork fitting is secured

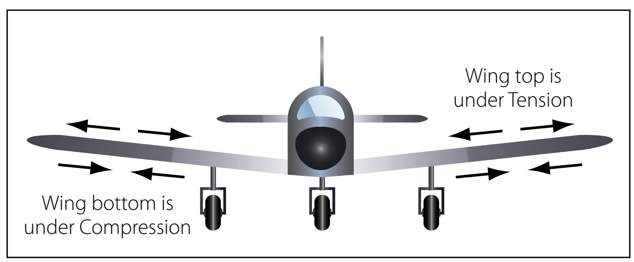

Figure 3-22. Airplane on the ground, wing under tension and compression.

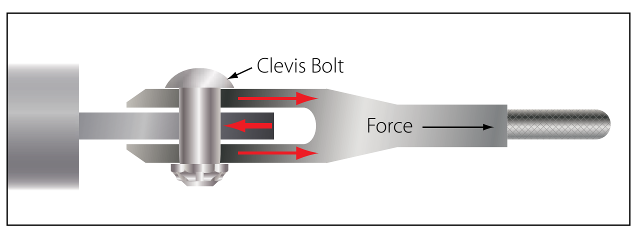

Figure 3-23. Clevis bolt, red arrows show opposing forces trying to shear the bolt.

to the end of the cable, and the fork attaches to an eye on the airframe with the clevis bolt. When the cable is put under tension, the fork tries to slide off the eye by cutting through the clevis bolt. This bolt would be designed to take very high shear loads.

Strain

If the stress acting on an object is great enough, it can cause the object to change its shape or to become distorted. One characteristic of matter is that it tends to be elastic, meaning it can be forced out of shape when a force is applied, and then return to its original shape when the force is removed. When an object becomes distorted by an applied force, the object is said to be strained.

On turbine engine test cells, the thrust of the engine is typically measured by what are called strain gages. When the force (thrust) of the engine is pulling out against the strain gages, the amount of distortion is measured and then translated into the appropriate thrust reading.

A deflecting beam style of torque wrench uses the strain on the drive end of the wrench and the resulting distortion of the beam to indicate the amount of torque on a bolt or nut. [Figure 3-24]

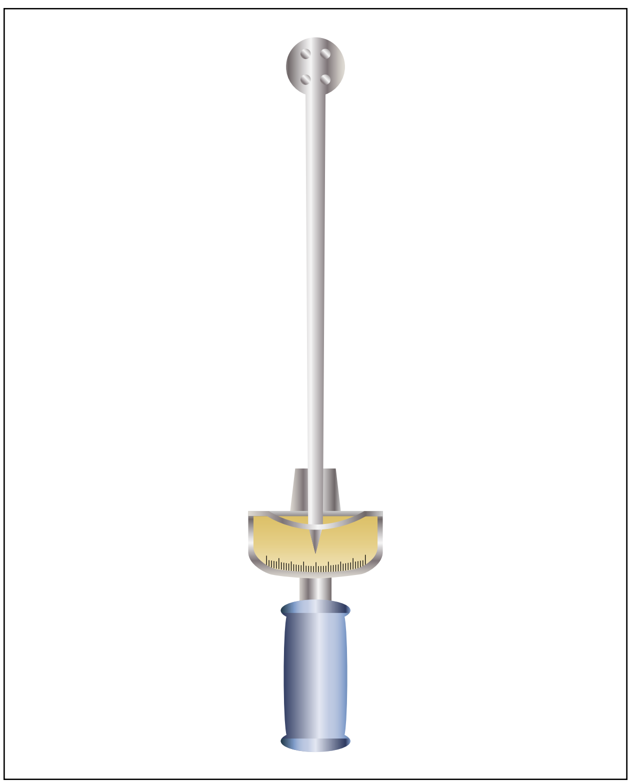

Figure 3-24. Deflecting beam torque wrench, measures strain by distortion.

Motion

The study of the relationship between the motion of bodies or objects and the forces acting on them is often called the study of "force and motion." In a more specific sense, the relationship between velocity, acceleration, and distance is known as kinematics.

Uniform Motion

Motion may be defined as a continuing change of position or place, or as the process in which a body undergoes displacement. When an object is at different points in space at different times, that object is said to be in motion, and if the distance the object moves remains the same for a given period of time, the motion may be described as uniform. Thus, an object in uniform motion always has a constant speed.

Speed and Velocity

In everyday conversation, speed and velocity are often used as if they mean the same thing. In physics they have definite and distinct meanings. Speed refers to how fast an object is moving, or how far the object will travel in a specific time. The speed of an object tells nothing about the direction an object is moving. For example, if the information is supplied that an airplane leaves New York City and travels 8 hours at a speed of 150 mph, this information tells nothing about the direction in which the airplane is moving. At the end of 8 hours, it might be in Kansas City, or if it traveled in a circular route, it could be back in New York City.

Velocity is that quantity in physics which denotes both the speed of an object and the direction in which the object moves. Velocity can be defined as the rate of motion in a particular direction. Velocity is also described as being a vector quantity, a vector being a line of specific length, having an arrow on one end or the other. The length of the line indicates the number value and the arrow indicates the direction in which that number is acting.

Two velocity vectors, such as one representing the velocity of an airplane and one representing the velocity of the wind, can be added together in what is called vector analysis. Figure 3-25 demonstrates this, with vectors "A" and "B" representing the velocity of the airplane and the wind, and vector "C" being the resultant. With no wind, the speed and direction of the airplane would be that shown by vector "A." When accounting for the wind direction and speed, the airplane ends up flying at the speed and direction shown by vector "C."

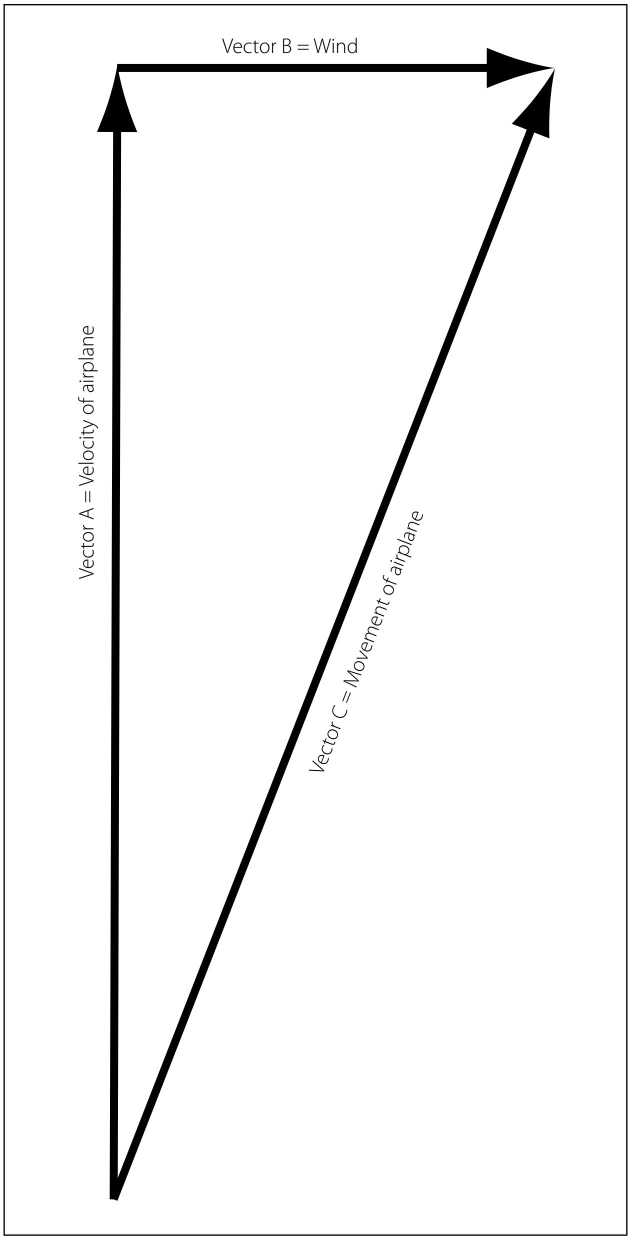

Figure 3-25. Vector analysis for airplane velocity and wind velocity.

Imagine that an airplane is flying in a circular pattern at a constant speed. Because of the circular pattern, the airplane is constantly changing direction, which means the airplane is constantly changing velocity. The reason for this is the fact that velocity includes direction.

To calculate the speed of an object, the distance it travels is divided by the elapsed time. If the distance is measured in miles and the time in hours, the units of speed will be miles per hour (mph). If the distance is measured in feet and the time in seconds, the units of speed will be feet per second (fps). To convert mph to fps, multiply by 1.467. Velocity is calculated the same way, the only difference being it must be recalculated every time the direction changes.

Acceleration

Acceleration is defined as the rate of change of velocity. If the velocity of an object is increased from 20 mph to 30 mph, the object has been accelerated. If the increase in velocity is 10 mph in 5 seconds, the rate of change in velocity is 10 mph in 5 seconds, or 2 mph per second. If this were multiplied by 1.467, it could also be expressed as an acceleration of 2.93 feet per second per second (fps/s). By comparison, the acceleration due to gravity is 32.2 fps/s.

To calculate acceleration, the following formula is used.

$$\text{Acceleration (A)} = \frac{\text{Velocity Final (Vf)} - \text{Velocity Initial (Vi)}}{\text{Time (t)}}$$

Example: *An Air Force F-15 fighter is cruising at 400 mph. The pilot advances the throttles to full afterburner and accelerates to 1,200 mph in 20 seconds. What is the average acceleration in mph/s and fps/s?*

$$A = \frac{Vf - Vi}{t}$$

$$A = \frac{1200 - 400}{20}$$

$$A = 40\ ^{mph}\!/_{s}\text{, or by multiplying by 1.467, } 58.7\ ^{fps}\!/_{s}$$

In the example just shown, the acceleration was found to be 58.7 fps/s. Since 32.2 fps/s is equal to the acceleration due to gravity, divide the F-15's acceleration by 32.2 to find out how many G forces the pilot is experiencing. In this case, it would be 1.82 Gs.

Newton's Law of Motion

First Law

When a magician snatches a tablecloth from a table and leaves a full setting of dishes undisturbed, he is not displaying a mystic art; he is demonstrating the principle of inertia. Inertia is responsible for the discomfort felt when an airplane is brought to a sudden halt in the parking area and the passengers are thrown forward in their seats. Inertia is a property of matter. This property of matter is described by Newton's first law of motion, which states:

Objects at rest tend to remain at rest and objects in motion tend to remain in motion at the same speed and in the same direction, unless acted on by an external force.

Second Law

Bodies in motion have the property called momentum. A body that has great momentum has a strong tendency to remain in motion and is therefore hard to stop. For example, a train moving at even low velocity is difficult to stop because of its large mass. Newton's second law applies to this property. It states:

When a force acts upon a body, the momentum of that body is changed. The rate of change of momentum is proportional to the applied force. Based on Newton's second law, the formula for calculating thrust is derived, which states that force equals mass times acceleration (F = MA). Earlier in this chapter, it was determined that mass equals weight divided by gravity, and acceleration equals velocity final minus velocity initial divided by time. Putting all these concepts together, the formula for thrust is:

$$\text{Force} = \frac{\text{Weight (Velocity final} - \text{Velocity initial)}}{\text{Gravity (Time)}}$$

$$\text{Force} = \frac{W\,(Vf - Vi)}{Gt}$$

Example: *A turbojet engine is moving 150 lb of air per second through the engine. The air enters going 100 fps and leaves going 1,200 fps. How much thrust, in pounds, is the engine creating?*

$$F = \frac{W\,(Vf - Vi)}{Gt}$$

$$F = \frac{150\,(1200 - 100)}{32.2\,(1)}$$

$$F = 5{,}124 \text{ lb of thrust}$$

Third Law

Newton's third law of motion is often called the law of action and reaction. It states that for every action there is an equal and opposite reaction. This means that if a force is applied to an object, the object will supply a resistive force exactly equal to and in the opposite direction of the force applied. It is easy to see how this might apply to objects at rest. For example, as a man stands on the floor, the floor exerts a force against his feet exactly equal to his weight. But this law is also applicable when a force is applied to an object in motion.

Forces always occur in pairs. The term "acting force" means the force one body exerts on a second body, and reacting force means the force the second body exerts on the first.

When an aircraft propeller pushes a stream of air backward with a force of 500 lb, the air pushes the blades forward with a force of 500 lb. This forward force causes the aircraft to move forward. A turbofan engine exerts a force on the air entering the inlet duct, causing it to accelerate out the fan duct and the tailpipe. The air accelerating to the rear is the action, and the force inside the engine that makes it happen is the reaction, also called thrust.

Circular Motion

Circular motion is the motion of an object along a curved path that has a constant radius. For example, if one end of a string is tied to an object and the other end is held in the hand, the object can be swung in a circle. The object is constantly deflected from a straight (linear) path by the pull exerted on the string, as shown in Figure 3-26. When the weight is at point A, due to inertia it wants to keep moving in a straight line and end up at point B. Because of the force being exerted on the string, it is forced to move in a circular path and end up at point C.

The string exerts a centripetal force on the object, and the object exerts an equal but opposite force on the string, obeying Newton's third law of motion. The

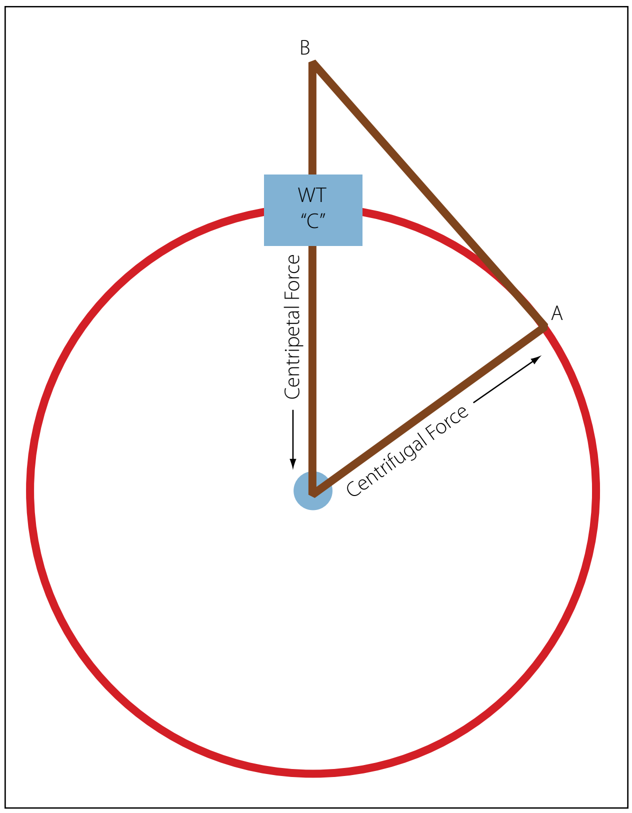

Figure 3-26. Circular motion.

force that is equal to centripetal force, but acting in an opposite direction, is called centrifugal force.

Centripetal force is always directly proportional to the mass of the object in circular motion. Thus, if the mass of the object in Figure 3-26 is doubled, the pull on the string must be doubled to keep the object in its circular path, provided the speed of the object remains constant.

Centripetal force is inversely proportional to the radius of the circle in which an object travels. If the string in Figure 3-26 is shortened and the speed remains constant, the pull on the string must be increased since the radius is decreased, and the string must pull the object from its linear path more rapidly. Using the same reasoning, the pull on the string must be increased if the object is swung more rapidly in its orbit. Centripetal force is thus directly proportional to the square of the velocity of the object. The formula for centripetal force is:

$$\text{Centripetal Force} = \text{Mass}\ (\text{Velocity}^2) \div \text{Radius}$$

For the formula above, mass would typically be converted to weight divided by gravity, velocity would be in feet per second, and the radius would be in feet.

Example: *What would the centripetal force be if a 10 pound weight was moving in a 3-ft radius circular path at a velocity of 500 fps?*

$$\text{Centripetal Force} = \text{Mass}\ (\text{Velocity}^2) \div \text{Radius}$$
$$\text{Centripetal Force} = 10\ (500^2) \div 32.2\ (3)$$
$$= 25{,}880\ \text{lb}$$

In the condition identified in the example, the object acts like it weighs 2,588 times more than it actually does. It can also be said that the object is experiencing 2,588 Gs (force of gravity). The fan blades in a large turbofan engine, when the engine is operating at maximum rpm, are experiencing many thousands of Gs for the same reason.

Heat

Heat is a form of energy. It is produced only by the conversion of one of the other forms of energy. Heat may also be defined as the total kinetic energy of the molecules of any substance.

Some forms of energy which can be converted into heat energy are as follows:

- *Mechanical Energy.* This includes all methods of producing increased motion of molecules such as friction, impact of bodies, or compression of gases.
- *Electrical Energy.* Electrical energy is converted to heat energy when an electric current flows through any form of resistance such as an electric iron, electric light, or an electric blanket.
- *Chemical Energy.* Most forms of chemical reaction convert stored potential energy into heat. Some examples are the explosive effects of gunpowder, the burning of oil or wood, and the combining of oxygen and grease.
- *Radiant Energy.* Electromagnetic waves of certain frequencies produce heat when they are absorbed by the bodies they strike such as x-rays, light rays, and infrared rays.
- *Nuclear Energy.* Energy stored in the nucleus of atoms is released during the process of nuclear fission in a nuclear reactor or atomic explosion.
- *The Sun.* All heat energy can be directly or indirectly traced to the nuclear reactions occurring in the sun.

When a gas is compressed, work is done and the gas becomes warm or hot. Conversely, when a gas under high pressure is allowed to expand, the expanding gas becomes cool. In the first case, work was converted into energy in the form of heat; in the second case heat energy was expended. Since heat is given off or absorbed, there must be a relationship between heat energy and work. Also, when two surfaces are rubbed together, the friction develops heat. However, work was required to cause the heat, and by experimentation, it has been shown that the work required and the amount of heat produced by friction are proportional. Thus, heat can be regarded as a form of energy.

According to this theory of heat as a form of energy, the molecules, atoms, and electrons in all bodies are in a continual state of motion. In a hot body, these small particles possess relatively large amounts of kinetic energy, but in cooler bodies they have less. Because the small particles are given motion, and hence kinetic energy, work must be done to slide one body over the other. Mechanical energy apparently is transformed, and what we know as heat is really kinetic energy of the small molecular subdivisions of matter.

Heat Energy Units

Two different units are used to express quantities of heat energy. They are the calorie and the BTU. One calorie is equal to the amount of heat required to change the temperature of 1 gram of water 1 degree Centigrade.

This term "calorie" (spelled with a lower case c) is 1/1,000 of the Calorie (spelled with a capital C) used in the measurement of the heat energy in foods. One BTU is defined as the amount of heat required to change the temperature of 1 lb of water 1 degree Fahrenheit (1°F). The calorie and the gram are seldom used in discussing aviation maintenance. The BTU, however, is commonly referred to in discussions of engine thermal efficiencies and the heat content of aviation fuel.

A device known as the calorimeter is used to measure quantities of heat energy. For example, it may be used to determine the quantity of heat energy available in 1 pound of aviation gasoline. A given weight of the fuel is burned in the calorimeter, and the heat energy is absorbed by a large quantity of water. From the weight of the water and the increase in its temperature, it is possible to compute the heat yield of the fuel. A definite relationship exists between heat and mechanical energy. This relationship has been established and verified by many experiments which show that:

One BTU of heat energy = 778 ft-lb of work

As discussed earlier in this chapter under the topic "Potential Energy," one pound of aviation gasoline contains 18,900 BTU of heat energy. Since each BTU is capable of 778 ft-lb of work, 1 lb of aviation gasoline is capable of 14,704,200 ft-lb of work.

Heat Energy and Thermal Efficiency

Thermal efficiency is the relationship between the potential for power contained in a specific heat source, and how much usable power is actually created when that heat source is used. The formula for calculating thermal efficiency is:

Thermal Efficiency =
Horsepower Produced ÷ Potential Horsepower in Fuel

For example, consider the piston engine used in a small general aviation airplane, which typically consumes 0.5 lb of fuel per hour for each horsepower it creates. Imagine that the engine is creating 200 hp. If we multiply 0.5 by the horsepower of 200, we find the engine is consuming 100 lb of fuel per hour, or 1.67 lb per minute. Earlier in this chapter, one horsepower was found to be 33,000 ft-lb of work per minute. The potential horsepower in the fuel burned for this example engine would be:

$$\text{Hp} = \frac{1.67 \text{ lb per minute} \times 18{,}900 \text{ BTU per lb} \times 778 \text{ ft lb per BTU}}{33{,}000 \text{ ft-lb/min}}$$

$$\text{Hp} = 744$$

The example engine is burning enough fuel that it has the potential to create 744 horsepower, but it is only creating 200. The thermal efficiency of the engine would be:

Thermal Efficiency = Hp Produced ÷ Hp in Fuel
= 200 ÷ 744
= .2688 or 26.88%

More than 70 percent of the energy in the fuel is not being used to create usable horsepower. The wasted energy is in the form of friction and heat. A tremendous amount of heat is given up to the atmosphere and not used inside the engine to create power.

Heat Transfer

There are three methods by which heat is transferred from one location to another or from one substance to another. These three methods are conduction, convection, and radiation.

Conduction

Heat transfer always takes place by areas of high heat energy migrating to areas of low heat energy. Heat transfer by conduction requires that there be physical contact between an object that has a large amount of heat energy and one that has a smaller amount of heat energy.

Everyone knows from experience that the metal handle of a heated pan can burn the hand. A plastic or wood handle, however, remains relatively cool even though it is in direct contact with the pan. The metal transmits the heat more easily than the wood because it is a better conductor of heat. Different materials conduct heat at different rates. Some metals are much better conductors of heat than others. Aluminum and copper are used in pots and pans because they conduct heat very rapidly. Woods and plastics are used for handles because they conduct heat very slowly.

Figure 3-27 illustrates the different rates of conduction of various metals. Of those listed, silver is the best conductor and lead is the poorest. As previously mentioned, copper and aluminum are used in pots and pans because they are good conductors. It is interesting to note that silver, copper, and aluminum are also excellent conductors of electricity.

Liquids are poorer conductors of heat than metals. Notice that the ice in the test tube shown in Figure 3-28 is not melting rapidly even though the water at the top is boiling. The water conducts heat so poorly that not enough heat reaches the ice to melt it.

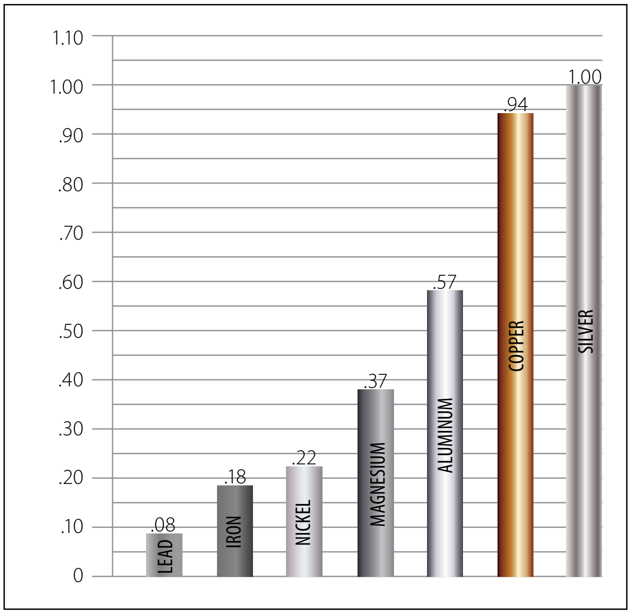

Figure 3-27. Conductivity of various metals.

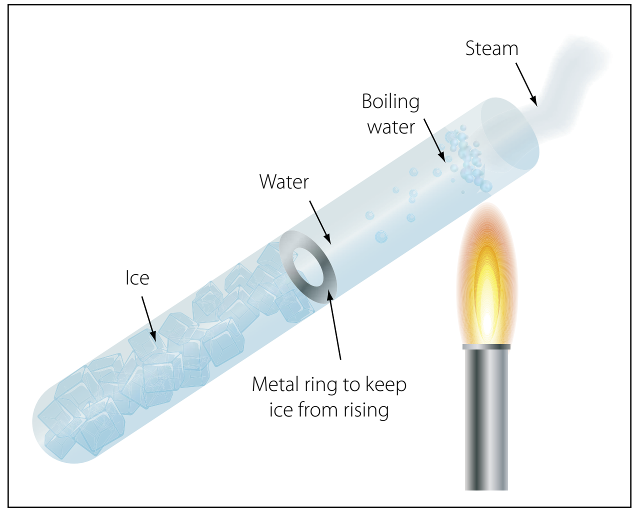

Figure 3-28. Water as a poor conductor.

Gases are even poorer conductors of heat than liquids. It is possible to stand quite close to a stove without being burned because air is such a poor conductor. Since conduction is a process whereby the increase in molecular energy is passed along by actual contact, gases are poor conductors.

At the point of application of the heat source, the molecules become violently agitated. These molecules strike adjacent molecules causing them to become agitated. This process continues until the heat energy is distributed evenly throughout the substance. Because molecules are farther apart in gases than in solids, the gases are much poorer conductors of heat.

Materials that are poor conductors are used to prevent the transfer of heat and are called heat insulators. A wooden handle on a pot or a soldering iron serves as a heat insulator. Certain materials, such as finely spun glass or asbestos, are particularly poor heat conductors. These materials are therefore used for many types of insulation.

Convection

Convection is the process by which heat is transferred by movement of a heated fluid (gas or liquid). For example, an incandescent light bulb will, when heated, become increasingly hotter until the air surrounding it begins to move. The motion of the air is upward. This upward motion of the heated air carries the heat away from the hot light bulb by convection. Transfer of heat by convection may be hastened by using a ventilating fan to move the air surrounding a hot object. The rate of cooling of a hot electronics component, such as the CPU in a computer, can be increased if it is provided with copper fins that conduct heat away from the hot surface. The fins provide large surfaces against which cool air can be blown.

A convection process may take place in a liquid as well as in a gas. A good example of this is a pan of water sitting on the stove. The bottom of the pan becomes hot because it conducts heat from the surface it is in contact with. The water on the bottom of the pan also heats up because of conduction. As the heated water starts to rise and cooler water moves in to take its place, the convection process begins.

When the circulation of gas or liquid is not rapid enough to remove sufficient heat, fans or pumps are used to accelerate the motion of the cooling material. In some installations, pumps are used to circulate water or oil to help cool large equipment. In airborne installations, electric fans and blowers are used to aid convection.

An aircraft air-cooled piston engine is a good example of convection being used to transfer heat. The engine shown in Figure 3-29 is a Continental IO-520, with six heavily finned air-cooled cylinders. This engine does not depend on natural convection for cooling, but rather forced air convection coming from the propeller on the engine. The heat generated inside the engine finds its way to the cylinder cooling fins by conduction, meaning transfer within the metal of the cylinder. Once the heat gets to the fins, forced air flowing around the cylinders carries the heat away.

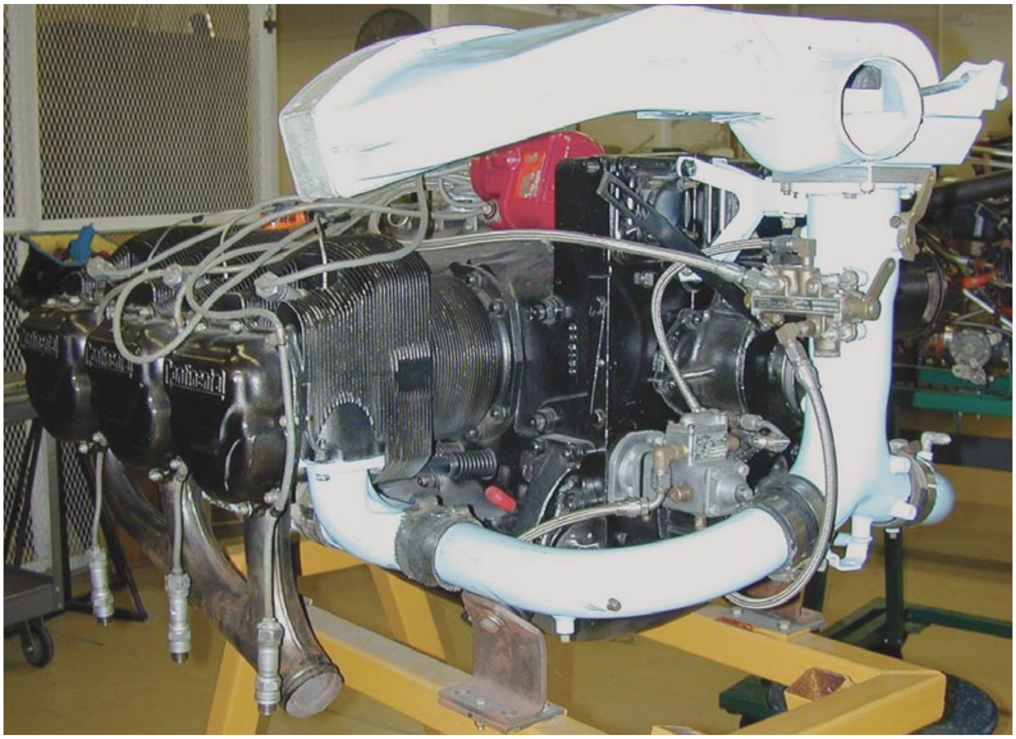

Figure 3-29. Aircraft piston engine cooled by convection.

Radiation

Conduction and convection cannot wholly account for some of the phenomena associated with heat transfer. For example, the heat one feels when sitting in front of an open fire cannot be transferred by convection because the air currents are moving toward the fire. It cannot be transferred through conduction because the conductivity of the air is very small, and the cooler currents of air moving toward the fire would more than overcome the transfer of heat outward. Therefore, there must be some way for heat to travel across space other than by conduction and convection.

The existence of another process of heat transfer is still more evident when the heat from the sun is considered. Since conduction and convection take place only through some medium, such as a gas or a liquid, heat from the sun must reach the earth by another method, since space is an almost perfect vacuum. Radiation is the name given to this third method of heat transfer.

The term "radiation" refers to the continual emission of energy from the surface of all bodies. This energy is known as radiant energy. It is in the form of electromagnetic waves, radio waves, or x-rays, which are all alike except for a difference in wave length. These waves travel at the velocity of light and are transmitted through a vacuum more easily than through air because air absorbs some of them. Most forms of energy can be traced back to the energy of sunlight. Sunlight is a form of radiant heat energy that travels through space to reach the earth. These electromagnetic heat waves are absorbed when they come in contact with non-transparent bodies. The result is that the motion of the molecules in the body is increased as indicated by an increase in the temperature of the body.

The differences between conduction, convection, and radiation may now be considered. First, although conduction and convection are extremely slow, radiation takes place at the speed of light. This fact is evident at the time of an eclipse of the sun when the shutting off of the heat from the sun takes place at the same time as the shutting off of the light. Second, radiant heat may pass through a medium without heating it. For example, the air inside a greenhouse may be much warmer than the glass through which the sun's rays pass. Third, although heat transfer by conduction or convection may travel in roundabout routes, radiant heat always travels in a straight line. For example, radiation can be cut off with a screen placed between the source of heat and the body to be protected.

Specific Heat

One important way in which substances differ is in the requirement of different quantities of heat to produce the same temperature change in a given mass of the substance. Each substance requires a quantity of heat, called its specific heat capacity, to increase the temperature of a unit of its mass 1°C. The specific heat of a substance is the ratio of its specific heat capacity to the specific heat capacity of water. Specific heat is expressed as a number which, because it is a ratio, has no units and applies to both the English and the metric systems.

It is fortunate that water has a high specific heat capacity. The larger bodies of water on the earth keep the air and solid matter on or near the surface of the earth at a fairly constant temperature. A great quantity of heat is required to change the temperature of a large lake or river. Therefore, when the temperature falls below that of such bodies of water, they give off large quantities of heat. This process keeps the atmospheric temperature at the surface of the earth from changing rapidly.

The specific heat values of some common materials are listed in Figure 3-30.

Temperature

Temperature is a dominant factor affecting the physical properties of fluids. It is of particular concern when calculating changes in the state of gases.

The four temperature scales used extensively are the Centigrade, the Fahrenheit, the absolute or Kelvin, and the Rankine scales. The Centigrade scale is constructed by using the freezing and boiling points of water, under standard conditions, as fixed points of zero and 100, respectively, with 100 equal divisions between. The Fahrenheit scale uses 32° as the freezing point of water and 212° as the boiling point, and has 180 equal divisions between. The absolute or Kelvin scale is constructed with its zero point established as minus 273°C, meaning 273° below the freezing point of water. The relationships of the other fixed points of the scales are shown in Figure 3-31.

When working with temperatures, always make sure which system of measurement is being used and know how to convert from one to another. The conversion formulas are as follows:

$$\text{Degrees Fahrenheit} = (1.8 \times \text{Degrees Celsius}) + 32$$
$$\text{Degrees Celsius} = (\text{Degrees Fahrenheit} - 32) \times \tfrac{5}{9}$$
$$\text{Degrees Kelvin} = \text{Degrees Celsius} + 273$$
$$\text{Degrees Rankine} = \text{Degrees Fahrenheit} + 460$$

For purposes of calculations, the Rankine scale is commonly used to convert Fahrenheit to absolute. For Fahrenheit readings above zero, 460° is added. Thus, 72°F equals 460° plus 72°, or 532° absolute. If the Fahrenheit reading is below zero, it is subtracted from 460°. Thus −40°F equals 460° minus 40°, or 420° absolute. It should be stressed that the Rankine scale does not indicate absolute temperature readings in accordance with the Kelvin scale, but these conversions may be used for the calculations of changes in the state of gases.

The Kelvin and Centigrade scales are used more extensively in scientific work; therefore, some technical manuals may use these scales in giving directions and operating instructions. The Fahrenheit scale is commonly used in the United States, and most people are familiar with it. Therefore, the Fahrenheit scale is used in most areas of this book.

Material	Specific Heat
Lead	0.031
Mercury	0.033
Brass	0.094
Copper	0.095
Iron or Steel	0.113
Glass	0.195
Alcohol	0.547
Aluminum	0.712
Water	1.000

Figure 3-30. Specific heat value for various substances.

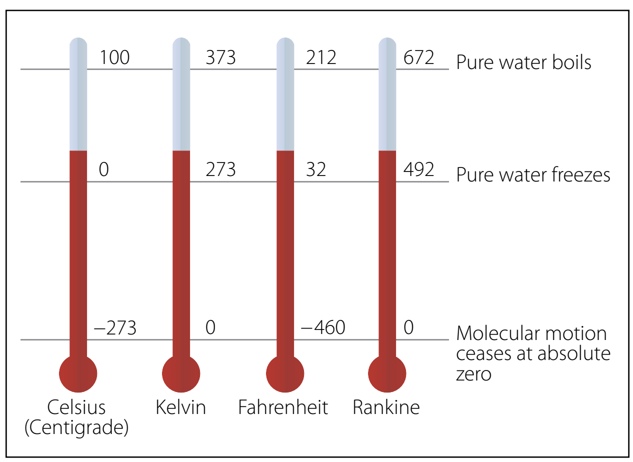

Figure 3-31. Comparison of temperature scales.

Thermal Expansion/Contraction

Thermal expansion takes place in solids, liquids, and gases when they are heated. With few exceptions, solids will expand when heated and contract when cooled. Because the molecules of solids are much closer together and are more strongly attracted to each other, the expansion of solids when heated is very slight in comparison to the expansion in liquids and gases. The expansion of fluids is discussed in the study of Boyle's law. Thermal expansion in solids must be explained in some detail because of its close relationship to aircraft metals and materials.

Because some substances expand more than others, it is necessary to measure experimentally the exact rate of expansion of each one. The amount that a unit length of any substance expands for a one degree rise in temperature is known as the coefficient of linear expansion for that substance. The coefficient of linear expansion for various materials is shown in Figure 3-32.

To estimate the expansion of any object, such as a steel rail, it is necessary to know three things about it: its length, the rise in temperature to which it is subjected, and its coefficient of expansion. This relationship is expressed by the equation:

$$\text{Expansion} = (\text{coefficient}) \times (\text{length}) \times (\text{rise in temperature})$$

If a steel rod measures exactly 9 ft at 21°C, what is its length at 55°C? The coefficient of expansion for steel is 11×10^{-6}.

$$\text{Expansion} = (11 \times 10^{-6}) \times (9 \text{ feet}) \times 34°$$
$$\text{Expansion} = 0.003366 \text{ feet}$$

Substance	Coefficient of Expansion Per Degree Centigrade
Aluminum	25×10^{-6}
Brass or Bronze	19×10^{-6}
Brick	9×10^{-6}
Copper	17×10^{-6}
Glass (Plate)	9×10^{-6}
Glass (Pyrex)	3×10^{-6}
Ice	51×10^{-6}
Iron or Steel	11×10^{-6}
Lead	29×10^{-6}
Quartz	0.4×10^{-6}
Silver	19×10^{-6}

Figure 3-32. Coefficient of expansion for various materials.

This amount, when added to the original length of the rod, makes the rod 9.003366 ft long. Its length has only increased by $^4/_{100}$ of an inch.

The increase in the length of the rod is relatively small, but if the rod were placed where it could not expand freely, there would be a tremendous force exerted due to thermal expansion. Thus, thermal expansion must be taken into consideration when designing airframes, powerplants, or related equipment.

Pressure

Pressure is the amount of force acting on a specific amount of surface area. The force is typically measured in pounds and the surface area in square inches, making the units of pressure pounds per square inch or psi. If a 100-lb weight was placed on top of a block with a surface area of 10 in^2, the average weight distribution would be 10 lb for each of the square inches (100 ÷ 10), or 10 psi.

When atmospheric pressure is being measured, in addition to psi, other means of pressure measurement can be used. These include inches or millimeters of mercury, and millibars. Standard day atmospheric pressure is equal to 14.7 psi, 29.92 inches of mercury ("Hg), 760 millimeters of mercury (mm Hg), or 1013.2 millibars. The relationship between these units of measure is as follows:

1 psi = 2.04 "Hg
1 psi = 51.7 mm Hg
1 psi = 68.9 millibars

The concept behind measuring pressure in inches of mercury involves filling a test tube with the liquid mercury and then covering the top. The test tube is then turned upside down and placed in an open container of mercury, and the top is uncovered. Gravity acting on the mercury in the test tube will try to make the mercury run out. Atmospheric pressure pushing down on the mercury in the open container tries to make the mercury stay in the test tube. At some point these two forces (gravity and atmospheric pressure) will equal out and the mercury will stabilize at a certain height in the test tube. Under standard day atmospheric conditions, the air in a 1-in^2 column extending all the way to the top of the atmosphere would weigh 14.7 lb. A 1 in^2 column of mercury, 29.92 inches tall, would also weigh 14.7 lb. That is why 14.7 psi is equal to 29.92 "Hg. Figure 3-33 demonstrates this point.

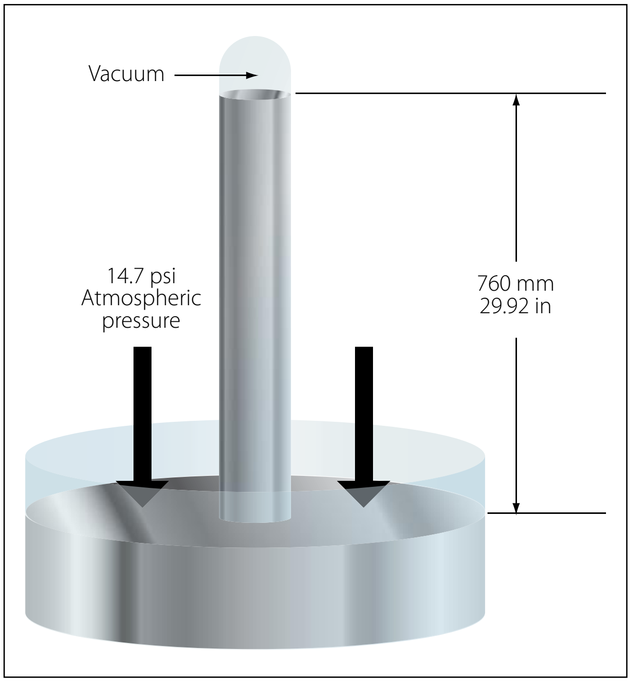

Figure 3-33. Atmospheric pressure as inches of mercury.

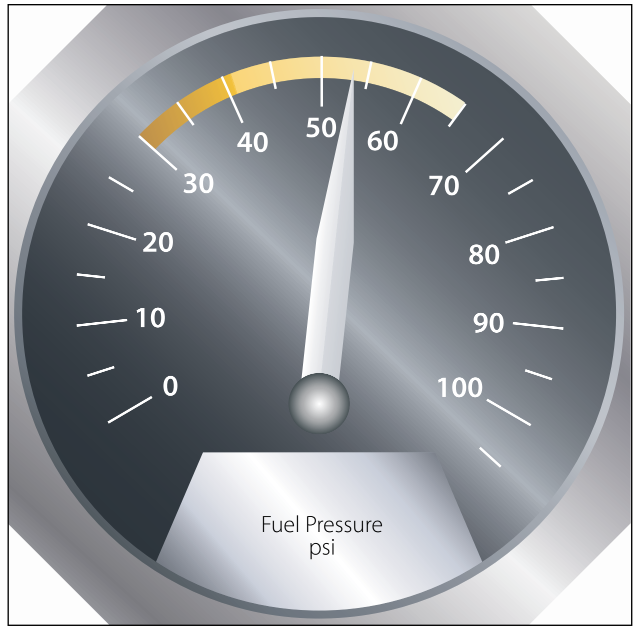

Figure 3-34. Psig read on a fuel pressure gauge.

Gauge Pressure

When an instrument, such as an oil pressure gauge, fuel pressure gauge, or hydraulic system pressure gauge, displays pressure which is over and above ambient, the reading is referred to as gauge pressure (psig). This can be seen on the fuel pressure gauge shown in Figure 3-34. When the oil, fuel, or hydraulic pump is not turning, and there is no pressure being created, the gauge will read zero.

Absolute Pressure

A gauge that includes atmospheric pressure in its reading is measuring what is known as absolute pressure, or psia. Absolute pressure is equal to gauge pressure plus atmospheric pressure. If someone hooked up a psia indicating instrument to an engine's oil system, the gauge would read atmospheric pressure when the engine was not running. Since this would not make good sense to the typical operator, psia gauges are not used in this type of application. For the manifold pressure on a piston engine, a psia gauge does make good sense. Manifold pressure on a piston engine can read anywhere from less than atmospheric pressure if the engine is not supercharged, to more than atmospheric if it is supercharged. The only gauge that has the flexibility to show this variety of readings is the absolute pressure gauge. Figure 3-35 shows a manifold pressure gauge, with a readout that ranges from 10 "Hg to 35 "Hg. Remember that 29.92 "Hg is standard day atmospheric.

Figure 3-35. Manifold pressure gauge indicating absolute pressure.

Differential Pressure

Differential pressure, or psid, is the difference between pressures being read at two different locations within a system. For example, in a turbine engine oil system the pressure is read as it enters the oil filter, and also as it leaves the filter. These two readings are sent to a transmitter which powers a light located on the flight deck. Across anything that poses a resistance to flow, like an oil filter, there will be a drop in pressure. If the filter starts to clog, the pressure drop will become

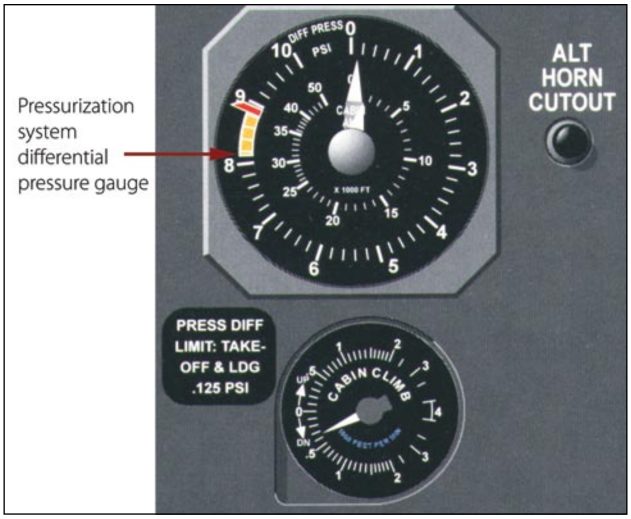

Figure 3-36. Differential pressure gauge.

greater, eventually causing the advisory light on the flight deck to come on.

Figure 3-36 shows a differential pressure gauge for the pressurization system on a Boeing 737. In this case, the difference in pressure is between the inside and the outside of the airplane. If the pressure difference becomes too great, the structure of the airplane could become overstressed.

Gas Laws

The simple structure of gases makes them readily adaptable to mathematical analysis from which has evolved a detailed theory of the behavior of gases. This is called the kinetic theory of gases. The theory assumes that a body of gas is composed of identical molecules which behave like minute elastic spheres, spaced relatively far apart and continuously in motion.

The degree of molecular motion is dependent upon the temperature of the gas. Since the molecules are continuously striking against each other and against the walls of the container, an increase in temperature with the resulting increase in molecular motion causes a corresponding increase in the number of collisions between the molecules. The increased number of collisions results in an increase in pressure because a greater number of molecules strike against the walls of the container in a given unit of time.

If the container were an open vessel, the gas would expand and overflow from the container. However, if the container is sealed and possesses elasticity (such as a rubber balloon), the increased pressure causes the container to expand. For instance, when making a long drive on a hot day, the pressure in the tires of an automobile increases, and a tire which appeared to be somewhat "soft" in cool morning temperature may appear normal at a higher midday temperature.

Such phenomena as these have been explained and set forth in the form of laws pertaining to gases and tend to support the kinetic theory.

Boyle's Law

As previously stated, compressibility is an outstanding characteristic of gases. The English scientist, Robert Boyle, was among the first to study this characteristic that he called the "springiness of air." By direct measurement he discovered that when the temperature of a combined sample of gas was kept constant and the absolute pressure doubled, the volume was reduced to half the former value. As the applied absolute pressure was decreased, the resulting volume increased. From these observations, he concluded that for a constant temperature the product of the volume and absolute pressure of an enclosed gas remains constant. Boyle's law is normally stated: "The volume of an enclosed dry gas varies inversely with its absolute pressure, provided the temperature remains constant." The following formula is used for Boyle's law calculations. Remember, pressure needs to be in the absolute.

$$\text{Volume 1} \times \text{Pressure 1} = \text{Volume 2} \times \text{Pressure 2}$$
Or
$$V1P1 = V2P2$$

Example: *10 ft^3 of nitrogen is under a pressure of 500 psia. If the volume is reduced to 7 ft^3, what will the new pressure be? [Figure 3-37]*

$$V1P1 = V2P2$$
$$10\,(500) = 7\,(P2)$$
$$10\,(500) \div 7 = P2$$
$$P2 = 714.29 \text{ psia}$$

The useful applications of Boyle's law are many and varied. Some applications more common to aviation are: (1) the carbon dioxide (CO_2) bottle used to inflate life rafts and life vests; (2) the compressed oxygen and the acetylene tanks used in welding; (3) the compressed air brakes and shock absorbers; and (4) the use of oxygen tanks for high altitude flying and emergency use.

Charles' Law

The French scientist, Jacques Charles, provided much of the foundation for the modern kinetic theory of gases. He found that all gases expand and contract in direct proportion to the change in the absolute tem-

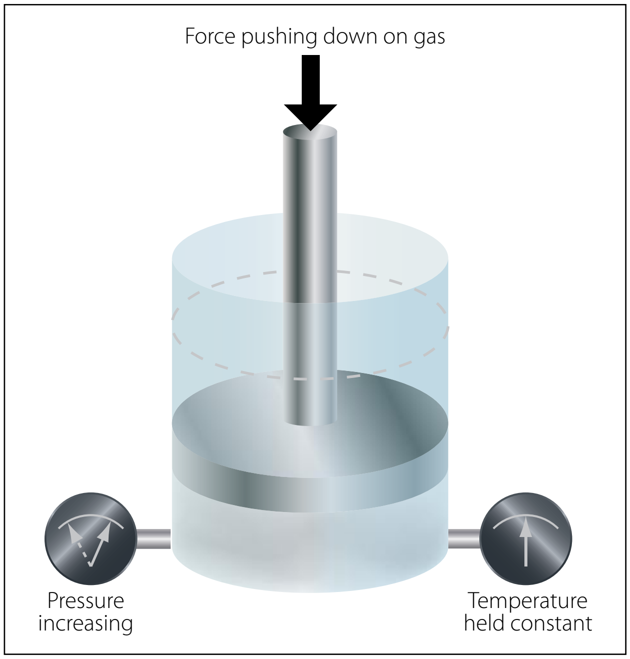

Figure 3-37. Boyle's law example.

perature, provided the pressure is held constant. As a formula, this law is shown as follows:

Volume 1 × Absolute Temperature 2 =
Volume 2 × Absolute Temperature 1
Or
V1T2 = V2T1

Charles' law also works if the volume is held constant, and pressure and temperature are the variables. In this case, the formula would be as follows:

P1T2 = P2T1

For this second formula, pressure and temperature must be in the absolute.

Example: *A 15-ft^3 cylinder of oxygen is at a temperature of 70°F and a pressure of 750 psig. The cylinder is placed in the sun and the temperature of the oxygen increases to 140°F. What would be the new pressure in psig?*

70 degrees Fahrenheit = 530 degrees Rankine
140 degrees Fahrenheit = 600 degrees Rankine
750 psig + 14.7 = 764.7 psia
P1T2 = P2T1
764.7 (600) = P2 (530)
P2 = 764.7 (600) ÷ 530
P2 = 865.7 psia
P2 = 851 psig

General Gas Law

By combining Boyle's and Charles' laws, a single expression can be derived which states all the information contained in both. The formula which is used to express the general gas law is as follows:

$$\frac{\text{Pressure 1 (Volume 1)}}{\text{Temperature 1}} = \frac{\text{Pressure 2 (Volume 2)}}{\text{Temperature 2}}$$

Or

P1 (V1) (T2) = P2 (V2) (T1)

When using the general gas law formula, temperature and pressure must be in the absolute.

Example: *20 ft^3 of the gas argon is compressed to 15 ft^3. The gas starts out at a temperature of 60°F and a pressure of 1,000 psig. After being compressed, its temperature is 90°F. What would its new pressure be in psig?*

60 degrees Fahrenheit = 520 degrees Rankine
90 degrees Fahrenheit = 550 degrees Rankine
1,000 psig + 14.7 = 1,014.7 psia
P1 (V1) (T2) = P2 (V2) (T1)
1,014.7 (20) (550) = P2 (15) (520)
P2 = 1,431 psia
P2 = 1,416.3 psig

Dalton's Law

If a mixture of two or more gases that do not combine chemically is placed in a container, each gas expands throughout the total space and the absolute pressure of each gas is reduced to a lower value, called its partial pressure. This reduction is in accordance with Boyle's law. The pressure of the mixed gases is equal to the sum of the partial pressures. This fact was discovered by Dalton, an English physicist, and is set forth in Dalton's law: "A mixture of several gases which do not react chemically exerts a pressure equal to the sum of the pressures which the several gases would exert separately if each were allowed to occupy the entire space alone at the given temperature."

Fluid Mechanics

A fluid, by definition, is any substance that is able to flow if it is not in some way confined or restricted. Liquids and gases are both classified as fluids, and often act in a very similar way. One significant difference comes into play when a force is applied to these fluids. In this case, liquids tend to be incompressible and gases are highly compressible. Many of the principles that aviation is based on, such as the theory of lift on a wing and the force generated by a hydraulic system, can be explained and quantified by using the laws of fluid mechanics.

Buoyancy

A solid body submerged in a liquid or a gas weighs less than when weighed in free space. This is because of the upward force, called buoyant force, which any fluid exerts on a body submerged in it. An object will float if this upward force of the fluid is greater than the weight of the object. Objects denser than the fluid, even though they sink readily, appear to lose a part of their weight when submerged. A person can lift a larger weight under water than he or she can possibly lift in the air.

The following experiment is illustrated in Figure 3-38. The overflow can is filled to the spout with water. The heavy metal cube is first weighed in still air and weighs 10 lb. It is then weighed while completely submerged in the water and it weighs 3 lb. The difference between the two weights is the buoyant force of the water. As the cube is lowered into the overflow can, the water is caught in the catch bucket. The volume of water which overflows equals the volume of the cube. (The volume of irregular shaped objects can be measured by this method.) If this experiment is performed carefully, the weight of the water displaced by the metal cube exactly equals the buoyant force of the water, which the scale shows to be 7 lb.

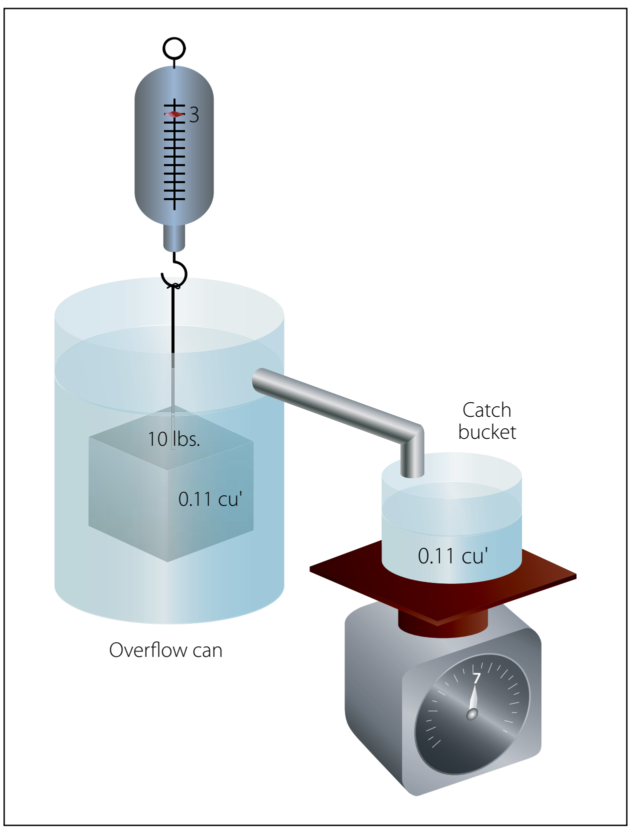

Figure 3-38. Example of buoyancy.

Archimedes (287–212 B.C.) performed similar experiments. As a result, he discovered that the buoyant force which a fluid exerts upon a submerged body is equal to the weight of the fluid the body displaces. This statement is referred to as Archimedes' principle. This principle applies to all fluids, gases as well as liquids. Just as water exerts a buoyant force on submerged objects, air exerts a buoyant force on objects submerged in it.

The amount of buoyant force available to an object can be calculated by using the following formula:

Buoyant Force = Volume of Object × Density of Fluid Displaced

If the buoyant force is more than the object weighs, the object will float. If the buoyant force is less than the object weighs, the object will sink. For the object that sinks, its measurable weight will be less by the weight of the displaced fluid.

Example: *A 10-ft^3 object weighing 700 lb is placed in pure water. Will the object float? If the object sinks, what is its measurable weight in the submerged condition? If the object floats, how many cubic feet of its volume is below the water line?*

Buoyant Force = Volume of Object × Density of Fluid Displace
= 10 (62.4)
= 624 lb

Because the buoyant force is less than the object weighs, the object will sink. The difference between the buoyant force and the object's weight will be its measurable weight, or 76 lb.

Two good examples of buoyancy are a helium filled airship and a seaplane on floats. An airship is able to float in the atmosphere and a seaplane is able to float on water. That means both have more buoyant force than weight. Figure 3-39 is a DeHavilland Twin Otter seaplane, with a gross takeoff weight of 12,500 lb. At a minimum, the floats on this airplane must be large enough to displace a weight in water equal to the airplane's weight. According to Title 14 of the Code of Federal Regulations (14 CFR) part 23, the floats must be 80 percent larger than the minimum needed to support the airplane. For this airplane, the necessary size of the floats would be calculated as follows:

Divide the airplane weight by the density of water.
$12{,}500 \div 62.4 = 200.3 \text{ ft}^3$

Multiply this volume by 80%.
$200.3 \times 80\% = 160.2 \text{ ft}^3$

Add the two volumes together to get the total volume of the floats.
$200.3 + 160.2 = 360.5 \text{ ft}^3$

By looking at the Twin Otter in Figure 3-39, it is obvious that much of the volume of the floats is out of the water. This is accomplished by making sure the floats have at least 80 percent more volume than the minimum necessary.

Figure 3-39. De Havilland Twin Otter seaplane.

Some of the large Goodyear airships have a volume of 230,000 ft^3. Since the fluid they are submerged in is air, to find the buoyant force of the airship, the volume of the airship is multiplied by the density of air (.07651 $^{\text{lb}}/_{\text{ft}^3}$). For this Goodyear airship, the buoyant force is 17,597 lb. Figure 3-40 shows an inside view of the Goodyear airship.

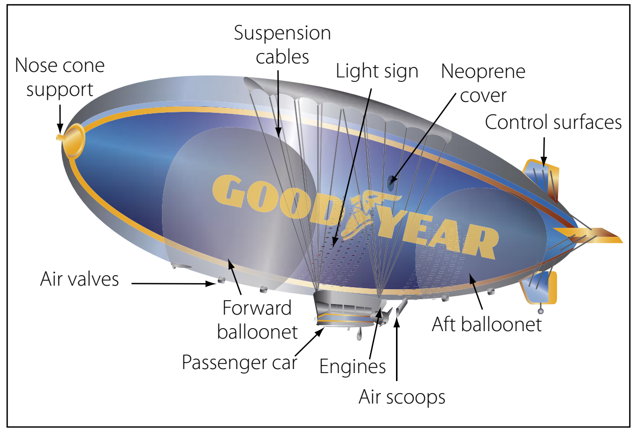

Figure 3-40. The Goodyear Airship and buoyancy.

The ballonets, items 2 and 4 in the picture, are air chambers within the airship. Through the air scoop, item 9, air can be pumped into the ballonets or evacuated from the ballonets in order to control the weight of the airship. Controlling the weight of the airship controls how much positive or negative lift it has. Although the airship is classified as a lighter-than-air aircraft, it is in fact flown in a condition slightly heavier than air.

Fluid Pressure

The pressure exerted on the bottom of a container by a liquid is determined by the height of the liquid and not by the shape of the container. This can be seen in Figure 3-41, where three different shapes and sizes of containers are full of colored water. Even though they are different shapes and have different volumes of liquid, each one has a height of 231 inches. Because of this height, each one would exert a pressure on the bottom of 8.34 psi. The container on the left, with a surface area of 1 in^2, contains a volume of 231 in^3 (one gallon). One gallon of water weighs 8.34 lb, which is why the pressure on the bottom is 8.34 psi.

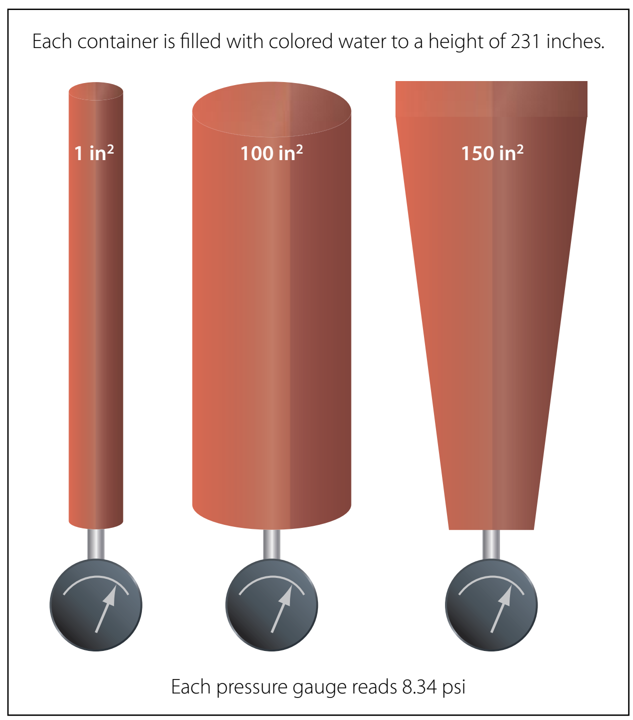

Figure 3-41. Fluid pressure based on column height.

Still thinking about Figure 3-41, if the pressure was measured half way down, it would be half of 8.34, or 4.17 psi. In other words, the pressure is adjustable by varying the height of the column. Pressure based on the column height of a fluid is known as static pressure. With liquids, such as gasoline, it is sometimes referred to as a head of pressure. For example, if a carburetor needs to have 2 psi supplied to its inlet (head of pressure), this could be accomplished by having the fuel tank positioned the appropriate number of inches higher than the carburetor.

As identified in the previous paragraph, pressure due to the height of a fluid column is known as static pressure. When a fluid is in motion, and its velocity is converted to pressure, that pressure is known as ram. When ram pressure and static pressure are added together, the result is known as total pressure. In the inlet of a gas turbine engine, for example, total pressure is often measured to provide a signal to the fuel metering device or to provide a signal to a gauge on the flight deck.

Pascal's Law

The foundations of modern hydraulics and pneumatics were established in 1653 when Pascal discovered that pressure set up in a fluid acts equally in all directions. This pressure acts at right angles to containing surfaces. When the pressure in the fluid is caused solely by the fluid's height, the pressure against the walls of the container is equal at any given level, but it is not equal if the pressure at the bottom is compared to the pressure half way down. The concept of the pressure set up in a fluid, and how it relates to the force acting on the fluid and the surface area through which it acts, is Pascal's law.

In Figure 3-41, if a piston is placed at the top of the cylinder and an external force pushes down on the piston, additional pressure will be created in the liquid. If the additional pressure is 100 psi, this 100 psi will act equally and undiminished from the top of the cylinder all the way to the bottom. The gauge at the bottom will now read 108.34 psi, and if a gauge were positioned half way down the cylinder, it would read 104.17 psi (100 plus half of 8.34).

Pascal's law, when dealing with the variables of force, pressure, and area, is dealt with by way of the following formula.

$$\text{Force} = \text{Pressure} \times \text{Area}$$

In this formula, the force is in units of pounds, the pressure is in pounds per square inch (psi), and the area is in square inches. By transposing the original formula, we have two additional formulas, as follows:

$$\text{Pressure} = \text{Force} \div \text{Area}$$

And

$$\text{Area} = \text{Force} \div \text{Pressure}$$

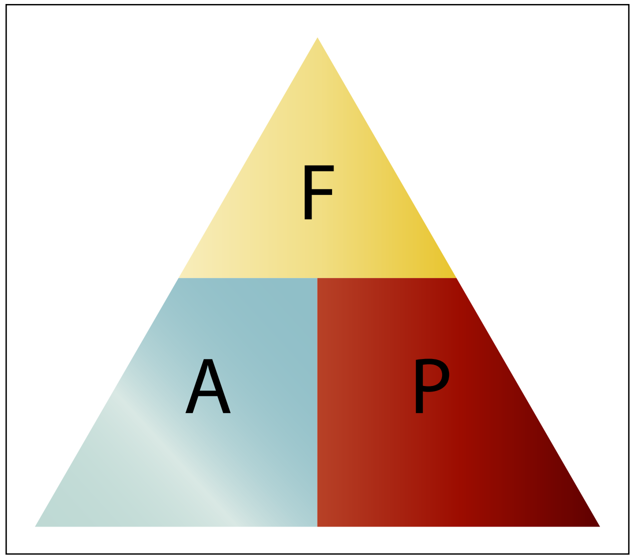

Figure 3-42. Force, area, pressure relationship.

An easy and convenient way to remember the formulas for Pascal's law, and the relationship between the variables, is with the triangle shown in Figure 3-42. If the variable we want to solve for is covered up, the position of the remaining two variables shows the proper math relationship. For example, if the "A" (area) is covered up, what remains is the "F" on the top and the "P" on the bottom, meaning force divided by pressure.

The simple hydraulic system in Figure 3-43 has a 5-lb force acting on a piston with a $\frac{1}{2}$-in^2 surface area. Based on Pascal's law, the pressure in the system would be equal to the force applied divided by the area of the piston, or 10 psi. As shown in Figure 3-43, the pressure of 10 psi is present everywhere in the fluid.

The hydraulic system in Figure 3-44 is a little more complex than the one in Figure 3-43. In Figure 3-44, the input force of 5 lb is acting on a $\frac{1}{2}$-in^2 piston, creating a pressure of 10 psi. The input cylinder and piston is connected to a second cylinder, which contains a 5-in^2 piston. The pressure of 10 psi created by the

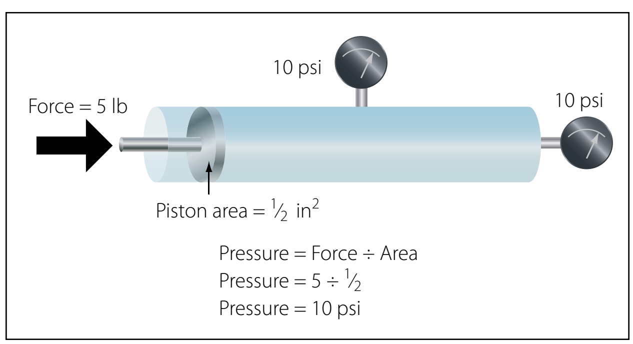

Figure 3-43. Pressure created in a hydraulic system.

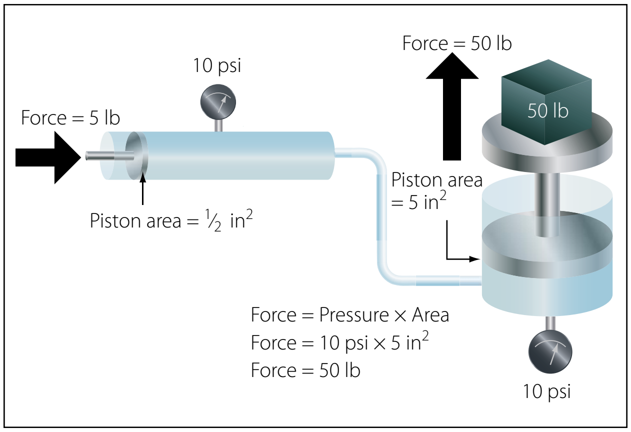

Figure 3-44. Output force created in a hydraulic system.

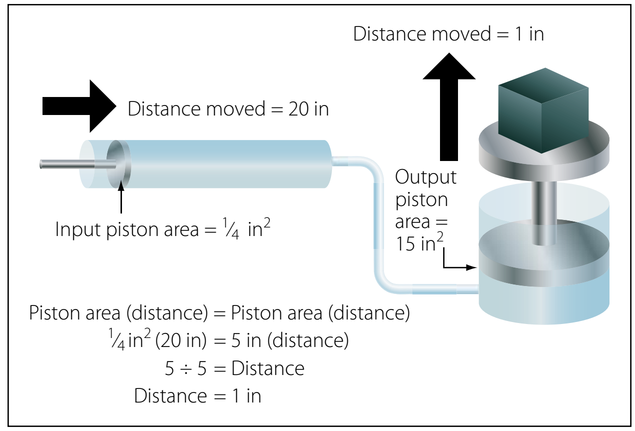

Figure 3-45. Piston movement in a hydraulic system.

input piston pushes on the piston in the second cylinder, creating an output force of 50 pounds.

More often than not, the purpose of a hydraulic system is to generate a large output force, with the input force being much less. In Figure 3-44, the input force is 5 lb and the output force is 50 lb, or 10 times greater. The relationship between the output force and the input force, as discussed earlier in this chapter, is known as mechanical advantage. The mechanical advantage in Figure 3-44 would be 50 divided by 5, or 10. The following formulas can be used to calculate mechanical advantage.

Mechanical Advantage = Force Out ÷ Force In
Or
Mechanical Advantage = Distance Out ÷ Distance In

Earlier in this chapter when simple machines, such as levers and gears were discussed, it was identified that no machine allows us to gain work. The same statement holds true for a hydraulic system, that we get no more work out of a hydraulic system than we put in. Since work is equal to force times distance, if we gain force with a hydraulic system, we must lose distance. We only get the same work out, if the system is 100 percent efficient.

In order to think about the distance that the output piston will move in response to the movement of the input piston, the volume of fluid displaced must be considered. In the study of geometry, one learns that the volume of a cylinder is equal to the cylinder's surface area multiplied by its height. So when a piston of 2 in^2 moves down in a cylinder a distance of 10 in, it displaces a volume of fluid equal to 20 in^3 (2 in^2 × 10 in). The 20 in^3 displaced by the first piston is what moves over to the second cylinder and causes its piston to move. In a simple two-piston hydraulic system, the relationship between the piston area and the distance moved is shown by the following formula.

Input Piston Area (Distance Moved) =
Output Piston Area (Distance Moved)

In essence, this formula shows that the volume in is equal to the volume out. This concept is shown in Figure 3-45, where a small input piston moves a distance of 20 inches, and the larger output piston only moves a distance of 1 inch.

Example: *A two-piston hydraulic system, like that shown in Figure 3-45, has an input piston with an area of $\frac{1}{4}$ in^2 and an output piston with an area of 15 in^2. An input force of 50 lb is applied, and the input piston moves 30 inches. What is the pressure in the system, how much force is generated by the output piston, how far would the output piston move, and what is the mechanical advantage?*

Pressure = Force ÷ Area
= 50 ÷ ¼
= 200 psi

Force = Pressure × Area
= 200 × 15
= 3,000 lb

Mechanical Advantage = Force Out ÷ Force In
= 3,000 ÷ 50
= 60

Input Piston Area (Distance Moved) = Output Piston Area (Distance Moved)
¼ (30) = 15 (Distance Moved)
¼ (30) ÷ 15 = Distance Moved
Distance Moved = ½ in

Part of understanding Pascal's law and hydraulics involves utilizing formulas, and recognizing the relationship between the individual variables. Before the numbers are plugged into the formulas, it is often possible to analyze the variables in the system and come to a realization about what is happening. For example, look at the variables in Figure 3-45 and notice that the output piston is 20 times larger than the input piston (5 in^2 compared to ¼ in^2). That comparison tells us that the output force will be 20 times greater than the input force, and also that the output piston will only move 1/20 as far. Without doing any formula based calculations, we can conclude that the hydraulic system in question has a mechanical advantage of 20.

Bernoulli's Principle

Bernoulli's principle was originally stated to explain the action of a liquid flowing through the varying cross-sectional areas of tubes. In Figure 3-46 a tube is shown in which the cross-sectional area gradually decreases to a minimum diameter in its center section. A tube constructed in this manner is called a "venturi," or "venturi tube." Where the cross-sectional area is decreasing, the passageway is referred to as a converging duct. As the passageway starts to spread out, it is referred to as a diverging duct.

As a liquid (fluid) flows through the venturi tube, the gauges at points "A," "B," and "C" are positioned to register the velocity and the static pressure of the liquid. The venturi in Figure 3-46 can be used to illustrate Bernoulli's principle, which states that: The static pressure of a fluid (liquid or gas) decreases at points where the velocity of the fluid increases, provided no energy is added to nor taken away from the fluid. The velocity of the air is kinetic energy and the static pressure of the air is potential energy.

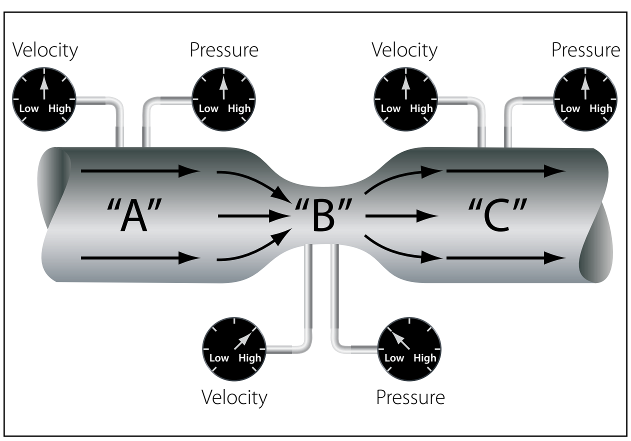

Figure 3-46. Bernoulli's principle and a venturi.

In the wide section of the venturi (points A and C of Figure 3-46), the liquid moves at low velocity, producing a high static pressure, as indicated by the pressure gauge. As the tube narrows in the center, it must contain the same volume of fluid as the two end areas. In this narrow section, the liquid moves at a higher velocity, producing a lower pressure than that at points A and C, as indicated by the velocity gauge reading high and the pressure gauge reading low. A good application for the use of the venturi principle is in a float-type carburetor. As the air flows through the carburetor on its way to the engine, it goes through a venturi, where the static pressure is reduced. The fuel in the carburetor, which is under a higher pressure, flows into the lower pressure venturi area and mixes with the air.

Bernoulli's principle is extremely important in understanding how some of the systems used in aviation work, including how the wing of an airplane generates lift or why the inlet duct of a turbine engine on a subsonic airplane is diverging in shape. The wing on a slow moving airplane has a curved top surface and a relatively flat bottom surface. The curved top surface acts like half of the converging shaped middle of a venturi. As the air flows over the top of the wing, the air speeds up, and its static pressure decreases. The static pressure on the bottom of the wing is now greater than the pressure on the top, and this pressure difference creates the lift on the wing. Bernoulli's principle and the concept of lift on a wing is covered in greater depth in "Aircraft Theory of Flight" located in this chapter.

Sound

Sound has been defined as a series of disturbances in matter that the human ear can detect. This definition can also be applied to disturbances which are beyond the range of human hearing. There are three elements which are necessary for the transmission and reception of sound. These are the source, a medium for carrying the sound, and the detector. Anything which moves back and forth (vibrates) and disturbs the medium around it may be considered a sound source.

An example of the production and transmission of sound is the ring of a bell. When the bell is struck and begins to vibrate, the particles of the medium (the surrounding air) in contact with the bell also vibrate. The vibrational disturbance is transmitted from one particle of the medium to the next, and the vibrations travel in a "wave" through the medium until they reach the ear. The eardrum, acting as detector, is set in motion by the vibrating particles of air, and the brain interprets the eardrum's vibrations as the characteristic sound associated with a bell.

Wave Motion

Since sound is a wave motion in matter, it can best be understood by first considering water waves. When an object is thrown into a pool, a series of circular waves travel away from the disturbance. In Figure 3-47 such waves are seen from a top perspective, with the waves traveling out from the center. In the cross-section perspective in Figure 3-47, notice that the water waves are a succession of crests and troughs. The wavelength is the distance from the crest of one wave to the crest of the next. Water waves are known as transverse waves because the motion of the water molecules is up and down, or at right angles to the direction in which the waves are traveling. This can be seen by observing a cork on the water, bobbing up and down as the waves pass by.

Sound travels through matter in the form of longitudinal wave motions. These waves are called longitudinal waves because the particles of the medium vibrate back and forth longitudinally in the direction of propagation. [Figure 3-48] When the tine of a tuning fork moves in an outward direction, the air immediately in front of the tine is compressed so that its momentary pressure is raised above that at other points in the surrounding medium. Because air is elastic, this disturbance is transmitted progressively in an outward direction from the tine in the form of a compression wave.

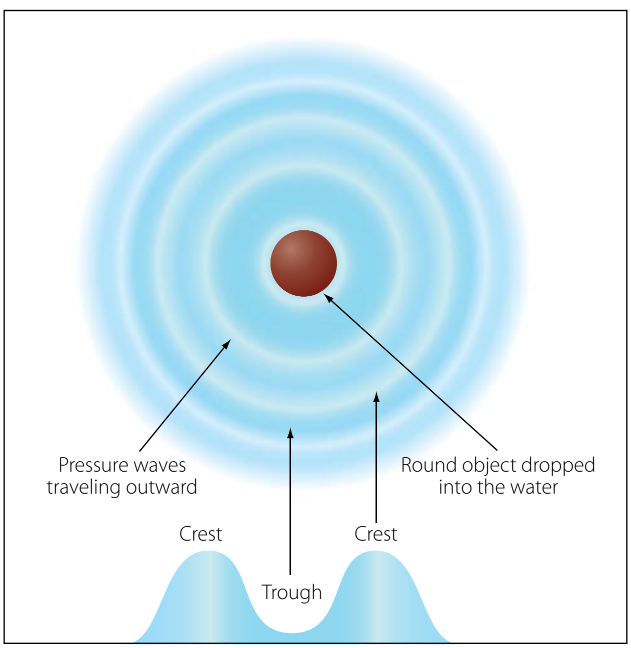

Figure 3-47. Relationship between sound and waves in water.

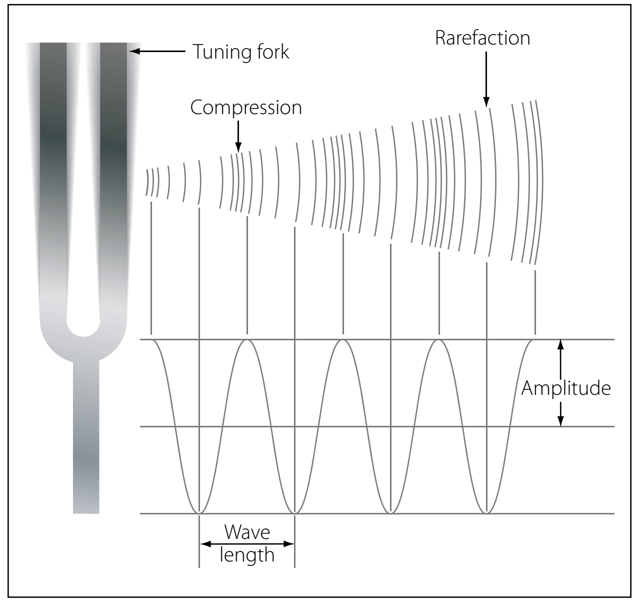

Figure 3-48. Sound propagation by a tuning fork.

When the tine returns and moves in an inward direction, the air in front of the tine is rarefied so that its momentary pressure is reduced below that at other points in the surrounding medium. This disturbance is transmitted in the form of a rarefaction (expansion) wave and follows the compression wave through the medium. The progress of any wave involves two distinct motions: (1) The wave itself moves forward with constant speed, and (2) simultaneously, the particles of the medium that convey the wave vibrate harmonically. Examples of harmonic motion are the motion of a clock pendulum, the balance wheel in a watch, and the piston in a reciprocating engine.

Speed of Sound

In any uniform medium, under given physical conditions, sound travels at a definite speed. In some substances, the velocity of sound is higher than in others. Even in the same medium under different conditions of temperature, pressure, and so forth, the velocity of sound varies. Density and elasticity of a medium are the two basic physical properties which govern the velocity of sound.

In general, a difference in density between two substances is sufficient to indicate which one will be the faster transmission medium for sound. For example, sound travels faster through water than it does through air at the same temperature. However, there are some surprising exceptions to this rule of thumb. An outstanding example among these exceptions involves comparison of the speed of sound in lead and aluminum at the same temperature. Sound travels at 16,700 fps in aluminum at 20°C, and only 4,030 fps in lead at 20°C, despite the fact that lead is much more dense than aluminum. The reason for such exceptions is found in the fact, mentioned above, that sound velocity depends on elasticity as well as density.

Using density as a rough indication of the speed of sound in a given substance, it can be stated as a general rule that sound travels fastest in solid materials, slower in liquids, and slowest in gases. The velocity of sound in air at 0°C (32°F) is 1,087 fps and increases by 2 fps for each Centigrade degree of temperature rise (1.1 fps for each degree Fahrenheit).

Mach Number

In the study of aircraft that fly at supersonic speeds, it is customary to discuss aircraft speed in relation to the velocity of sound (approximately 760 miles per hour (mph) at 59°F). The term "Mach number" has been given to the ratio of the speed of an aircraft to the speed of sound, in honor of Ernst Mach, an Austrian scientist. If the speed of sound at sea level is 760 mph, an aircraft flying at a Mach number of 1.2 at sea level would be traveling at a speed of 760 mph × 1.2 = 912 mph.

Frequency of Sound

The term "pitch" is used to describe the frequency of a sound. The outstanding recognizable difference between the tones produced by two different keys on a piano is a difference in pitch. The pitch of a tone is proportional to the number of compressions and rarefactions received per second, which in turn, is determined by the vibration frequency of the sounding source. A good example of frequency is the noise generated by a turbofan engine on a commercial airliner. The high tip speeds of the fan in the front of the engine creates a high frequency sound, and the hot exhaust creates a low frequency sound.

Loudness

When a bell rings, the sound waves spread out in all directions and the sound is heard in all directions. When a bell is struck lightly, the vibrations are of small amplitude and the sound is weak. A stronger blow produces vibrations of greater amplitude in the bell, and the sound is louder. It is evident that the amplitude of the air vibrations is greater when the amplitude of the vibrations of the source is increased. Hence, the loudness of the sound depends on the amplitude of the vibrations of the sound waves. As the distance from the source increases, the energy in each wave spreads out, and the sound becomes weaker.

As the sound wave advances, variations in pressure occur at all points in the transmitting medium. The greater the pressure variations, the more intense the sound wave. The intensity is proportional to the square of the pressure variation regardless of the frequency. Thus, by measuring pressure changes, the intensities of sounds having different frequencies can be compared directly.

Measurement of Sound Intensity

Sound intensity is measured in decibels, with a decibel being the ratio of one sound to another. One decibel (dB) is the smallest change in sound intensity the human ear can detect. A faint whisper would have an intensity of 20 dB, and a pneumatic drill would be 80 dB. The engine on a modern jetliner, at takeoff thrust, would have a sound intensity of 90 dB when heard by someone standing 150 ft away. A 110 dB noise, by comparison, would sound twice as loud as the jetliner's engine. Figure 3-49 shows the sound intensity from a variety of different sources.

Doppler Effect

When sound is coming from a moving object, the object's forward motion adds to the frequency as sensed from the front and takes away from the frequency as sensed from the rear. This change in frequency is known as the Doppler effect, and it explains

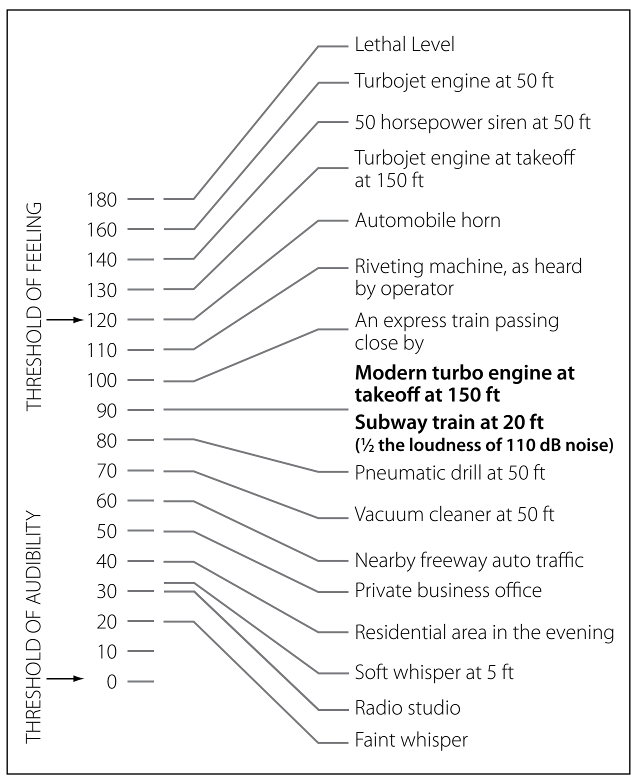

Figure 3-49. Sound intensity from different sources.

why the sound from an airplane seems different as it approaches compared to how it sounds as it flies overhead. As it approaches, it becomes both louder and higher pitched. As it flies away, the loudness and pitch both decrease noticeably.

If an airplane is flying at or higher than the speed of sound, the sound energy cannot travel out ahead of the airplane, because the airplane catches up to it the instant it tries to leave. The sound energy being created by the airplane piles up, and attaches itself to the structure of the airplane. As the airplane approaches, a person standing on the ground will not be able to hear it until it gets past their position, because the sound energy is actually trailing behind the airplane. When the sound of the airplane is heard, it will be in the form of what is called a sonic boom.

Resonance

All types of matter, regardless of whether it is a solid, liquid, or gas, have a natural frequency at which the atoms within that matter vibrate. If two pieces of matter have the same natural frequency, and one of them starts to vibrate, it can transfer its wave energy to the other one and cause it to vibrate. This transfer of energy is known as resonance. Some piston engine powered airplanes have an rpm range that they are placarded to avoid, because spinning the prop at that rpm can cause vibration problems. The difficulty lies in the natural frequency of the metal in the prop, and the frequency of vibration that will be set up with a particular tip speed for the prop. At that particular rpm, stresses can be set up that could lead to the propeller coming apart.

The Atmosphere

Aviation is so dependent upon that category of fluids called gases and the effect of forces and pressures acting upon gases, that a discussion of the subject of the atmosphere is important to the persons maintaining and repairing aircraft.

Data available about the atmosphere may determine whether a flight will succeed, or whether it will even become airborne. The various components of the air around the earth, the changes in temperatures and pressures at different levels above the earth, the properties of weather encountered by aircraft in flight, and many other detailed data are considered in the preparation of flight plans.

Pascan and Torricelli have been credited with developing the barometer, an instrument for measuring atmospheric pressure. The results of their experiments are still used today with very little improvement in design or knowledge. They determined that air has weight which changes as altitude is changed with respect to sea level. Today scientists are also interested in how the atmosphere affects the performance of the aircraft and its equipment.

Composition of the Atmosphere

The atmosphere is a complex and ever changing mixture. Its ingredients vary from place to place and from day to day. In addition to a number of gases, it contains quantities of foreign matter such as pollen, dust, bacteria, soot, volcanic ash, spores, and dust from outer space. The composition of the air remains almost constant from sea level up to its highest level, but its density diminishes rapidly with altitude. Six miles up, for example, it is too thin to support respiration, and 12 miles up, there is not enough oxygen to support combustion, except in some specially designed turbine engine powered airplanes. At a point several hundred miles above the earth, some gas particles spray out into space, some are dragged by gravity and fall back into the ocean of air below, while others never return. Physicists disagree as to the boundaries of the outer fringes of the atmosphere. Some think it begins 240 miles above the earth and extends to 400 miles; others place its lower edge at 600 miles and its upper boundary at 6,000 miles.

There are also certain nonconformities at various levels. Between 12 and 30 miles, high solar ultraviolet radiation reacts with oxygen molecules to produce a thin curtain of ozone, a very poisonous gas without which life on earth could not exist. This ozone filters out a portion of the sun's lethal ultraviolet rays, allowing only enough to come through to give us sunburn, kill bacteria, and prevent rickets. At 50 to 65 miles up, most of the oxygen molecules begin to break down under solar radiation into free atoms, and to form hydroxy ions (OH) from water vapor. Also in this region, all the atoms become ionized.

Studies of the atmosphere have revealed that the temperature does not decrease uniformly with increasing altitude; instead it gets steadily colder up to a height of about 7 miles, where the rate of temperature change slows down abruptly and remains almost constant at −55° Centigrade (218° Kelvin) up to about 20 miles. Then the temperature begins to rise to a peak value of 77° Centigrade (350° Kelvin) at the 55 mile level. Thereafter it climbs steadily, reaching 2,270° Centigrade (2,543° Kelvin) at a height of 250 to 400 miles. From the 50 mile level upward, a man or any other living creature, without the protective cover of the atmosphere, would be broiled on the side facing the sun and frozen on the other.

The atmosphere is divided into concentric layers or levels. Transition through these layers is gradual and without sharply defined boundaries. However, one boundary, the tropopause, exists between the first and second layer. The tropopause is defined as the point in the atmosphere at which the decrease in temperature (with increasing altitude) abruptly ceases. The four atmosphere layers are the troposphere, stratosphere, ionosphere, and the exosphere. The upper portion of the stratosphere is often called the chemosphere or ozonosphere, and the exosphere is also known as the mesosphere.

The troposphere extends from the earth's surface to about 35,000 ft at middle latitudes, but varies from 28,000 ft at the poles to about 54,000 ft at the equator. The troposphere is characterized by large changes in temperature and humidity and by generally turbulent conditions. Nearly all cloud formations are within the troposphere. Approximately three-fourths of the total weight of the atmosphere is within the troposphere. The stratosphere extends from the upper limits of the troposphere (and the tropopause) to an average altitude of 60 miles.

The ionosphere ranges from the 50 mile level to a level of 300 to 600 miles. Little is known about the characteristics of the ionosphere, but it is thought that many electrical phenomena occur there. Basically, this layer is characterized by the presence of ions and free electrons, and the ionization seems to increase with altitude and in successive layers.

The exosphere (or mesosphere) is the outer layer of the atmosphere. It begins at an altitude of 600 miles and extends to the limits of the atmosphere. In this layer, the temperature is fairly constant at 2,500° Kelvin, and propagation of sound is thought to be impossible due to lack of molecular substance.

Atmospheric Pressure

The human body is under pressure, since it exists at the bottom of a sea of air. This pressure is due to the weight of the atmosphere. On a standard day at sea level, if a 1-in^2 column of air extending to the top of the atmosphere was weighed, it would weigh 14.7 lb. That is why standard day atmospheric pressure is said to be 14.7 pounds per square inch (14.7 psi).

Since atmospheric pressure at any altitude is due to the weight of air above it, pressure decreases with increased altitude. Obviously, the total weight of air above an area at 15,000 ft would be less than the total weight of the air above an area at 10,000 ft.

Atmospheric pressure is often measured by a mercury barometer. A glass tube somewhat over 30 inches in length is sealed at one end and then filled with mercury. It is then inverted and the open end placed in a dish of mercury. Immediately, the mercury level in the inverted tube will drop a short distance, leaving a small volume of mercury vapor at nearly zero absolute pressure in the tube just above the top of the liquid mercury column. Gravity acting on the mercury in the tube will try to make the mercury run out. Atmospheric pressure pushing down on the mercury in the open container tries to make the mercury stay in the tube. At some point these two forces (gravity and atmospheric pressure) will equilibrate and the mercury will stabilize at a certain height in the tube. Under standard day atmospheric conditions, the air in a 1-in^2 column extending to the top of the atmosphere would weigh 14.7 lb. A 1-in^2 column of mercury, 29.92 inches tall, would also weigh 14.7 lb. That is why 14.7 psi is equal to 29.92 "Hg. Figure 3-50 demonstrates this point.

A second means of measuring atmospheric pressure is with an aneroid barometer. This mechanical instrument is a much better choice than a mercury barometer for use on airplanes. Aneroid barometers (altimeters) are used to indicate altitude in flight. The calibrations are made in thousands of feet rather than in psi or inches of mercury. For example, the standard pressure at sea

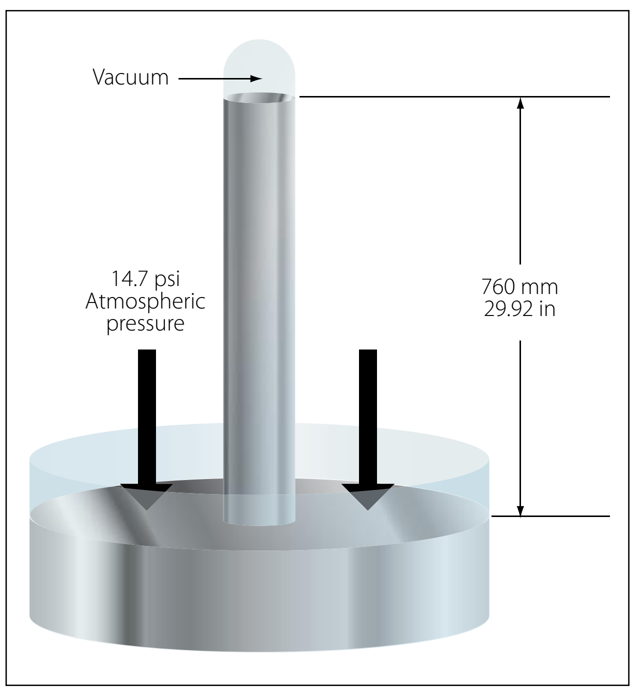

Figure 3-50. Atmospheric pressure as inches of mercury.

Figure 3-51. An airplane's altimeter is an aneroid barometer.

level is 29.92 "Hg, or 14.7 psi. At 10,000 feet above sea level, standard pressure is 20.58 "Hg, or 10.10 psi. Altimeters are calibrated so that if the pressure exerted by the atmosphere is 10.10 psi, the altimeter will point to 10,000 ft. [Figure 3-51]

Atmospheric Density

Since both temperature and pressure decrease with altitude, it might appear that the density of the atmosphere would remain fairly constant with increased altitude. This is not true, however, because pressure drops more rapidly with increased altitude than does the temperature. The result is that density decreases with increased altitude.

By use of the general gas law, studied earlier, it can be shown that for a particular gas, pressure and temperature determine the density. Since standard pressure and temperatures have been associated with each altitude, the density of the air at these standard temperatures and pressures must also be considered standard. Thus, a particular atmospheric density is associated with each altitude. This gives rise to the expression "density altitude," symbolized "Hd." A density altitude of 15,000 ft is the altitude at which the density is the same as that considered standard for 15,000 ft. Remember, however, that density altitude is not necessarily true altitude. For example, on a day when the atmospheric pressure is higher than standard and the temperature is lower than standard, the density which is standard at 10,000 ft might occur at 12,000 ft. In this case, at an actual altitude of 12,000 ft, we have air that has the same density as standard air at 10,000 ft. Density altitude is a calculated altitude obtained by correcting pressure altitude for temperature.

Water Content of the Atmosphere

In the troposphere, the air is rarely completely dry. It contains water vapor in one of two forms: (1) fog or (2) water vapor. Fog consists of minute droplets of water held in suspension by the air. Clouds are composed of fog. The height to which some clouds extend is a good indication of the presence of water in the atmosphere almost up to the stratosphere. The presence of water vapor in the air is quite evident in Figure 3-52, with a military F-18 doing a high-speed fly-by at nearly Mach 1. The temperature and pressure changes that occur as the airplane approaches supersonic flight cause the water vapor in the air to condense and form the vapor cloud that is visible.

As a result of evaporation, the atmosphere always contains some moisture in the form of water vapor. The moisture in the air is called the humidity of the air. Moisture does not consist of tiny particles of liquid held in suspension in the air as in the case of fog, but is an invisible vapor truly as gaseous as the air with which it mixes. Fog and humidity both affect the performance of an aircraft. In flight, at cruising power, the effects are small and receive no consideration. During takeoff, however, humidity has important effects. Two things are done to compensate for the effects of humidity on takeoff performance. Since humid air is less dense than dry air, the allowable takeoff gross weight of an aircraft is generally reduced for operation in areas that are

Figure 3-52. F-18 high-speed fly-by and a vapor cloud.

consistently humid. Second, because the power output of reciprocating engines is decreased by humidity, the manifold pressure may need to be increased above that recommended for takeoff in dry air in order to obtain the same power output.

Engine power output is calculated on dry air. Since water vapor is incombustible, its pressure in the atmosphere is a total loss as far as contributing to power output. The mixture of water vapor and air is drawn through the carburetor, and fuel is metered into it as though it were all air. This mixture of water vapor, air, and fuel enters the combustion chamber where it is ignited. Since the water vapor will not burn, the effective fuel/air ratio is enriched and the engine operates as though it were on an excessively rich mixture. The resulting horsepower loss under humid conditions can therefore be attributed to the loss in volumetric efficiency due to displaced air, and the incomplete combustion due to an excessively rich fuel/air mixture.

The reduction in power that can be expected from humidity is usually given in charts in the flight manual. There are several types of charts in use. Some merely show the expected reduction in power due to humidity; others show the boost in manifold pressure necessary to restore full takeoff power.

The effect of fog on the performance of an engine is very noticeable, particularly on engines with high compression ratios. Normally, some detonation will occur during acceleration, due to the high BMEP (brake mean effective pressures) developed. However, on a foggy day it is difficult to cause detonation to occur. The explanation of this lies in the fact that fog consists of particles of water that have not vaporized. When these particles enter the cylinders, they absorb a tremendous amount of heat energy in the process of vaporizing. The temperature is thus lowered, and the decrease is sufficient to prevent detonation.

Fog will generally cause a decrease in horsepower output. However, with a supercharged engine, it will be possible to use higher manifold pressures without danger of detonation.

Absolute Humidity

Absolute humidity is the actual amount of the water vapor in a mixture of air and water. It is expressed either in grams per cubic meter or pounds per cubic foot. The amount of water vapor that can be present in the air is dependent upon the temperature and pressure. The higher the temperatures, the more water vapor the air is capable of holding, assuming constant pressure. When air has all the water vapor it can hold at the prevailing temperature and pressure, it is said to be saturated.

Relative Humidity

Relative humidity is the ratio of the amount of water vapor actually present in the atmosphere to the amount that would be present if the air were saturated at the prevailing temperature and pressure. This ratio is usually multiplied by 100 and expressed as a percentage. Suppose, for example, that a weather report includes the information that the temperature is 75°F and the relative humidity is 56 percent. This indicates that the air holds 56 percent of the water vapor required to saturate it at 75°F. If the temperature drops and the absolute humidity remains constant, the relative humidity will increase. This is because less water vapor is required to saturate the air at the lower temperature.

Dew Point

The dew point is the temperature to which humid air must be cooled at constant pressure to become saturated. If the temperature drops below the dew point, condensation occurs. People who wear eyeglasses have experience going from cold outside air into a warm room and having moisture collect quickly on their glasses. This happens because the glasses were below the dew point temperature of the air in the room. The air immediately in contact with the glasses was cooled below its dew point temperature, and some of the water vapor was condensed out. This principle is applied in determining the dew point. A vessel is cooled until water vapor begins to condense on its surface. The temperature at which this occurs is the dew point.

Vapor Pressure

Vapor pressure is the portion of atmospheric pressure that is exerted by the moisture in the air (expressed in tenths of an inch of mercury). The dew point for a given condition depends on the amount of water pressure present; thus, a direct relationship exists between the vapor pressure and the dew point.

Standard Atmosphere

If the performance of an aircraft is computed, either through flight tests or wind tunnel tests, some standard reference condition must be determined first in order to compare results with those of similar tests. The conditions in the atmosphere vary continuously, and it is generally not possible to obtain exactly the same set of conditions on two different days or even on two successive flights. For this reason, a set group of standards must be used as a point of reference. The set of standard conditions presently used in the United States is known as the U.S. Standard Atmosphere.

The standard atmosphere approximates the average conditions existing at 40° latitude, and is determined on the basis of the following assumptions. The standard sea level conditions are:

Pressure at 0 altitude (P0) = 29.92 "Hg
Temperature at 0 altitude (T0) = 15°C or 59°F
Gravity at 0 altitude (G0) = 32.174 fps/s

The U.S. Standard Atmosphere is in agreement with the International Civil Aviation Organization (ICAO) Standard Atmosphere over their common altitude range. The ICAO Standard Atmosphere has been adopted as standard by most of the principal nations of the world.

Aircraft Theory of Flight

Before a technician can consider performing maintenance on an aircraft, it is necessary to understand the pieces that make up the aircraft. Names like fuselage, empennage, wing, and so many others, come into play when describing what an airplane is and how it operates. For helicopters, names like main rotor, anti-torque rotor, and autorotation come to mind as a small portion of what needs to be understood about rotorcraft. The study of physics, which includes basic aerodynamics, is a necessary part of understanding why aircraft operate the way they do.

Four Forces of Flight

During flight, there are four forces acting on an airplane. These forces are lift, weight, thrust, and drag. [Figure 3-53] Lift is the upward force created by the wing, weight is the pull of gravity on the airplane's mass, thrust is the force created by the airplane's propeller or turbine engine, and drag is the friction caused by the air flowing around the airplane.

All four of these forces are measured in pounds. Any time the forces are not in balance, something about the airplane's condition is changing. The possibilities are as follows:

1. When an airplane is accelerating, it has more thrust than drag.
2. When an airplane is decelerating, it has less thrust than drag.
3. When an airplane is at a constant velocity, thrust and drag are equal.

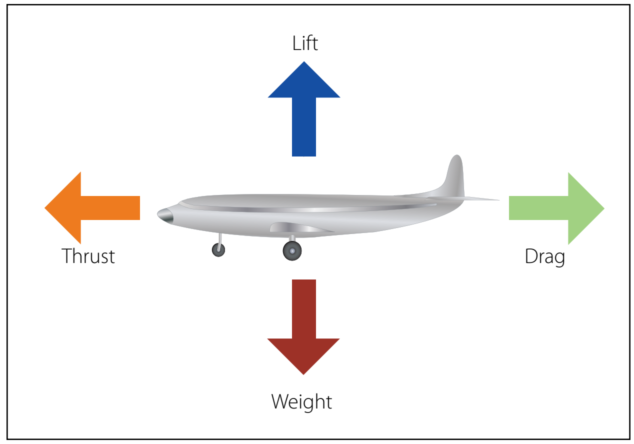

Figure 3-53. Four forces acting on an airplane.

4. When an airplane is climbing, it has more lift than weight.
5. When an airplane is descending, it has more weight than lift.
6. When an airplane is at a constant altitude, lift and weight are equal.

Bernoulli's Principle and Subsonic Flow

The basic concept of subsonic airflow and the resulting pressure differentials was discovered by Daniel Bernoulli, a Swiss physicist. Bernoulli's principle, as we refer to it today, states that "as the velocity of a fluid increases, the static pressure of that fluid will decrease, provided there is no energy added or energy taken away." A direct application of Bernoulli's principle is the study of air as it flows through either a converging or a diverging passage, and to relate the findings to some aviation concepts.

A converging shape is one whose cross-sectional area gets progressively smaller from entry to exit. A diverging shape is just the opposite, with the cross-sectional area getting larger from entry to exit. Figure 3-54 shows a converging shaped duct, with the air entering on the left at subsonic velocity and exiting on the right. Looking at the pressure and velocity gauges, and the indicated velocity and pressure, notice that the air exits at an increased velocity and a decreased static pressure. Because a unit of air must exit the duct when another unit enters, the unit leaving must increase its velocity as it flows into a smaller space.

In a diverging duct, just the opposite would happen. From the entry point to the exit point, the duct is spreading out and the area is getting larger. [Figure 3-55] With the increase in cross-sectional area, the velocity of the air decreases and the static pressure increases. The total energy in the air has not changed. What has

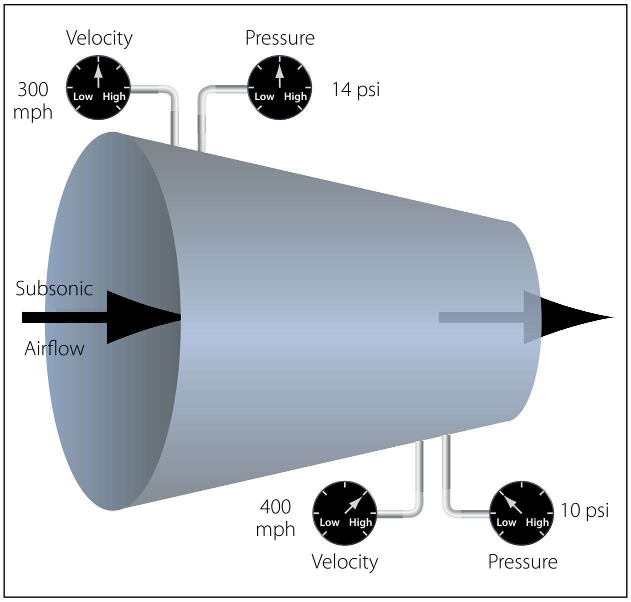

Figure 3-54. Bernoulli's principle and a converging duct.

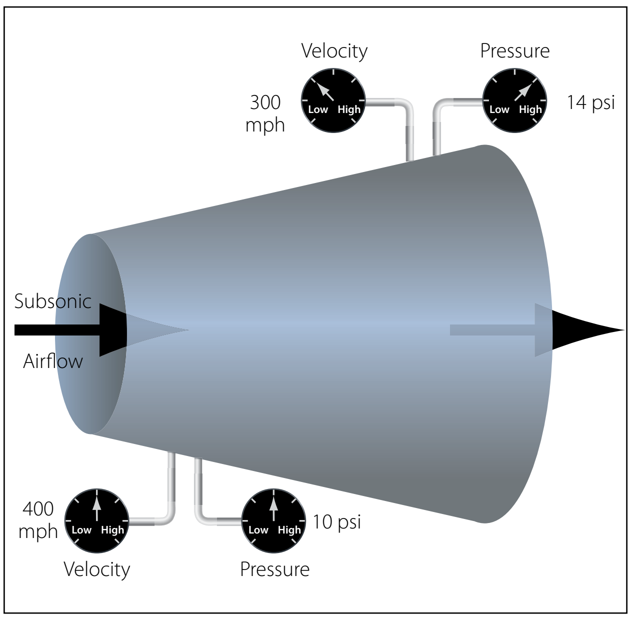

Figure 3-55. Bernoulli's principle and a diverging duct.

been lost in velocity (kinetic energy) is gained in static pressure (potential energy).

In the discussion of Bernoulli's principle earlier in this chapter, a venturi was shown in Figure 3-46. In Figure 3-56, a venturi is shown again, only this time a wing is shown tucked up into the recess where the venturi's converging shape is. There are two arrows showing airflow. The large arrow shows airflow within the venturi, and the small arrow shows airflow on the outside heading toward the leading edge of the wing.

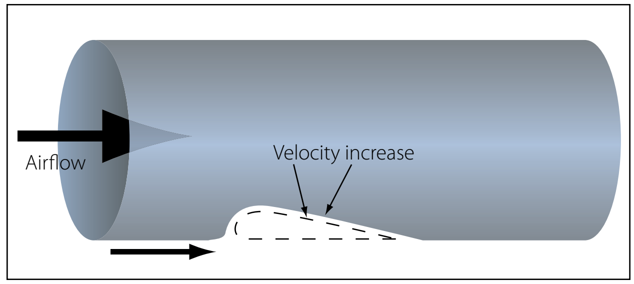

Figure 3-56. Venturi with a superimposed wing.

In the converging part of the venturi, velocity would increase and static pressure would decrease. The same thing would happen to the air flowing around the wing, with the velocity over the top increasing and static pressure decreasing.

In Figure 3-56, the air reaching the leading edge of the wing separates into two separate flows. Some of the air goes over the top of the wing and some travels along the bottom. The air going over the top, because of the curvature, has farther to travel. With a greater distance to travel, the air going over the top must move at a greater velocity. The higher velocity on the top causes the static pressure on the top to be less than it is on the bottom, and this difference in static pressures is what creates lift.

For the wing shown in Figure 3-56, imagine it is 5 ft wide and 15 ft long, for a surface area of 75 ft^2 (10,800 in^2). If the difference in static pressure between the top and bottom is 0.1 psi, there will be $^1/_{10}$ lb of lift for each square inch of surface area. Since there are 10,800 in^2 of surface area, there would be 1,080 lb of lift (0.1 × 10,800).

Lift and Newton's Third Law

Newton's third law identifies that for every force there is an equal and opposite reacting force. In addition to Bernoulli's principle, Newton's third law can also be used to explain the lift being created by a wing. As the air travels around a wing and leaves the trailing edge, the air is forced to move in a downward direction. Since a force is required to make something change direction, there must be an equal and opposite reacting force. In this case, the reacting force is what we call lift. In order to calculate lift based on Newton's third law, Newton's second law and the formula "Force = Mass × Acceleration" would be used. The mass would be the weight of air flowing over the wing every second, and the acceleration would be the change in velocity the wing imparts to the air.

The lift on the wing as described by Bernoulli's principle, and lift on the wing as described by Newton's third law, are not separate or independent of each other. They are just two different ways to describe the same thing, namely the lift on a wing.

Airfoils

An airfoil is any device that creates a force, based on Bernoulli's principles or Newton's laws, when air is caused to flow over the surface of the device. An airfoil can be the wing of an airplane, the blade of a propeller, the rotor blade of a helicopter, or the fan blade of a turbofan engine. The wing of an airplane moves through the air because the airplane is in motion, and generates lift by the process previously described. By comparison, a propeller blade, helicopter rotor blade, or turbofan engine fan blade rotates through the air. These rotating blades could be referred to as rotating wings, as is common with helicopters when they are called rotary wing aircraft. The rotating wing can be viewed as a device that creates lift, or just as correctly, it can be viewed as a device that creates thrust.

In Figure 3-57 an airfoil (wing) is shown, with some of the terminology that is used to describe a wing. The terms and their meaning are as follows:

Camber

The camber of a wing is the curvature which is present on top and bottom surfaces. The camber on the top is much more pronounced, unless the wing is a symmetrical airfoil, which has the same camber top and bottom. The bottom of the wing, more often than not, is relatively flat. The increased camber on top is what causes the velocity of the air to increase and the static pressure to decrease. The bottom of the wing has less velocity and more static pressure, which is why the wing generates lift.

Chord Line

The chord line is an imaginary straight line running from the wing's leading edge to its trailing edge. The angle between the chord line and the longitudinal axis of the airplane is known as the angle of incidence.

Relative Wind

Whatever direction the airplane is flying, the relative wind is in the opposite direction. If the airplane is flying due north, and someone in the airplane is not shielded from the elements, that person will feel like the wind is coming directly from the south.

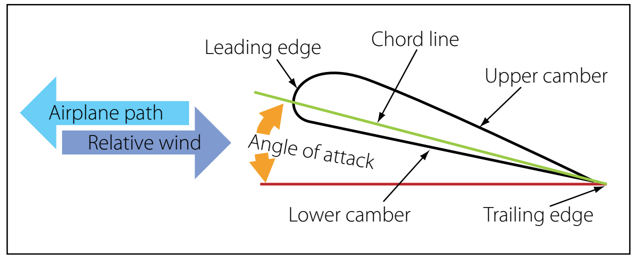

Figure 3-57. Wing terminology.

Angle of Attack

The angle between the chord line and the relative wind is the angle of attack. As the angle of attack increases, the lift on the wing increases. If the angle of attack becomes too great, the airflow can separate from the wing and the lift will be destroyed. When this occurs, a condition known as a stall takes place.

There are a number of different shapes, known as planforms, that a wing can have. A wing in the shape of a rectangle is very common on small general aviation airplanes. An elliptical shape or tapered wing can also be used, but these do not have as desirable a stall characteristic. For airplanes that operate at high subsonic speeds, sweptback wings are common, and for supersonic flight, a delta shape might be used.

The aspect ratio of a wing is the relationship between its span (wingtip to wingtip measurement) and the chord of the wing. If a wing has a long span and a very narrow chord, it is said to have a high aspect ratio. A higher aspect ratio produces less drag for a given flight speed, and is typically found on glider type aircraft.

The angle of incidence of a wing is the angle formed by the intersection of the wing chord line and the horizontal plane passing through the longitudinal axis of the aircraft. Many airplanes are designed with a greater angle of incidence at the root of the wing than at the tip, and this is referred to as washout. This feature causes the inboard part of the wing to stall before the outboard part, which helps maintain aileron control during the initial stages of a wing stall.

Boundary Layer Airflow

The boundary layer is a very thin layer of air lying over the surface of the wing and, for that matter, all other surfaces of the airplane. Because air has viscosity, this layer of air tends to adhere to the wing. As the wing moves forward through the air, the boundary layer at first flows smoothly over the streamlined shape of the airfoil. Here the flow is called the laminar layer.

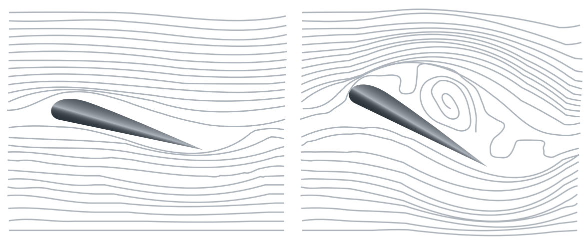

Figure 3-58. Wing boundary layer separation.

As the boundary layer approaches the center of the wing, it begins to lose speed due to skin friction and it becomes thicker and turbulent. Here it is called the turbulent layer. The point at which the boundary layer changes from laminar to turbulent is called the transition point. Where the boundary layer becomes turbulent, drag due to skin friction is relatively high. As speed increases, the transition point tends to move forward. As the angle of attack increases, the transition point also tends to move forward. With higher angles of attack and further thickening of the boundary layer, the turbulence becomes so great the air breaks away from the surface of the wing. At this point, the lift of the wing is destroyed and a condition known as a stall has occurred. In Figure 3-58, view A shows a normal angle of attack and the airflow staying in contact with the wing. View B shows an extreme angle of attack and the airflow separating and becoming turbulent on the top of the wing. In view B, the wing is in a stall.

Boundary Layer Control

One way of keeping the boundary layer air under control, or lessening its negative effect, is to make the wing's surface as smooth as possible and to keep it free of dirt and debris. As the friction between the air and the surface of the wing increases, the boundary layer thickens and becomes more turbulent and eventually a wing stall occurs. With a smooth and clean wing surface, the onset of a stall is delayed and the wing can operate at a higher angle of attack. One of the reasons ice forming on a wing can be such a serious problem is because of its effect on boundary layer air. On a high-speed airplane, even a few bugs splattered on the wing's leading edge can negatively affect boundary layer air.

Other methods of controlling boundary layer air include wing leading edge slots, air suction through small holes on the wing's upper surface, and the use of devices called vortex generators.

A wing leading edge slot is a duct that allows air to flow from the bottom of the wing, through the duct, to the top of the wing. As the air flows to the top of the wing, it is directed along the wing's surface at a high velocity and helps keep the boundary layer from becoming turbulent and separating from the wing's surface.

Another way of controlling boundary layer air is to create a suction on the top of the wing through a large number of small holes. The suction on the top of the wing draws away the slow-moving turbulent air, and helps keep the remainder of the airflow in contact with the wing.

Vortex generators are used on airplanes that fly at high subsonic speed, where the velocity of the air on the top of the wing can reach Mach 1. As the air reaches Mach 1 velocity, a shock wave forms on the top of the wing, and the subsequent shock wave causes the air to separate from the wing's upper surface. Vortex generators are short airfoils, arranged in pairs, located on the wing's upper surface. They are positioned such that they pull high-energy air down into the boundary layer region and prevent airflow separation.

Wingtip Vortices

Wingtip vortices are caused by the air beneath the wing, which is at the higher pressure, flowing over the wingtip and up toward the top of the wing. The end result is a spiral or vortex that trails behind the wingtip anytime lift is being produced. This vortex is also referred to as wake turbulence, and is a significant factor in determining how closely one airplane can follow behind another on approach to land. The wake turbulence of a large airplane can cause a smaller airplane, if it is following too closely, to be thrown out of control. Vortices from the wing and from the horizontal stabilizer are quite visible on the MD-11 shown in Figure 3-59.

Upwash and downwash refer to the effect an airfoil has on the free airstream. Upwash is the deflection of the oncoming airstream, causing it to flow up and over the wing. Downwash is the downward deflection of the airstream after it has passed over the wing and is leaving the trailing edge. This downward deflection is what creates the action and reaction described under lift and Newton's third law.

Axes of an Aircraft

An airplane in flight is controlled around one or more of three axes of rotation. These axes of rotation are the longitudinal, lateral, and vertical. On the airplane, all three axes intersect at the center of gravity (CG). As the airplane pivots on one of these axes, it is in essence

Figure 3-59. Wing and horizontal stabilizer vortices on an MD-11.

pivoting around the center of gravity (CG). The center of gravity is also referred to as the center of rotation.

On the brightly colored airplane shown in Figure 3-60, the three axes are shown in the colors red (vertical axis), blue (longitudinal axis), and orange (lateral axis). The flight control that makes the airplane move around the axis is shown in a matching color.

The rudder, in red, causes the airplane to move around the vertical axis and this movement is described as being a yaw. The elevator, in orange, causes the airplane to move around the lateral axis and this movement is described as being a pitch. The ailerons, in blue, cause the airplane to move around the longitudinal axis and this movement is described as being a roll.

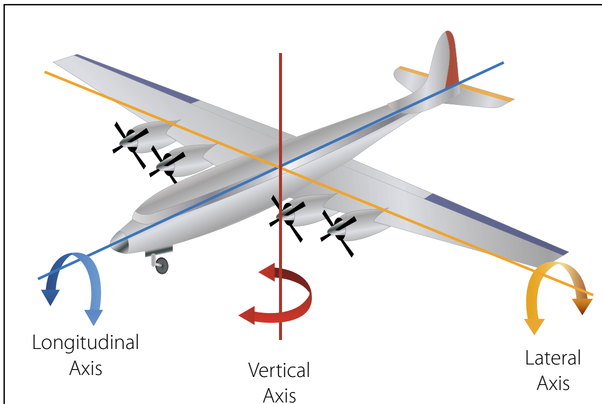

Figure 3-60. The three axes of an airplane.

Aircraft Stability

When an airplane is in straight-and-level flight at a constant velocity, all the forces acting on the airplane are in equilibrium. If that straight-and-level flight is disrupted by a disturbance in the air, such as wake turbulence, the airplane might pitch up or down, yaw left or right, or go into a roll. If the airplane has what is characterized as stability, once the disturbance goes away, the airplane will return to a state of equilibrium.

Static Stability

The initial response that an airplane displays after its equilibrium is disrupted is referred to as its static stability. If the static stability is positive, the airplane will tend to return to its original position after the disruptive force is removed. If the static stability is negative, the airplane will continue to move away from its original position after the disruptive force is removed. If an airplane with negative static stability has the nose pitch up because of wake turbulence, the tendency will be for the nose to continue to pitch up even after the turbulence goes away. If an airplane tends to remain in a displaced position after the force is removed, but does not continue to move toward even greater displacement, its static stability is described as being neutral.

Dynamic Stability

The dynamic stability of an airplane involves the amount of time it takes for it to react to its static stability after it has been displaced from a condition of equilibrium. Dynamic stability involves the oscillations that typically occur as the airplane tries to return to its original position or attitude. Even though an airplane may have positive static stability, it may have dynamic stability which is positive, neutral, or negative.

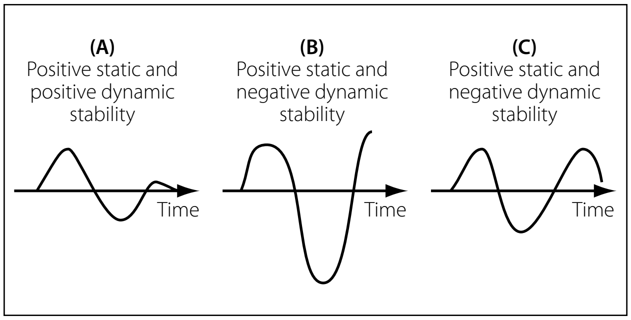

Figure 3-61. Dynamic stability.

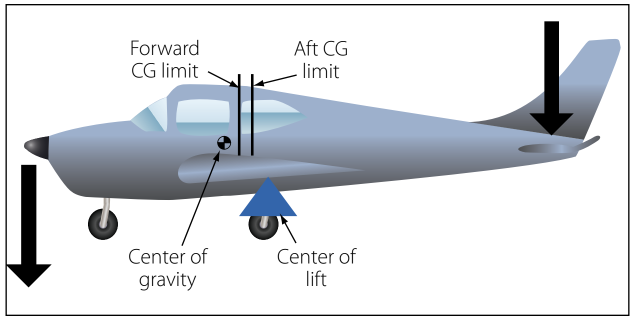

Figure 3-62. Longitudinal stability and balance.

Imagine that an airplane in straight-and-level flight is disturbed and pitches nose up. If the airplane has positive static stability, the nose will pitch back down after the disturbance is removed. If it immediately returns to straight-and-level flight, it is also said to have positive dynamic stability. The airplane, however, may pass through level flight and remain pitched down, and then continue the recovery process by pitching back up. This pitching up and then down is known as an oscillation. If the oscillations lessen over time, the airplane is still classified as having positive dynamic stability. If the oscillations increase over time, the airplane is classified as having negative dynamic stability. If the oscillations remain the same over time, the airplane is classified as having neutral dynamic stability.

Figure 3-61 shows the concept of dynamic stability. In view A, the displacement from equilibrium goes through three oscillations and then returns to equilibrium. In view B, the displacement from equilibrium is increasing after two oscillations, and will not return to equilibrium. In view C, the displacement from equilibrium is staying the same with each oscillation.

Longitudinal Stability

Longitudinal stability for an airplane involves the tendency for the nose to pitch up or pitch down, rotating around the lateral axis (wingtip to wingtip). If an airplane is longitudinally stable, it will return to a properly trimmed angle of attack after the force that upset its flightpath is removed.

The weight and balance of an airplane, which is based on both the design characteristics of the airplane and the way it is loaded, is a major factor in determining longitudinal stability. There is a point on the wing of an airplane, called the center of pressure or center of lift, where all the lifting forces concentrate. In flight, the airplane acts like it is being lifted from or supported by this point. This center of lift runs from wingtip to wingtip. There is also a point on the airplane, called the center of gravity, where the mass or weight of the airplane is concentrated. For an airplane to have good longitudinal stability, the center of gravity is typically located forward of the center of lift. This gives the airplane a nose-down pitching tendency, which is balanced out by the force generated at the horizontal stabilizer and elevator. The center of gravity has limits within which it must fall. If it is too far forward, the forces at the tail might not be able to compensate and it may not be possible to keep the nose of the airplane from pitching down.

In Figure 3-62, the center of lift, center of gravity, and center of gravity limits are shown. It can be seen that the center of gravity is not only forward of the center of lift, it is also forward of the center of gravity limit. At the back of the airplane, the elevator trailing edge is deflected upward to create a downward force on the tail, to try and keep the nose of the airplane up. This airplane would be highly unstable longitudinally, especially at low speed when trying to land. It is especially dangerous if the center of gravity is behind the aft limit. The airplane will now have a tendency to pitch nose up, which can lead to the wing stalling and possible loss of control of the airplane.

Lateral Stability

Lateral stability of an airplane takes place around the longitudinal axis, which is from the airplane's nose to its tail. If one wing is lower than the other, good lateral stability will tend to bring the wings back to a level flight attitude. One design characteristic that tends to give an airplane good lateral stability is called dihedral. Dihedral is an upward angle for the wings with respect to the horizontal, and it is usually just a few degrees.

Imagine a low wing airplane with a few degrees of dihedral experiencing a disruption of its flightpath such that the left wing drops. When the left wing drops, this will cause the airplane to experience a sideslip toward the low wing. The sideslip causes the low wing to experience a higher angle of attack, which increases

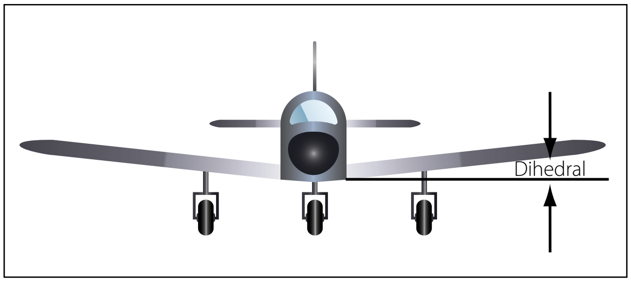

Figure 3-63. The dihedral of a wing.

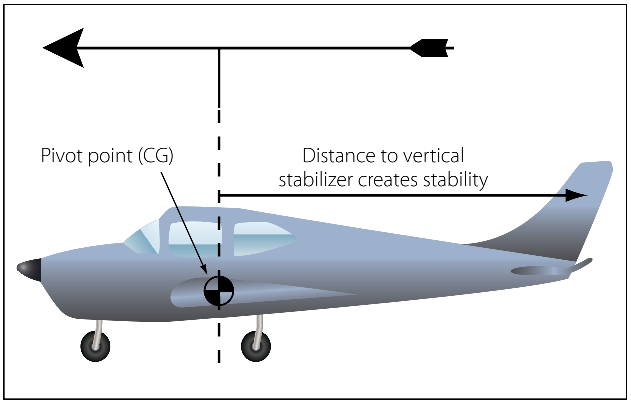

Figure 3-64. Directional stability caused by distance to vertical stabilizer.

its lift and raises it back to a level flight attitude. The dihedral on a wing is shown in Figure 3-63.

Directional Stability

Movement of the airplane around its vertical axis, and the airplane's ability to not be adversely affected by a force creating a yaw type of motion, is called directional stability. The vertical fin gives the airplane this stability, causing the airplane to align with the relative wind. In flight, the airplane acts like the weather vane we use around our home to show the direction the wind is blowing. The distance from the pivot point on a weather vane to its tail is greater than the distance from its pivot point to the nose. So when the wind blows, it creates a greater torque force on the tail and forces it to align with the wind. On an airplane, the same is true. With the CG being the pivot point, it is a greater distance from the CG to the vertical stabilizer than it is from the CG to the nose. [Figure 3-64]

Dutch Roll

The dihedral of the wing tries to roll the airplane in the opposite direction of how it is slipping, and the vertical fin will try to yaw the airplane in the direction of the slip. These two events combine in a way that affects lateral and directional stability. If the wing dihedral has the greatest effect, the airplane will have a tendency to experience a Dutch roll. A Dutch roll is a small amount of oscillation around both the longitudinal and vertical axes. Although this condition is not considered dangerous, it can produce an uncomfortable feeling for passengers. Commercial airliners typically have yaw dampers that sense a Dutch roll condition and cancel it out.

Flight Control Surfaces

The purpose of flight controls is to allow the pilot to maneuver the airplane, and to control it from the time it starts the takeoff roll until it lands and safely comes to a halt. Flight controls are typically associated with the wing and the vertical and horizontal stabilizers, because these are the parts of the airplane that flight controls most often attach to. In flight, and to some extent on the ground, flight controls provide the airplane with the ability to move around one or more of the three axes. Flight controls function by changing the shape or aerodynamic characteristics of the surface they are attached to.

Flight Controls and the Lateral Axis

The lateral axis of an airplane is a line that runs below the wing, from wingtip to wingtip, passing through the airplane's center of gravity. Movement around this axis is called pitch, and control around this axis is called longitudinal control. The flight control that handles this job is the elevator attached to the horizontal stabilizer, a fully moving horizontal stabilizer, or on a v-tail configured airplane, it is called ruddervators. An elevator on a Cessna 182 can be seen in Figure 3-65. In Figure 3-66, a fully moving horizontal stabilizer, known as a stabilator, can be seen on a Piper Cherokee Arrow, and Figure 3-67 shows a ruddervator on a Beechcraft Bonanza.

Depending on the airplane being discussed, movement around the lateral axis happens as a result of the pilot moving the control wheel or yoke, the control stick,

Figure 3-65. Elevator on a Cessna 182 provides pitch control.

Figure 3-66. Moving horizontal stabilizer, known as a stabilator, on a Piper Cherokee Arrow provides pitch control.

Figure 3-67. Ruddervators on a Beechcraft Bonanza provide pitch control.

Figure 3-68. Cessna 182 control wheel and rudder pedals.

or on some airplanes, a side stick. On the airplanes shown in Figures 3-65, 3-66, and 3-67, a control wheel or yoke is used.

On the Cessna 182 shown in Figure 3-65, pulling back on the control wheel causes the trailing edge of the elevator to deflect upward, causing an increased downward force that raises the nose of the airplane. Movement of the elevator causes the nose of the airplane to pitch up or pitch down by rotating around the lateral axis. The Cessna 182 control wheel can be seen in Figure 3-68.

On the Piper Cherokee Arrow shown in Figure 3-66, pulling back on the control wheel causes the entire horizontal surface (stabilator) to move, with the trailing edge deflecting upward. The anti-servo tab seen on the Cherokee provides a control feel similar to what would be experienced by moving an elevator. Without this tab, the stabilator might be too easy to move and a pilot could overcontrol the airplane.

The ruddervators shown on the Beechcraft Bonanza in Figure 3-67 are also moved by the control wheel, with their trailing edges deflecting upward when the control wheel is pulled back. As the name implies, these surfaces also act as the rudder for this airplane.

Flight Controls and the Longitudinal Axis

The longitudinal axis of the airplane runs through the middle of the airplane, from nose to tail, passing through the center of gravity. Movement around this axis is known as roll, and control around this axis is called lateral control. Movement around this axis is controlled by the ailerons, and on jet transport airplanes, it is aided by surfaces on the wing known as spoilers.

The ailerons move as a result of the pilot rotating the control wheel to the left or to the right, much the same as turning the steering wheel on an automobile. [Figure 3-68] When a pilot turns the control wheel to the left, the airplane is being asked to turn or bank to the left. Turning the control wheel to the left causes the trailing edge of the aileron on the left wing to rise up into the airstream, and the aileron on the right wing lowers down into the airstream. This increases the lift on the right wing and decreases the lift on the left wing, causing the right wing to move up and the airplane to bank to the left.

In Figure 3-69, an Air Force F-15 can be seen doing an aileron roll. Notice that the left aileron is up and the right aileron is down, which would cause the airplane to roll around the longitudinal axis in a counterclockwise direction.

Flight Controls and the Vertical Axis

The vertical axis of an airplane runs from top to bottom through the middle of the airplane, passing through the center of gravity. Movement around this axis is known as yaw, and control around this axis is called directional control. Movement around this axis is controlled by the rudder, or in the case of the Beechcraft Bonanza in Figure 3-67, by the ruddervators.

Figure 3-69. Air Force F-15 doing an aileron roll.

The feet of the pilot are on the rudder pedals, and pushing on the left or right rudder pedal makes the rudder move left or right. When the right rudder pedal is pushed, the trailing edge of the rudder moves to the right, and the nose of the airplane yaws to the right. The rudder pedals of a Cessna 182 can be seen in Figure 3-68.

Even though the rudder of the airplane will make the nose yaw to the left or the right, the rudder is not what turns the airplane. For what is called a coordinated turn to occur, both the ailerons and rudder come into play. Let's say we want to turn the airplane to the right. We start by turning the control wheel to the right, which raises the right aileron and lowers the left aileron and initiates the banking turn. The increased lift on the left wing also increases the induced drag on the left wing, which tries to make the nose of the airplane yaw to the left. To counteract this, when the control wheel is moved to the right, a small amount of right rudder is used to keep the nose of the airplane from yawing to the left. Once the nose of the airplane is pointing in the right direction, pressure on the rudder is no longer needed. The rudder of a Piper Cherokee Arrow can be seen in Figure 3-70.

Figure 3-70. Rudder on a Piper Cherokee Arrow.

Tabs

Trim Tabs

Trim tabs are small movable surfaces that attach to the trailing edge of flight controls. These tabs can be controlled from the flight deck, and their purpose is to create an aerodynamic force that keeps the flight control in a deflected position. Trim tabs can be installed on any of the primary flight controls.

A very common flight control to find fitted with a trim tab is the elevator. In order to be stable in flight, most airplanes have the center of gravity located forward of the center of lift on the wing. This causes a nose heavy condition, which needs to be balanced out by having the elevator deflect upwards and create a downward force. To relieve the pilot of the need to hold back pressure on the control wheel, a trim tab on the elevator can be adjusted to hold the elevator in a slightly deflected position. An elevator trim tab for a Cessna 182 is shown in Figure 3-71.

Anti-servo Tab

Some airplanes, like a Piper Cherokee Arrow, do not have a fixed horizontal stabilizer and movable elevator. The Cherokee uses a moving horizontal surface known as a stabilator. Because of the location of the pivot point for this movable surface, it has a tendency to be extremely sensitive to pilot input. To reduce the sensitivity, a full length anti-servo tab is installed on the trailing edge of the stabilator. As the trailing edge of the stabilator moves down, the anti-servo tab moves down and creates a force trying to raise the trailing edge. With this force acting against the movement of the stabilator, it reduces the sensitivity to pilot input. The anti-servo tab on a Piper Cherokee Arrow is shown in Figure 3-70.

Figure 3-71. Elevator trim tab on a Cessna 182.

Balance Tab

On some airplanes, the force needed to move the flight controls can be excessive. In these cases, a balance tab can be used to generate a force that assists in the movement of the flight control. Just the opposite of anti-servo tabs, balance tabs move in the opposite direction of the flight control's trailing edge, providing a force that helps the flight control move.

Servo Tab

On large airplanes, because the force needed to move the flight controls is beyond the capability of the pilot, hydraulic actuators are used to provide the necessary force. In the event of a hydraulic system malfunction or failure, some of these airplanes have servo tabs on the trailing edge of the primary flight controls. When the control wheel is pulled back in an attempt to move the elevator, the servo tab moves and creates enough aerodynamic force to move the elevator. The servo tab is acting like a balance tab, but rather than assisting the normal force that moves the elevator, it becomes the sole force that makes the elevator move. Like the balance tab, the servo tab moves in the opposite direction of the flight control's trailing edge. The Boeing 727 has servo tabs that back up the hydraulic system in the event of a failure. During normal flight, the servo tabs act like balance tabs. [Figure 3-73]

Supplemental Lift-Modifying Devices

If the wing of an airplane was designed to produce the maximum lift possible at low airspeed, to accommodate takeoffs and landings, it would not be suited for higher speed flight because of the enormous amount of drag it would produce. To give the wing the ability to produce maximum low speed lift without being drag prohibitive, retractable high lift devices, such as flaps and slats, are utilized.

Flaps

The most often used lift-modifying device, for small airplanes and large, is the wing flap. Flaps can be installed on the leading edge or trailing edge, with the leading edge versions used only on larger airplanes. Flaps change the camber of the wing, and they increase both the lift and the drag for any given angle of attack. The four different types of flaps in use are the plain, split, slotted, and Fowler. [Figure 3-72]

Plain flaps attach to the trailing edge of the wing, inboard of the ailerons, and form part of the wing's overall surface. When deployed downward, they increase the effective camber of the wing and the wing's chord line. Both of these factors cause the wing to create more lift and more drag.

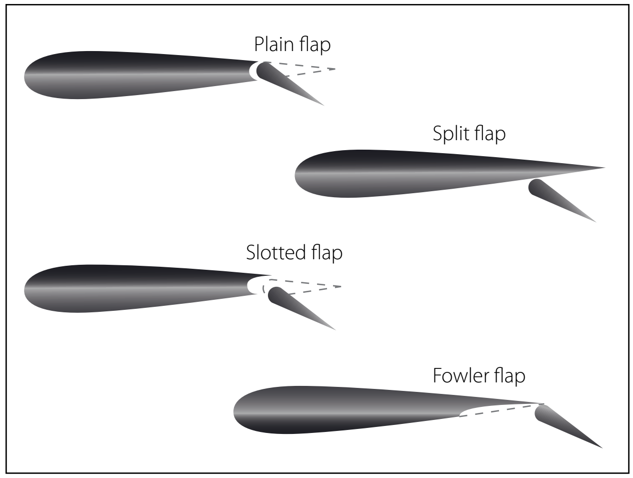

Figure 3-72. Four types of wing flaps.

The split flap attaches to the bottom of the wing, and deploys downward without changing the top surface of the wing. This type of flap creates more drag than the plain flap because of the increase in turbulence.

The slotted flap is similar to the plain flap, except when it deploys, the leading edge drops down a small amount. By having the leading edge drop down slightly, a slot opens up, which lets some of the high pressure air on the bottom of the wing flow over the top of the flap. This additional airflow over the top of the flap produces additional lift.

The Fowler flap attaches to the back of the wing using a track and roller system. When it deploys, it moves aft in addition to deflecting downward. This increases the total wing area, in addition to increasing the wing camber and chord line. This type of flap is the most effective of the four types, and it is the type used on commercial airliners and business jets.

Leading Edge Slots

Leading edge slots are ducts or passages in the leading edge of a wing that allow high pressure air from the bottom of the wing to flow to the top of the wing. This ducted air flows over the top of the wing at a high velocity and helps keep the boundary layer air from becoming turbulent and separating from the wing. Slots are often placed on the part of the wing ahead of the ailerons, so during a wing stall, the inboard part of the wing stalls first and the ailerons remain effective.

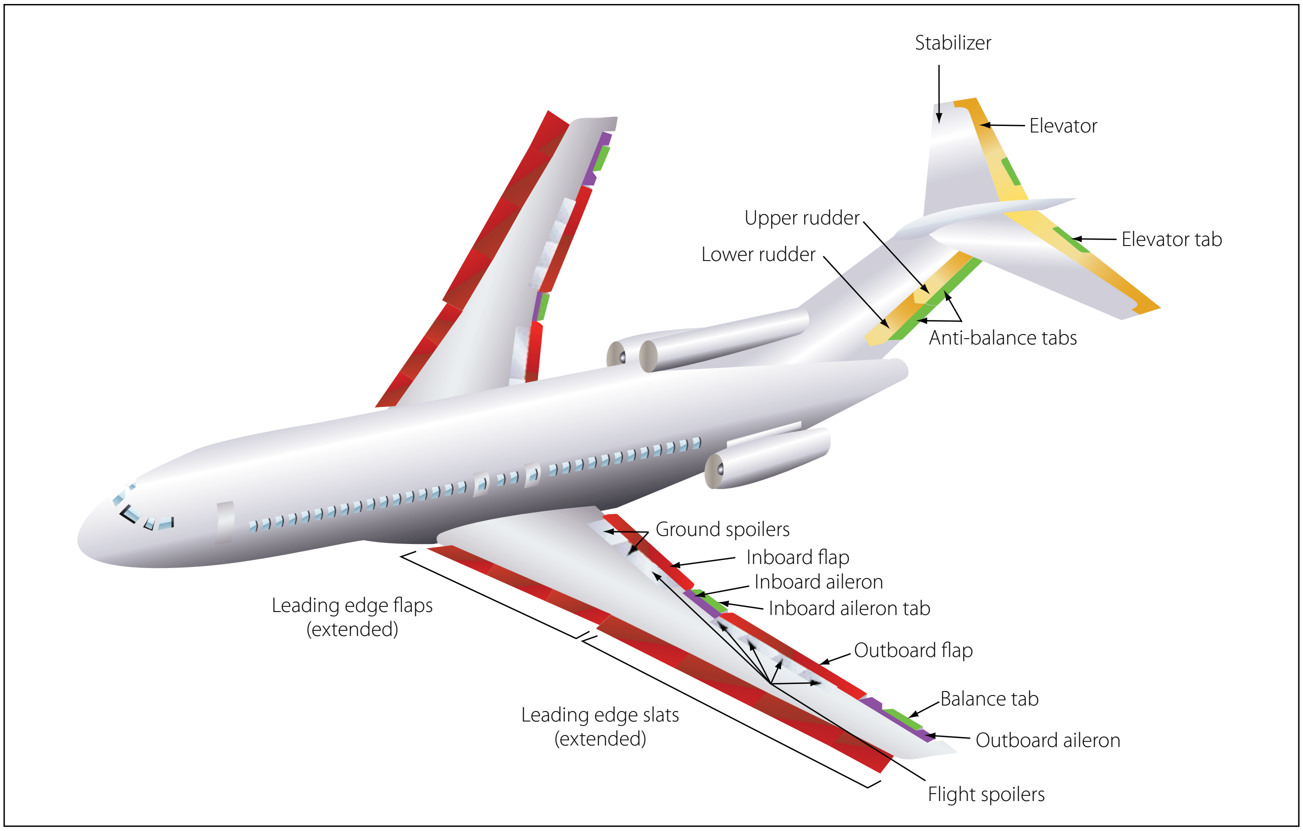

Figure 3-73. Boeing 727 flight controls.

Leading Edge Slats

Leading edge slats serve the same purpose as slots, the difference being that slats are movable and can be retracted when not needed. On some airplanes, leading edge slats have been automatic in operation, deploying in response to the aerodynamic forces that come into play during a high angle of attack. On most of today's commercial airliners, the leading edge slats deploy when the trailing edge flaps are lowered.

The flight controls of a large commercial airliner are shown in Figure 3-73. The controls by color are as follows:

1. All aerodynamic tabs are shown in green.
2. All leading and trailing edge high lift devices are shown in red (leading edge flaps and slats, trailing edge inboard and outboard flaps).
3. The tail mounted primary flight controls are in yellow (rudder and elevator).
4. The wing mounted primary flight controls are in purple (inboard and outboard aileron).

High-Speed Aerodynamics

Compressibility Effects

When air is flowing at subsonic speed, it acts like an incompressible fluid. As discussed earlier in this chapter, when air at subsonic speed flows through a diverging shaped passage, the velocity decreases and the static pressure rises, but the density of the air does not change. In a converging shaped passage, subsonic air speeds up and its static pressure decreases. When supersonic air flows through a converging passage, its velocity decreases and its pressure and density both increase. [Figure 3-74] At supersonic flow, air acts like a compressible fluid. Because air behaves differently

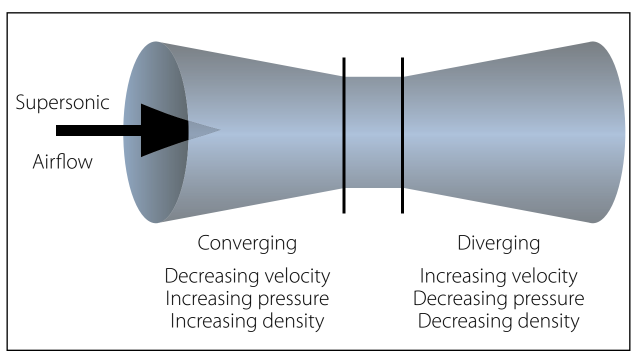

Figure 3-74. Supersonic airflow through a venturi.

when flowing at supersonic velocity, airplanes that fly supersonic must have wings with a different shape.

The Speed of Sound

Sound, in reference to airplanes and their movement through the air, is nothing more than pressure disturbances in the air. As discussed earlier in this chapter, it is like dropping a rock in the water and watching the waves flow out from the center. As an airplane flies through the air, every point on the airplane that causes a disturbance creates sound energy in the form of pressure waves. These pressure waves flow away from the airplane at the speed of sound, which at standard day temperature of 59°F, is 761 mph. The speed of sound in air changes with temperature, increasing as temperature increases. Figure 3-75 shows how the speed of sound changes with altitude.

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

* Altitude at which temperature stops decreasing

Figure 3-75. Altitude and temperature versus speed of sound.

Subsonic, Transonic, and Supersonic Flight

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

When an airplane is flying at transonic speed, part of the airplane is experiencing subsonic airflow and part is experiencing supersonic airflow. Over the top of the wing, probably about halfway back, the velocity of the air will reach Mach 1 and a shock wave will form. The shock wave forms 90 degrees to the airflow and is known as a normal shock wave. Stability problems can be encountered during transonic flight, because the shock wave can cause the airflow to separate from the wing. The shock wave also causes the center of lift to shift aft, causing the nose to pitch down. The speed at which the shock wave forms is known as the critical Mach number. Transonic speed is typically between Mach 0.80 and 1.20.

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

Shock Waves

Sound coming from an airplane is the result of the air being disturbed as the airplane moves through it, and the resulting pressure waves that radiate out from the source of the disturbance. For a slow moving airplane, the pressure waves travel out ahead of the airplane, traveling at the speed of sound. When the speed of the airplane reaches the speed of sound, however, the pressure waves (sound energy) cannot get away from the airplane. At this point the sound energy starts to pile up, initially on the top of the wing, and eventually attaching itself to the wing leading and trailing edges. This piling up of sound energy is called a shock wave. If the shock waves reach the ground, and cross the path of a person, they will be heard as a sonic boom. Figure 3-76A shows a wing in slow speed flight, with many

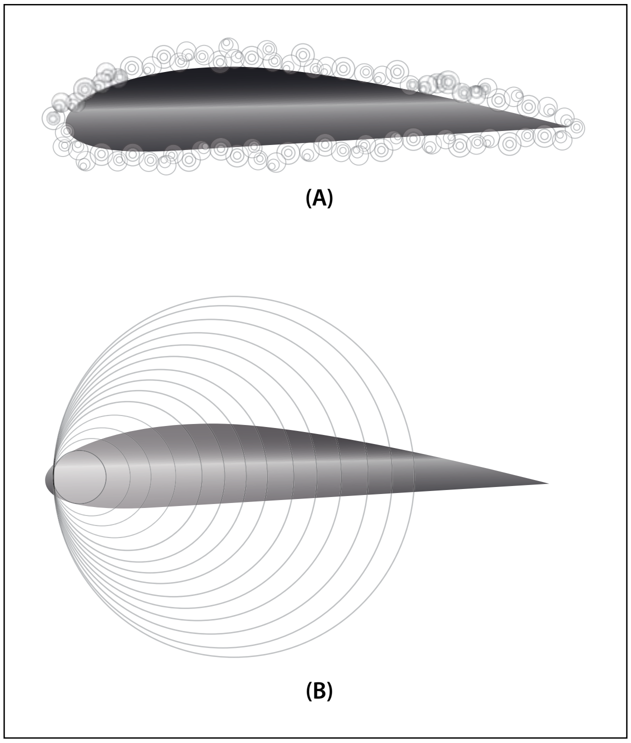

Figure 3-76. Sound energy in subsonic and supersonic flight.

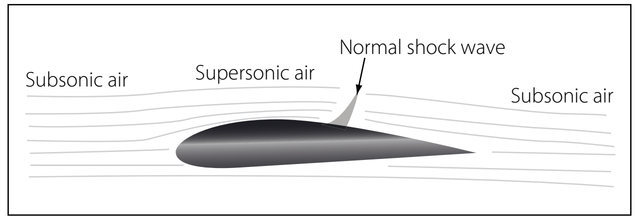

Figure 3-77. Normal shock wave.

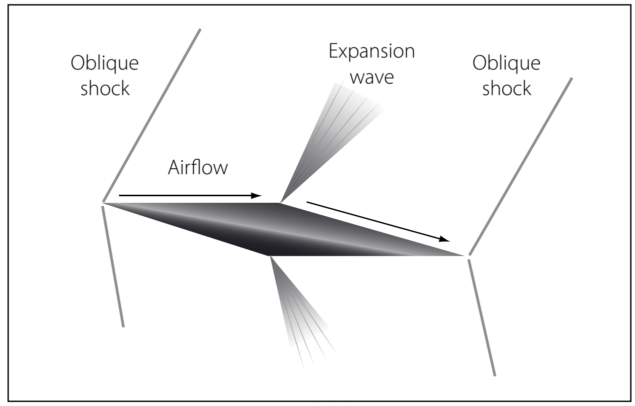

Figure 3-78. Supersonic airfoil with oblique shock waves and expansion waves.

disturbances on the wing generating sound pressure waves that are radiating outward. View B is the wing of an airplane in supersonic flight, with the sound pressure waves piling up toward the wing leading edge.

Normal Shock Wave

When an airplane is in transonic flight, the shock wave that forms on top of the wing, and eventually on the bottom of the wing, is called a normal shock wave. If the leading edge of the wing is blunted, instead of being rounded or sharp, a normal shock wave will also form in front of the wing during supersonic flight. Normal shock waves form perpendicular to the airstream. The velocity of the air behind a normal shock wave is subsonic, and the static pressure and density of the air are higher. Figure 3-77 shows a normal shock wave forming on the top of a wing.

Oblique Shock Wave

An airplane that is designed to fly supersonic will have very sharp edged surfaces, in order to have the least amount of drag. When the airplane is in supersonic flight, the sharp leading edge and trailing edge of the wing will have shock waves attach to them. These shock waves are known as oblique shock waves. Behind an oblique shock wave the velocity of the air is lower, but still supersonic, and the static pressure and density are higher. Figure 3-78 shows an oblique shock wave on the leading and trailing edges of a supersonic airfoil.

Expansion Wave

Earlier in the discussion of high-speed aerodynamics, it was stated that air at supersonic speed acts like a compressible fluid. For this reason, supersonic air, when given the opportunity, wants to expand outward. When supersonic air is flowing over the top of a wing, and the wing surface turns away from the direction of flow, the air will expand and follow the new direction. At the point where the direction of flow changes, an expansion wave will occur. Behind the expansion wave the velocity increases, and the static pressure and density decrease. An expansion wave is not a shock wave. Figure 3-78 shows an expansion wave on a supersonic airfoil.

High-Speed Airfoils

Transonic flight is the most difficult flight regime for an airplane, because part of the wing is experiencing subsonic airflow and part is experiencing supersonic airflow. For a subsonic airfoil, the aerodynamic center (the point of support) is approximately 25 percent of the way back from the wing leading edge. In supersonic flight, the aerodynamic center moves back to 50 percent of the wing's chord, causing some significant changes in the airplane's control and stability.

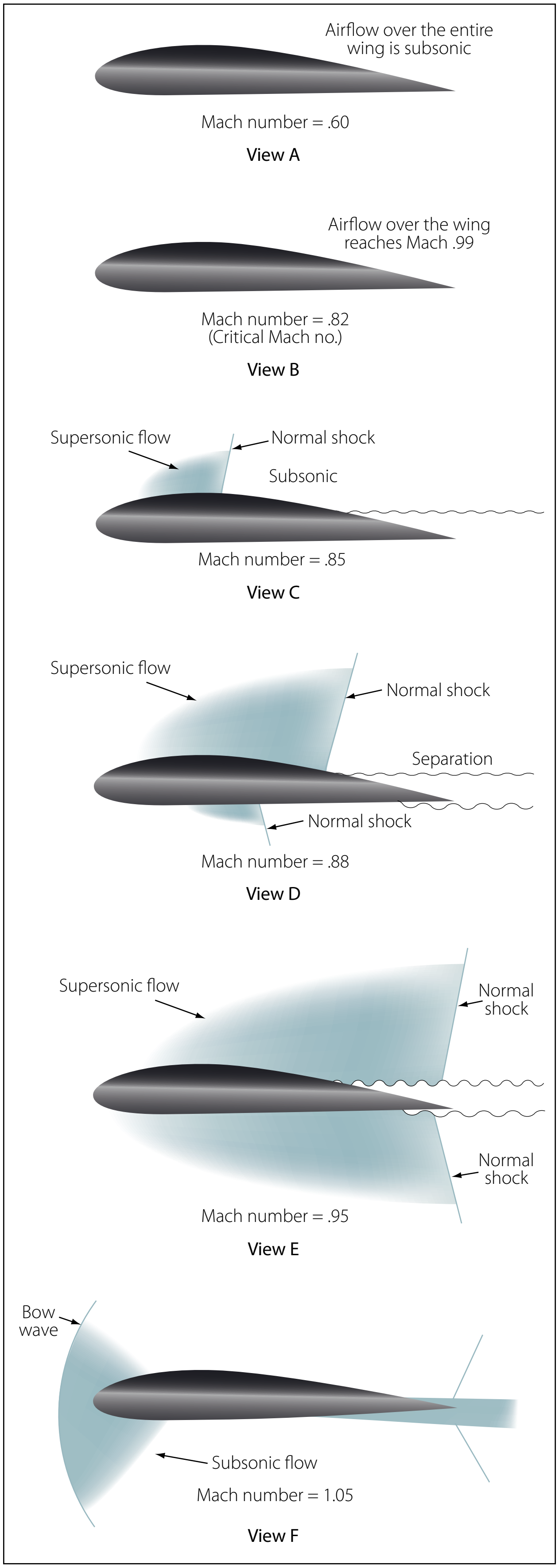

Figure 3-79. Airflow with progressively greater Mach numbers.

If an airplane designed to fly subsonic, perhaps at a Mach number of 0.80, flies too fast and enters transonic flight, some noticeable changes will take place with respect to the airflow over the wing. Figure 3-79 shows six views of a wing, with each view showing the Mach number getting higher. The scenario for the six views is as follows:

A. The Mach number is fairly low, and the entire wing is experiencing subsonic airflow.

B. The velocity has reached the critical Mach number, where the airflow over the top of the wing is reaching Mach 1 velocity.

C. The velocity has surpassed the critical Mach number, and a normal shock wave has formed on the top of the wing. Some airflow separation starts to occur behind the shock wave.

D. The velocity has continued to increase beyond the critical Mach number, and the normal shock wave has moved far enough aft that serious airflow separation is occurring. A normal shock wave is now forming on the bottom of the wing as well. Behind the normal shock waves, the velocity of the air is subsonic and the static pressure has increased.

E. The velocity has increased to the point that both shock waves on the wing (top and bottom) have moved to the back of the wing and attached to the trailing edge. Some airflow separation is still occurring.

F. The forward velocity of the airfoil is greater than Mach 1, and a new shock wave has formed just forward of the leading edge of the wing. If the wing has a sharp leading edge, the shock wave will attach itself to the sharp edge.

The airfoil shown in Figure 3-79 is not properly designed to handle supersonic airflow. The bow wave in front of the wing leading edge of view F would be attached to the leading edge, if the wing was a double wedge or biconvex design. These two wing designs are shown in Figure 3-80.

Aerodynamic Heating

One of the problems with airplanes and high-speed flight is the heat that builds up on the airplane's surface because of air friction. When the SR-71 Blackbird airplane is cruising at Mach 3.5, skin temperatures on its surface range from 450°F to over 1,000°F. To withstand this high temperature, the airplane was constructed of titanium alloy, instead of the traditional alu-

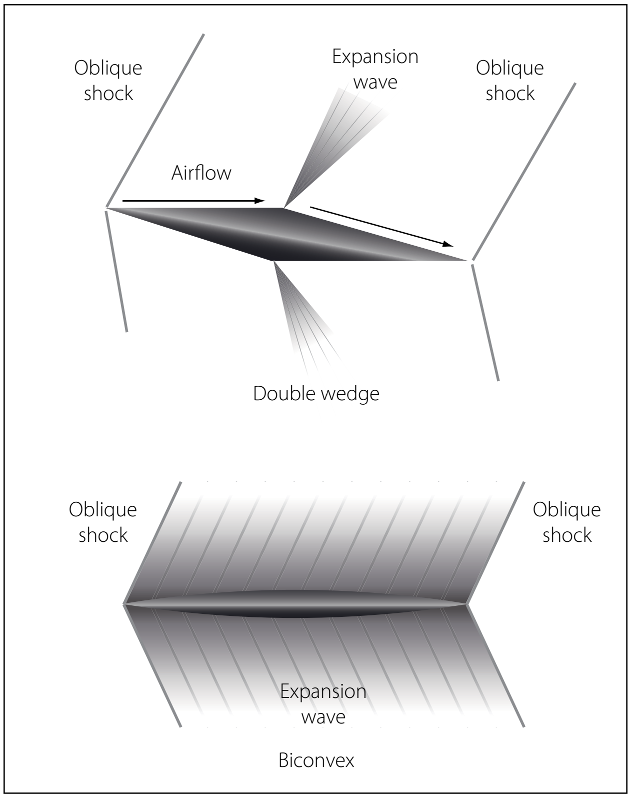

Figure 3-80. Double wedge and biconvex supersonic wing design.

minum alloy. The supersonic transport Concorde was originally designed to cruise at Mach 2.2, but its cruise speed was reduced to Mach 2.0 because of structural problems that started to occur because of aerodynamic heating. If airplanes capable of hypersonic flight are going to be built in the future, one of the obstacles that will have to be overcome is the stress on the airplane's structure caused by heat.

Helicopter Aerodynamics

The helicopter, as we know it today, falls under the classification known as rotorcraft. Rotorcraft are also known as rotary wing aircraft, because instead of their wing being fixed like it is on an airplane, the wing rotates. The rotating wing of a rotorcraft can be thought of as a lift producing device, like the wing of an airplane, or as a thrust producing device, like the propeller on a piston engine.

Helicopter Structures and Airfoils

The main parts that make up a helicopter are the cabin, landing gear, tail boom, powerplant, transmission, main rotor, and tail rotor. [Figure 3-81]

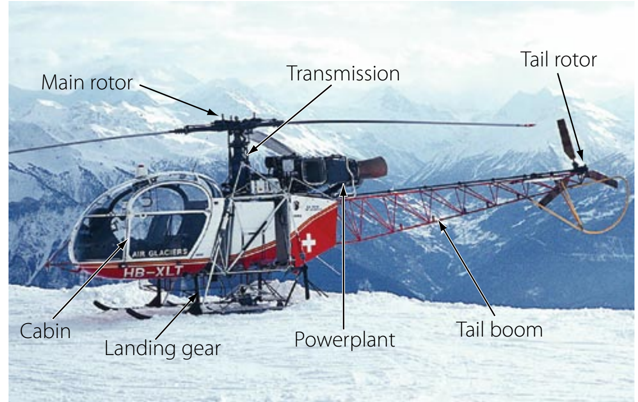

Figure 3-81. Main components of a helicopter.

Main Rotor Systems

The classification of main rotor systems is based on how the blades move relative to the main rotor hub. The principal classifications are known as fully articulated, semi-rigid, and rigid.

In the fully articulated rotor system, the blades are attached to the hub with multiple hinges. The blades are hinged in a way that allows them to move up and down and fore and aft, and bearings provide for motion around the pitch change axis. Rotor systems using this type of arrangement typically have three or more blades. The hinge that allows the blades to move up and down is called the flap hinge, and movement around this hinge is called flap. The hinge that allows the blades to move fore and aft is called a drag or lag hinge. Movement around this hinge is called dragging, lead/lag, or hunting. These hinges and their associated movement are shown in Figure 3-82. The main rotor head of a Eurocopter model 725 is shown in Figure 3-83, with the drag hinge and pitch change rods visible.

The semi-rigid rotor system is used with a two blade main rotor. The blades are rigidly attached to the hub, with the hub and blades able to teeter like a seesaw. The teetering action allows the blades to flap, with one blade dropping down while the other blade rises. The blades are able to change pitch independently of each other. Figure 3-84 shows a Bell Jet Ranger helicopter in flight. This helicopter uses a semi-rigid rotor system, which is evident because of the way the rotor is tilted forward when the helicopter is in forward flight.

With a rigid rotor system, the blades are not hinged for movement up and down (flapping) or for movement fore and aft (drag). The blades are able to move around the pitch change axis, with each blade being able to independently change its blade angle. The rigid

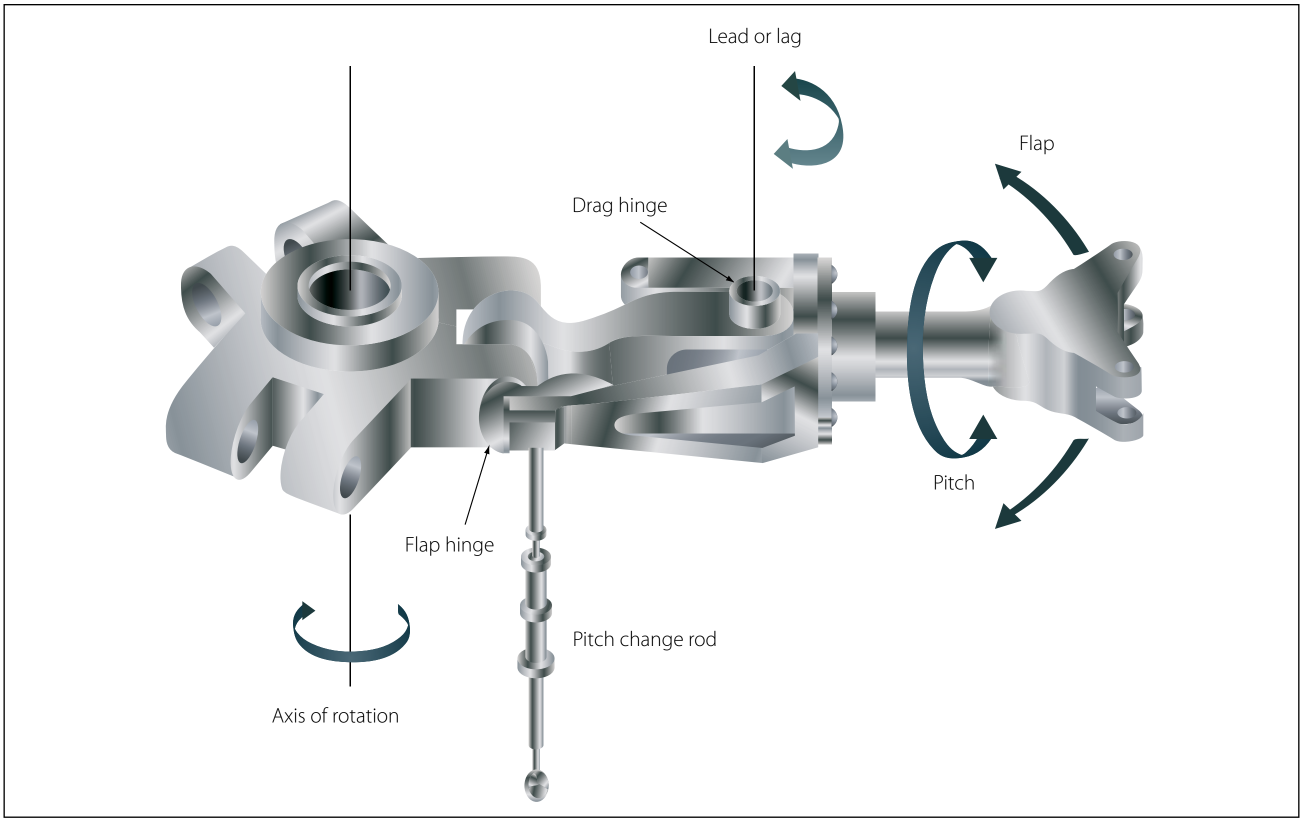

Figure 3-82. Fully articulated main rotor head.

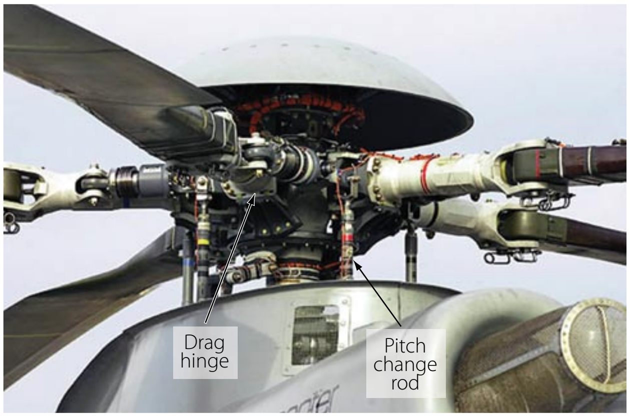

Figure 3-83. Eurocopter 725 main rotor head.

Figure 3-84. Bell Jet Ranger with semi-rigid main rotor.

rotor system uses blades that are very strong and yet flexible. They are flexible enough to bend when they need to, without the use of hinges or a teetering rotor, to compensate for the uneven lift that occurs in forward flight. The Eurocopter model 135 uses a rigid rotor system. [Figure 3-85]

Anti-Torque Systems

Any time a force is applied to make an object rotate, there will be an equal force acting in the opposite direction. If the helicopter's main rotor system rotates clockwise when viewed from the top, the helicopter will try to rotate counterclockwise. Earlier in this chapter, it was discovered that torque is what tries to make something rotate. For this reason, a helicopter uses what is called an anti-torque system to counteract the force trying to make it rotate.

One method that is used on a helicopter to counteract torque is to place a spinning set of blades at the end of the tail boom. These blades are called a tail rotor or anti-torque rotor, and their purpose is to create a force (thrust) that acts in the opposite direction of the way the helicopter is trying to rotate. The tail rotor force, in pounds, multiplied by the distance from the tail rotor to the main rotor, in feet, creates a torque in pound-feet that counteracts the main rotor torque.

Figure 3-85. Eurocopter Model 135 rigid rotor system.

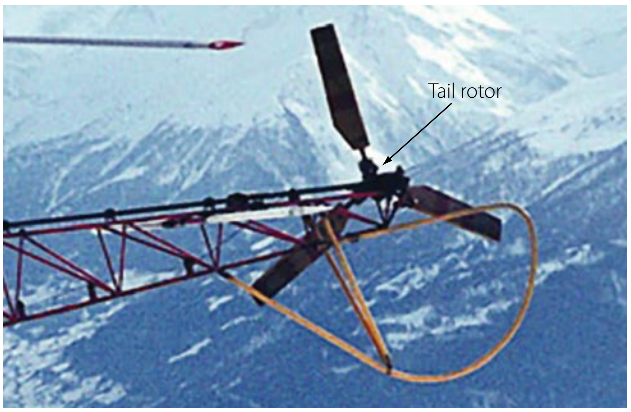

Figure 3-86. Aerospatiale helicopter tail rotor.

Figure 3-86 shows a three bladed tail rotor on an Aerospatiale AS-315B helicopter. This tail rotor has open tipped blades that are variable pitch, and the helicopter's anti-torque pedals (positioned like rudder pedals on an airplane) control the amount of thrust they create. Some potential problems with this tail rotor system are as follows:

- The spinning blades are deadly if someone walks into them.
- When the helicopter is in forward flight and a vertical fin may be in use to counteract torque, the tail rotor robs engine power and creates drag.

An alternative to the tail rotor seen in Figure 3-86 is a type of anti-torque rotor known as a fenestron, or "fan-in-tail" design as seen in Figure 3-87. Because the rotating blades in this design are enclosed in a shroud, they present less of a hazard to personnel on the ground and they create less drag in flight.

A third method of counteracting the torque of the helicopter's main rotor is a technique called the "no tail rotor" system, or NOTAR. This system uses a high

Figure 3-87. Fenestron on a Eurocopter Model 135.

volume of air at low pressure, which comes from a fan driven by the helicopter's engine. The fan forces air into the tail boom, where a portion of it exits out of slots on the right side of the boom and, in conjunction with the main rotor downwash, creates a phenomenon called the "Coanda effect." The air coming out of the slots on the right side of the boom causes a higher velocity, and therefore lower pressure, on that side of the boom. The higher pressure on the left side of the boom creates the primary force that counteracts the torque of the main rotor. The remainder of the air travels back to a controllable rotating nozzle in the helicopter's tail. The air exits the nozzle at a high velocity, and creates an additional force (thrust) that helps counteracts the torque of the main rotor. A NOTAR system is shown in Figures 3-88 and 3-89.

For helicopters with two main rotors, such as the Chinook that has a main rotor at each end, no anti-torque

Figure 3-88. McDonnell Douglas 520 NOTAR.

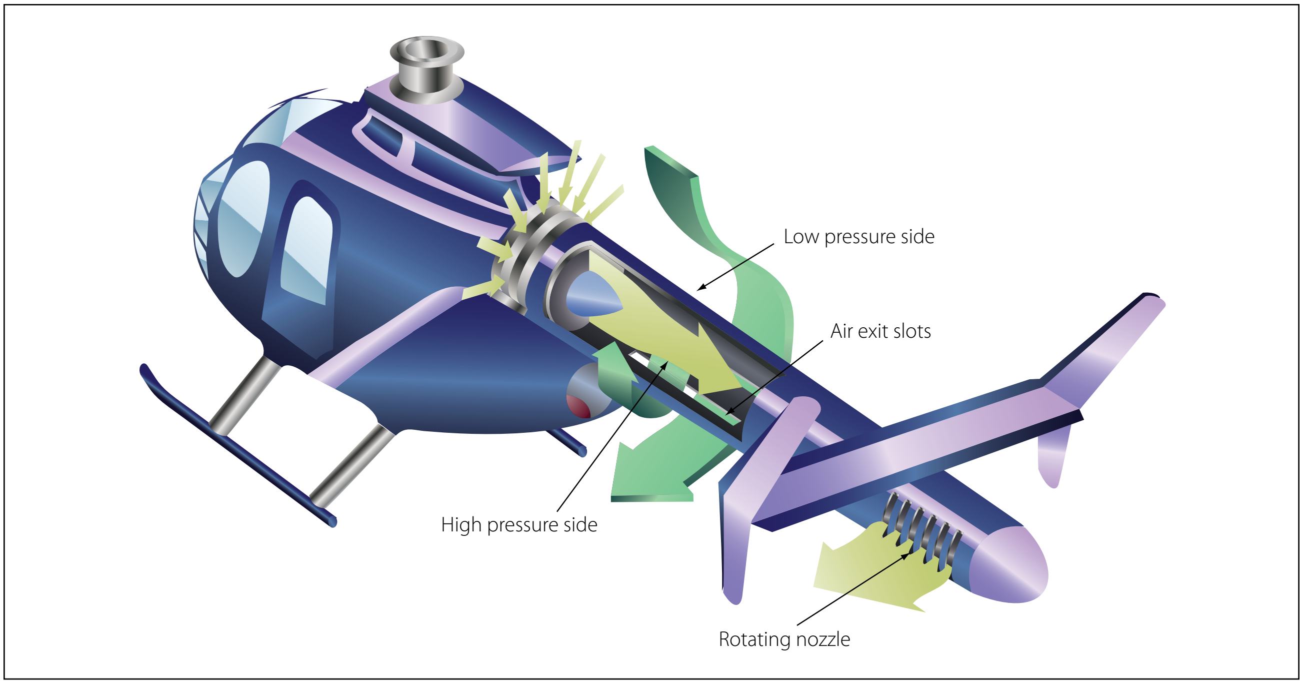

Figure 3-89. Airflow for a NOTAR.

rotor is needed. For this type of helicopter, the two main rotors turn in opposite directions, and each one cancels out the torque of the other.

Helicopter Axes of Flight

Helicopters, like airplanes, have a vertical, lateral, and longitudinal axis that passes through the helicopter's center of gravity. Helicopters yaw around the vertical axis, pitch around the lateral axis, and rotate around the longitudinal axis. Figure 3-90 shows the three axes of a helicopter and how they relate to the helicopter's movement. All three axes will intersect at the helicopter's center of gravity, and the helicopter pivots around this point. Notice in the figure that the vertical axis passes almost through the center of the main rotor, because the helicopter's center of gravity needs to be very close to this point.

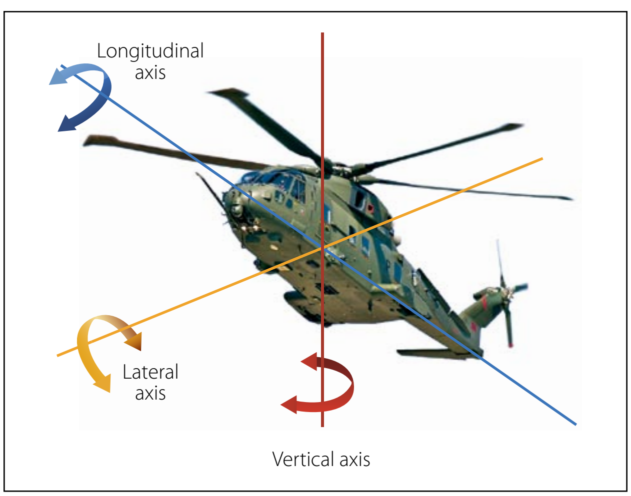

Figure 3-90. Three axes of rotation for a helicopter.

Control Around the Vertical Axis

For a single main rotor helicopter, control around the vertical axis is handled by the anti-torque rotor (tail rotor) or from the fan's airflow on a NOTAR type helicopter. Like in an airplane, rotation around this axis is known as yaw. The pilot controls yaw by pushing on the anti-torque pedals located on the cockpit floor, in the same way the airplane pilot controls yaw by pushing on the rudder pedals. To make the nose of the helicopter yaw to the right, the pilot pushes on the right anti-torque pedal. When viewed from the top, if the helicopter tries to spin in a counterclockwise direction because of the torque of the main rotor, the pilot will also push on the right anti-torque pedal to counteract the main rotor torque. By using the anti-torque pedals, the pilot can intentionally make the helicopter rotate in either direction around the vertical axis. The anti-torque pedals can be seen in Figure 3-91.

Some helicopters have a vertical stabilizer, such as those shown in Figures 3-90 and 3-92. In forward flight, the vertical stabilizer creates a force that helps counteract the torque of the main rotor, thereby reducing the power needed to drive the anti-torque system located at the end of the tail boom.

Figure 3-91. Helicopter cockpit controls.

Control Around the Longitudinal and Lateral Axes

Movement around the longitudinal and lateral axes is handled by the helicopter's main rotor. In the cockpit, there are two levers that control the main rotor, known as the collective and cyclic pitch controls. The collective pitch lever is on the side of the pilot's seat, and the cyclic pitch lever is at the front of the seat in the middle. [Figure 3-91]

When the collective pitch control lever is raised, the blade angle of all the rotor blades increases uniformly and they create the lift that allows the helicopter to take off vertically. The grip on the end of the collective pitch control is the throttle for the engine, which is rotated to increase engine power as the lever is raised. On many helicopters, the throttle automatically rotates and increases engine power as the collective lever is raised. The collective pitch lever may have adjustable friction built into it, so the pilot does not have to hold upward pressure on it during flight.

The cyclic pitch control lever, like the yoke of an airplane, can be pulled back or pushed forward, and can be moved left and right. When the cyclic pitch lever is pushed forward, the rotor blades create more lift as they pass through the back half of their rotation and less lift as they pass through the front half. The difference in lift is caused by changing the blade angle (pitch) of the rotor blades. The pitch change rods that were seen earlier, in Figures 3-82 and 3-83, are controlled by the cyclic pitch lever and they are what change the pitch of the rotor blades. The increased lift in the back either causes the main rotor to tilt forward, the nose of the helicopter to tilt downward, or both. The end result is the helicopter moves in the forward direction. If the cyclic pitch lever is pulled back, the rotor blade lift will be greater in the front and the helicopter will back up.

If the cyclic pitch lever is moved to the left or the right, the helicopter will bank left or bank right. For the helicopter to bank to the right, the main rotor blades must create more lift as they pass by the left side of the helicopter. Just the opposite is true if the helicopter is banking to the left. By creating more lift in the back than in the front, and more lift on the left than on the right, the helicopter can be in forward flight and banking to the right. In Figure 3-92, an Agusta A-109 can be seen in forward flight and banking to the right. The

Figure 3-92. Agusta A-109 banking to the right.

Figure 3-93. Air Force CH-53 in a hover.

rotor blade in the rear and the one on the left are both in an upward raised position, meaning they have both experienced the condition called flap.

Some helicopters use a horizontal stabilizer, similar to what is seen on an airplane, to help provide additional stability around the lateral axis. A horizontal stabilizer can be seen on the Agusta A-109 in Figure 3-92.

Helicopters in Flight

Hovering

For a helicopter, hovering means that it is in flight at a constant altitude, with no forward, aft, or sideways movement. In order to hover, a helicopter must be producing enough lift in its main rotor blades to equal the weight of the aircraft. The engine of the helicopter must be producing enough power to drive the main rotor, and also to drive whatever type of anti-torque system is being used. The ability of a helicopter to hover is affected by many things, including whether or not it is in ground effect, the density altitude of the air, the available power from the engine, and how heavily loaded it is.

For a helicopter to experience ground effect, it typically needs to be no higher off the ground than one half of its main rotor system diameter. If a helicopter has a main rotor diameter of 40 ft, it will be in ground effect up to an altitude of approximately 20 ft. Being close to the ground affects the velocity of the air through the rotor blades, causing the effective angle of attack of the blades to increase and the lift to increase. So, if a helicopter is in ground effect, it can hover at a higher gross weight than it can when out of ground effect. On a windy day, the positive influence of ground effect is lessened, and at a forward speed of 5 to 10 mph the positive influence becomes less. In Figure 3-93, an Air Force CH-53 is seen in a hover, with all the rotor blades flapping up as a result of creating equal lift.

Forward Flight

In the early days of helicopter development, the ability to hover was mastered before there was success in attaining forward flight. The early attempts at forward flight resulted in the helicopter rolling over when it tried to depart from the hover and move in any direction. The cause of the rollover is what we now refer to as dissymmetry of lift.

When a helicopter is in a hover, all the rotor blades are experiencing the same velocity of airflow. When the helicopter starts to move, the velocity of airflow seen by the rotor blades changes. For helicopters built in the United States, the main rotor blades turn in a counterclockwise direction when viewed from the top. Viewed from the top, as the blades move around the right side of the helicopter, they are moving toward the nose; as they move around the left side of the helicopter, they are moving toward the tail. When the helicopter starts moving forward, the blade on the right side is moving toward the relative wind, and the blade on the left side is moving away from the relative wind. This causes the blade on the right side to create more lift and the blade on the left side to create less lift. Figure 3-94 shows how this occurs.

In Figure 3-94, blade number 2 would be called the advancing blade, and blade number 1 would be called the retreating blade. The advancing blade is moving toward the relative wind, and therefore experiences a greater velocity of airflow. The increased lift created by the blade on the right side will try to roll the helicopter to the left. If this condition is allowed to exist, it will ultimately lead to the helicopter crashing.

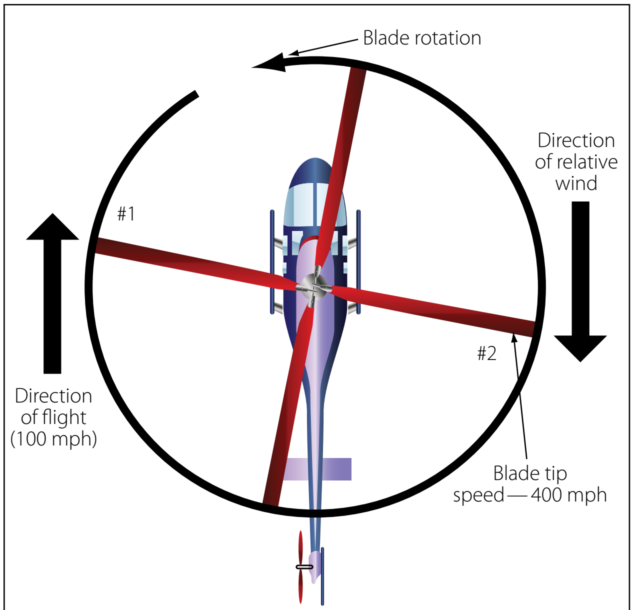

Figure 3-94. Dissymmetry of lift for rotor blades.

Blade Flapping

To solve the problem of dissymmetry of lift, helicopter designers came up with a hinged design that allows the rotor blade to flap up when it experiences increased lift, and to flap down when it experiences decreased lift. When a rotor blade advances toward the front of the helicopter and experiences an increased velocity of airflow, the increase in lift causes the blade to flap up. This upward motion of the blade changes the direction of the relative wind in relation to the chord line of the blade, and causes the angle of attack to decrease. The decrease in the angle of attack decreases the lift on the blade. The retreating blade experiences a reduced velocity of airflow and reduced lift, and flaps down. By flapping down, the retreating blade ends up with an increased angle of attack and an increase in lift. The end result is the lift on the blades is equalized, and the tendency for the helicopter to roll never materializes.

The semi-rigid and fully articulated rotor systems have flapping hinges that automatically allow the blades to move up or down with changes in lift. The rigid type of rotor system has blades that are flexible enough to bend up or down with changes in lift.

Advancing Blade and Retreating Blade Problems

As a helicopter flies forward at higher and higher speeds, the blade advancing toward the relative wind sees the airflow at an ever increasing velocity. Eventually, the velocity of the air over the rotor blade will reach sonic velocity, much like the critical Mach number for the wing of an airplane. When this happens, a shock wave will form and the air will separate from the rotor blade, resulting in a high-speed stall.

As the helicopter's forward speed increases, the relative wind over the retreating blade decreases, resulting in a loss of lift. The loss of lift causes the blade to flap down and the effective angle of attack to increase. At a high enough forward speed, the angle of attack will increase to a point that the rotor blade stalls. The tip of the blade stalls first, and then progresses in toward the blade root.

When approximately 25 percent of the rotor system is stalled, due to the problems with the advancing and retreating blades, control of the helicopter will be lost. Conditions that will lead to the rotor blades stalling include high forward speed, heavy gross weight, turbulent air, high-density altitude, and steep or abrupt turns.

Autorotation

The engine on a helicopter drives the main rotor system by way of a clutch and a transmission. The clutch allows the engine to be running and the rotor system not to be turning, while the helicopter is on the ground, and it also allows the rotor system to disconnect from the engine while in flight, if the engine fails. Having the rotor system disconnect from the engine in the event of an engine failure is necessary if the helicopter is to be capable of a flight condition called autorotation.

Autorotation is a flight condition where the main rotor blades are driven by the force of the relative wind passing through the blades, rather than by the engine. This flight condition is similar to an airplane gliding if its engine fails while in flight. As long as the helicopter maintains forward airspeed, while decreasing altitude, and the pilot lowers the blade angle on the blades with the collective pitch, the rotor blades will continue to rotate. The altitude of the helicopter, which equals potential energy, is given up in order to have enough energy (kinetic energy) to keep the rotor blades turning. As the helicopter nears the ground, the cyclic pitch control is used to slow the forward speed and to flare the helicopter for landing. With the airspeed bled off, and the helicopter now close to the ground, the final step is to use the collective pitch control to cushion the landing. The airflow through the rotor blades in normal forward flight and in an autorotation flight condition are shown in Figure 3-95. In Figure 3-96, a Bell Jet Ranger is shown approaching the ground in the final stage of an autorotation.

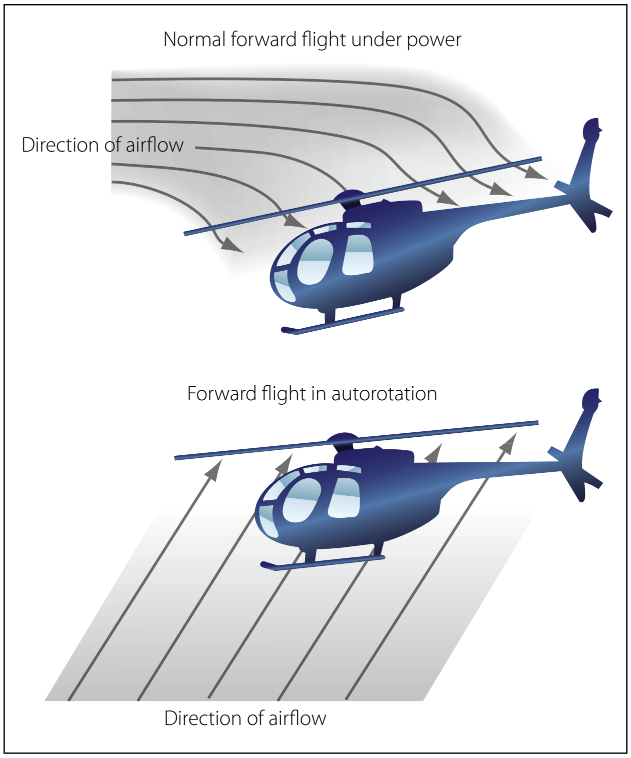

Figure 3-95. Rotor blade airflow during normal flight and during autorotation.

Figure 3-96. Bell Jet Ranger in final stage of autorotation.

Weight-Shift Control, Flexible Wing Aircraft Aerodynamics

A weight-shift control, flexible wing type aircraft consists of a fabric-covered wing, often referred to as the sail, attached to a tubular structure that has wheels, seats, and an engine and propeller. The wing structure is also tubular, with the fabric covering creating the airfoil shape. The shape of the wing varies among the

Figure 3-97. Weight-shift control aircraft in level flight.

different models of weight-shift control aircraft being produced, but a delta shaped wing is a very popular design. Within the weight-shift control aircraft community, these aircraft are typically referred to as trikes. [Figure 3-97]

In Figure 3-97, the trike's mast is attached to the wing at the hang point on the keel of the wing with a hang point bolt and safety cable. There is also a support tube, known as a king post, extending up from the top of the wing, with cables running down and secured to the tubular wing structure. The cables running down from the king post as part of the upper rigging are there to support the wing when the aircraft is on the ground, and to handle negative loads when in flight. The lines that run from the king post to the trailing edge of the wing are known as reflex cables. These cables maintain the shape of the wing when it is in a stalled state by holding the trailing edge of the wing up which helps raise the nose during recovery from the stall. If the aircraft goes into an inadvertent stall, having the trailing edge of the wing in a slightly raised position helps raise the nose of the aircraft and get it out of the stall. The passenger seat is centered under the wing's aerodynamic center, with the weight of the pilot being forward of this point and the weight of the engine and propeller being aft.

Unlike a traditional airplane, the trike does not have a rudder, elevator, or ailerons. Instead, it has a wing that can be pivoted forward or aft, and left or right. In Figure 3-98, the pilot's hand is on a control bar that is connected to a pivot point just forward of where the wing attaches. There are cables attached to the ends of the bar that extend up to the wing's leading and

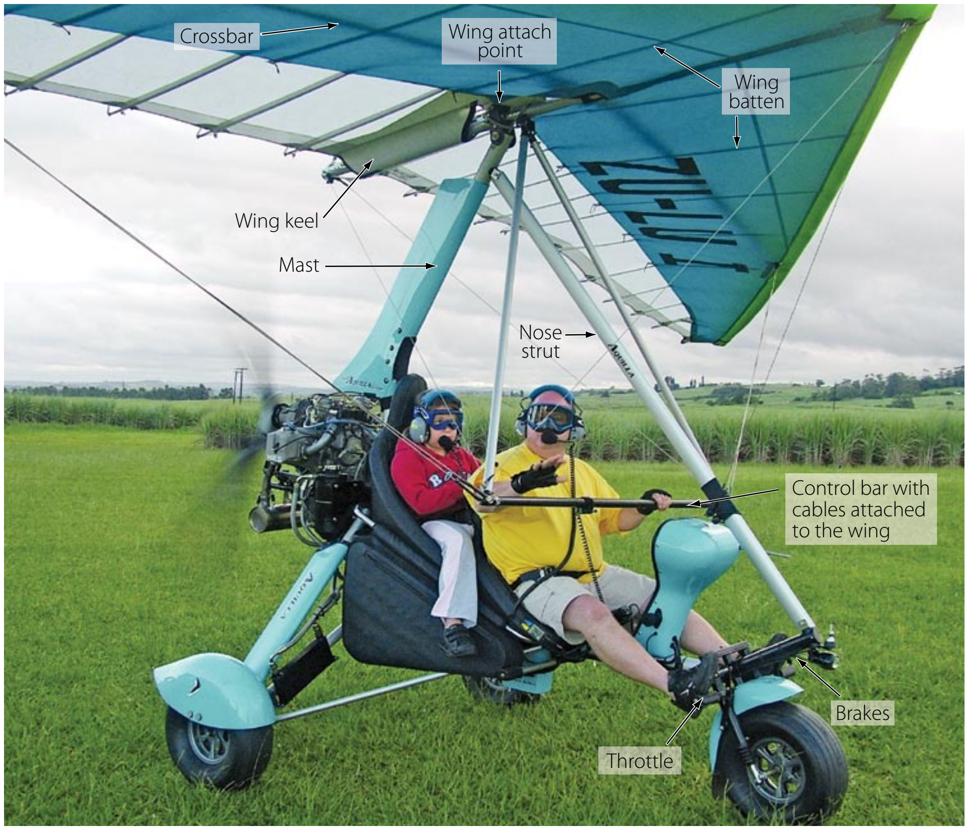

Figure 3-98. Weight-shift control aircraft getting ready for flight.

trailing edge, and to the left and right side of the cross bar. Running from the wing leading edge to trailing edge are support pieces known as battens. The battens fit into pockets, and they give the wing its cambered shape. The names of some of the primary parts of the trike are shown in Figure 3-98, and these parts will be referred to when the flight characteristics of the trike are described in the paragraphs that follow.

In order to fly the trike, engine power is applied to get the aircraft moving. As the groundspeed of the aircraft reaches a point where flight is possible, the pilot pushes forward on the control bar, which causes the wing to pivot where it attaches to the mast and the leading edge of the wing tilts up. When the leading edge of the wing tilts up, the angle of attack and the lift of the wing increase. With sufficient lift, the trike rotates and starts climbing. Pulling back on the bar reduces the angle of attack, and allows the aircraft to stop climbing and to fly straight and level. Once the trike is in level flight, airspeed can be increased or decreased by adding or taking away engine power by use of the throttle.

Stability in flight along the longitudinal axis (nose to tail), for a typical airplane, is achieved by having the horizontal stabilizer and elevator generate a force that balances out the airplane's nose heavy tendency. Because the trike does not have a horizontal stabilizer or elevator, it must create stability along the longitudinal axis in a different way. The trike has a sweptback delta wing, with the trailing edge of the wingtips located well aft of the aircraft center of gravity. Pressure acting on the tips of the delta wing creates the force that balances out the nose heavy tendency.

The wings of weight-shift control aircraft are designed in a way that allows them to change their shape when subjected to an external force. This is possible because the frame leading edges and the sail are flexible, which is why they are sometimes referred to as flexible wing aircraft. This produces somewhat different aerodynamic effects when compared with a normal fixed-wing aircraft. A traditional small airplane, like a Cessna 172, turns or banks by using the ailerons, effectively altering the camber of the wing and thereby generating differential lift. By comparison, weight shift on a trike actually causes the wing to twist, which changes the angle of attack on the wing and causes the differential lift to exist that banks the trike. The cross-bar (wing spreader) of the wing frame is allowed to float slightly with respect to the keel, and this, along with some other geometric considerations allows the sail to "billow shift." Billow shift can be demonstrated on the ground by grabbing the trailing edge of one end of the

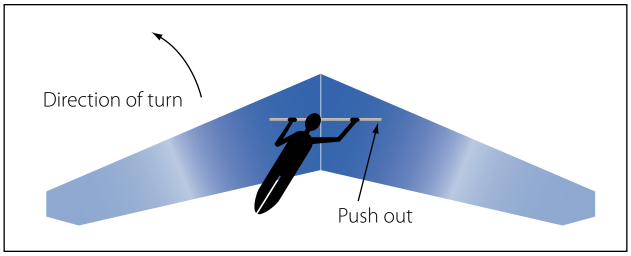

Figure 3-99. Direction of turn based on weight shift.

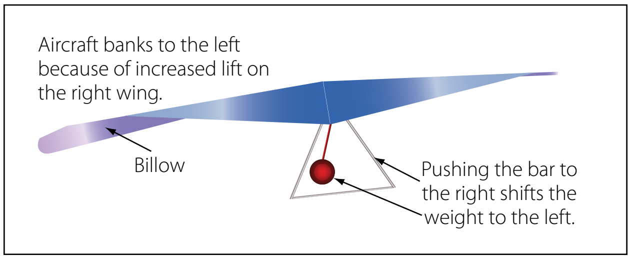

Figure 3-100. Weight shift to the left causing a left-hand turn.

wing and lifting up on it. If this was done, the fabric on the other end of the wing would become slightly flatter and tighter, and the wing's angle of attack would increase.

If the pilot pushes the bar to the right, the wing pivots with the left wingtip dropping down and the right wingtip rising up, causing the aircraft to bank to the left. This motion is depicted in Figure 3-99, showing a hang glider as an example. The shift in weight to the left increases the wing loading on the left, and lessens it on the right. The increased loading on the left wing increases its washout and reduces its angle of attack and lift. The increased load on the left wing causes the left wing to billow, which causes the fabric to tighten on the right wing and the angle of attack and lift to increase. The change in lift is what banks the aircraft to the left. Billow on the left wing is depicted in Figure 3-100.

Shifting weight to the right causes the aircraft to bank right. The weight of the trike and its occupants acts like a pendulum, and helps keep the aircraft stable in flight. Pushing or pulling on the bar while in flight causes the weight hanging below the wing to shift its position relative to the wing, which is why the trike is referred to as a weight-shift aircraft.

Once the trike is in flight and flying straight and level, the pilot only needs to keep light pressure on the bar that controls the wing. If the trike is properly balanced and there is no air turbulence, the aircraft will remain stable even if the pilot's hands are removed from the bar. The same as with any airplane, increasing engine power will make the aircraft climb and decreasing power will make it descend. The throttle is typically controlled with a foot pedal, like a gas pedal in an automobile.

A trike lands in a manner very similar to an airplane. When it is time to land, the pilot reduces engine power with the foot-operated throttle, causing airspeed and wing lift to decrease. As the trike descends, the rate of descent can be controlled by pushing forward or pulling back on the bar, and varying engine power. When the trike is almost to the point of touchdown, the engine power will be reduced and the angle of attack of the wing will be increased, to cushion the descent and provide a smooth landing. If the aircraft is trying to land in a very strong crosswind, the landing may not be so smooth. When landing in a cross wind, the pilot will land in a crab to maintain direction down the runway. Touchdown is done with the back wheels first, then letting the front wheel down.

A trike getting ready to touch down can be seen in Figure 3-101. The control cables coming off the control bar can be seen, and the support mast and the cables on top of the wing, including the luff lines, can also be seen.

Powered Parachute Aerodynamics

A powered parachute has a carriage very similar to the weight-shift control aircraft. Its wing, however, has no support structure or rigidity and only takes on the shape of an airfoil when it is inflated by the blast of air from the propeller and the forward speed of the aircraft. In Figure 3-102, a powered parachute is on its approach to land with the wing fully inflated and rising up above the aircraft. Each colored section of the inflated wing is made up of cells that are open in the front to allow air to ram in, and closed in the back to keep the air trapped inside. In between all the cells there are holes that allow the air to flow from one cell to the next, in order to equalize the pressure within the inflated wing. The wing is attached to the carriage of the aircraft by a large number of nylon or kevlar lines that run from the tips of the wing all the way to the center. The weight of the aircraft acting on these lines and their individual lengths cause the inflated wing to take its shape. The lines attach to the carriage of the aircraft at a location very close to where the center of gravity is located, and this attachment point is adjustable to account for balance changes with occupants of varying weights.

As in weight-shift control aircraft, the powered parachute does not have the traditional flight controls of a fixed-wing airplane. When the wing of the aircraft

Figure 3-101. Weight-shift control aircraft landing.

is inflated and the aircraft starts moving forward, the wing starts generating lift. Once the groundspeed is sufficient for the wing's lift greater than the weight of the aircraft, the aircraft lifts off the ground. Unlike an airplane, where the pilot has a lot of control over when the airplane rotates by deciding when to pull back on the yoke, the powered parachute will not take off until it reaches a specific airspeed. The powered parachute will typically lift off the ground at a speed somewhere between 28 and 30 mph, and will have an airspeed in flight of approximately 30 mph.

Figure 3-102. Powered parachute with the wing inflated.

Once the powered parachute is in flight, control over climbing and descending is handled with engine power. Advancing the throttle makes the aircraft climb, and retarding the throttle makes it descend. The inflated wing creates a lot of drag in flight, so reducing the engine power creates a very controllable descent of the aircraft. The throttle, for controlling engine power, is typically located on the right-hand side of the pilot. [Figure 3-103]

Turning of the powered parachute in flight is handled by foot-operated pedals (steering bars) located at the front of the aircraft. These bars can be seen in Figure 3-103. Each foot-operated pedal controls a set of lines, usually made out of nylon, that runs up to the trailing edge of each wingtip. When the right foot pedal is pushed, the line pulls down on the trailing edge of the right wingtip. As the trailing edge of the right wing drops down, drag is increased on the right side and the aircraft turns right. When pressure is taken off the foot

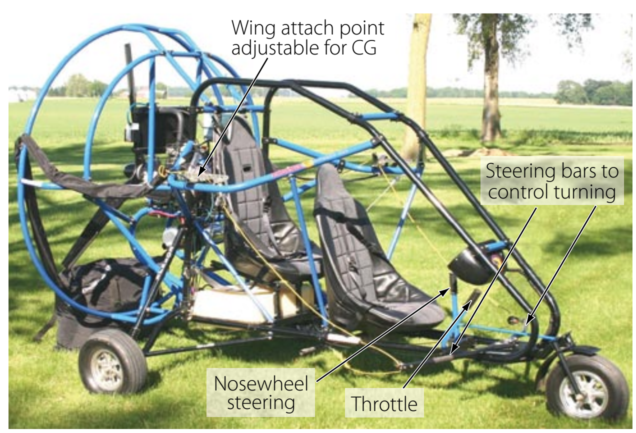

Figure 3-103. Two seat powered parachute.

Figure 3-104. Powered parachute wing trailing edge.

pedal, the drag on the entire airfoil equalizes and the aircraft resumes its straight-and-level flight.

To land a powered parachute, the first action the pilot takes is to reduce engine power and allow the aircraft to descend. With the power reduced to idle, the aircraft will descend at a rate of approximately 5 to 10 fps. As the aircraft approaches the ground, the descent rate can be lessened by increasing the engine power. Just before touchdown, the pilot pushes on both foot-operated pedals to drop the trailing edges on both sides of the wing. This action increases the drag on the wing uniformly, causing the wing to pivot aft, which raises the wing leading edge and increases the angle of attack and lift.

In Figure 3-104, the pilot is pushing on both foot pedals and the left and right wing trailing edges are deflected downward. The aircraft has just touched down and the wing is trailing behind the aircraft, caused by the high angle of attack and the additional drag on the wing. The increase in lift reduces the descent rate to almost nothing, and provides for a gentle landing. If the pilot pushes on the foot pedals too soon, the wing may pivot too far aft before touchdown, resulting in an unacceptable descent rate. In that case, it might be a relatively hard landing.