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ABSTRACT

This revised textbook, one in the Aerospace Education II series, provides answers to many questions related to airplanes and properties of air flight. The first chapter provides a description of aerodynamic forces and deals with concepts such as acceleration, velocity, and forces of flight. The second chapter is devoted to the discussion of properties of the atmosphere. How different characteristics of the atmosphere help make flight possible, how man can harness the air for flight, and several other questions related to balancing of forces in the air are discussed in chapter two and three. The discussion in the fourth and fifth chapters centers on how aircraft move through the air. The next two chapters discuss the aircraft structure and various kinds of instruments used to control flight. A brief description of navigation instruments is also included. The book is designed for use in the Air Force ROTC program. (PS)

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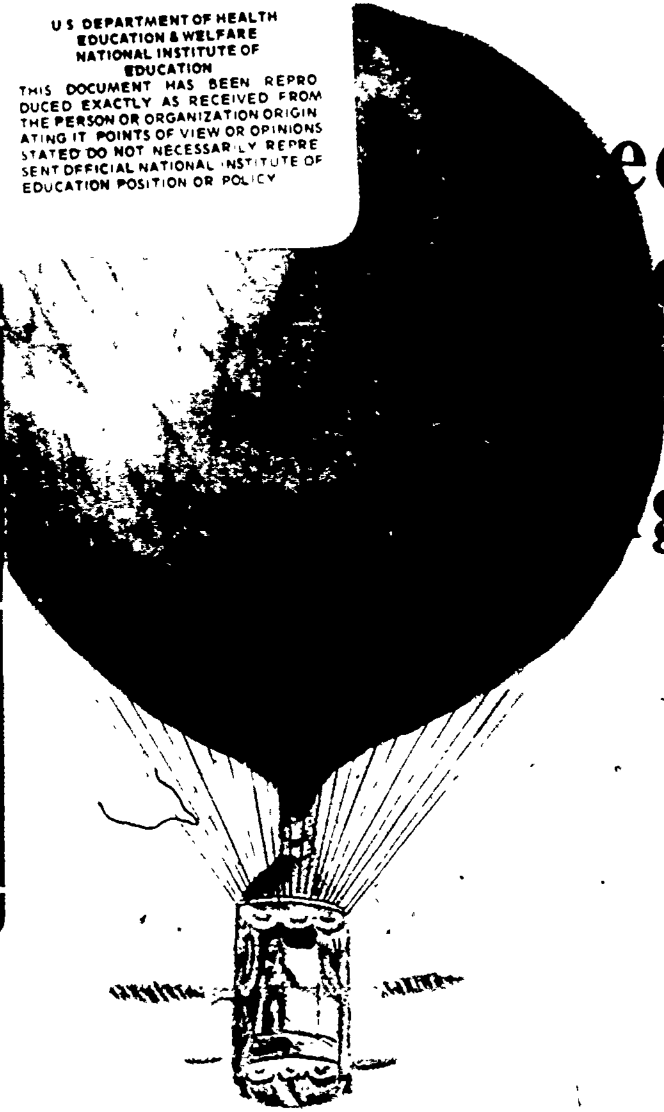

Air Force Junior ROTC
Air University/Maxwell Air Force Base, Alabama

AEROSPACE EDUCATION II

Theory of Aircraft Flight

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AIR FORCE JUNIOR ROTC
AIR UNIVERSITY
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1974

This publication has been reviewed and approved by competent personnel of the preparing command in accordance with current directives on doctrine, policy, essentiality, propriety, and quality.

This book will not be offered for sale. It is for use only in the Air Force ROTC program.

Preface

WE OFTEN READ about aircraft which do not fly, aircraft which have accidents, but how often do we think about why aircraft fly? And how often do we wonder about the nature of this science of aircraft flight, how does the aircraft get off the ground in the first place, how does it stay in the air, how is it controlled in the air; how is it landed. . . . Many more "how" questions might be added: how is a plane put together; how does one man control a complex modern aircraft. . . . and on and on.

This unit, *Theory of Aircraft Flight,* will provide answers for some of these questions about the complicated and serious business of flying aircraft. Odd as it may seem, the Wright brothers relied on many of the same principles used today when they built and flew their first successful heavier-than-air craft in 1903. Because today's highspeed aircraft use better propulsion systems, building materials, and designs from those of the early pioneers of aviation, they can fly much higher, farther, and faster than those early "iron birds." However, certain principles of flight are common to all aircraft, old and new.

In one sense, the history of aviation is the history of civilization. It has been said that advances in transportation have paralleled advances in degree of civilization. For the history of flight, this statement is certainly true. The purpose of this unit, however, is not to give you a history of aviation; rather, its purpose is to explain what enables man to fly. To do this it will be necessary to discuss some historical developments which have made flying an accepted means of transportation.

You will also learn about the air around you and what its properties are. We'll then move on to examine the balance of forces which hold an aircraft in the air and how an aircraft moves through the air. Next, we'll look at aircraft structure. the basic components of an aircraft; the hows and whys of aircraft design; and the stresses that occur on the airframe.

Finally, we'll examine aircraft instruments: what they are; what types there are; and, basically, how they work. It seems wiser to present an overall view of the aircraft and how it works before we examine the instruments which the pilot uses to tell how his aircraft is performing. In addition, the booklets on propulsion systems and navigation will discuss certain instruments in more depth than this brief overall treatment allows.

We might mention here that several writers on the subject of aerodynamics point out that "theory of flight" is something of a misnomer: human flight is fact. We know that an aircraft can fly, we know that the atmosphere has certain properties. Why, then, do we call it a theory? The "theory" involved is the tying together of all these known facts into an explainable package.

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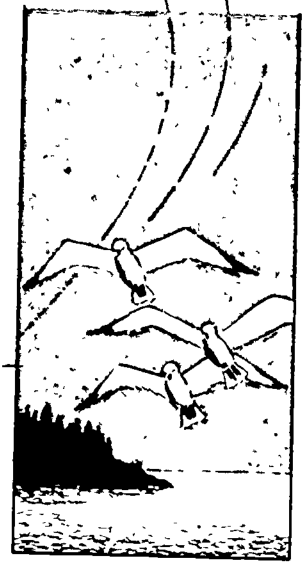
Chapter 1

Aerodynamic Forces



THIS CHAPTER places man's attempts to fly in historical perspective. First, you will briefly review man's early attempts to fly. Then, you will examine the physical laws which underlie flight, particularly Newton's Laws of Motion and Bernoulli's Principle. Finally, you will look at an aircraft in flight and examine the balance of forces which keeps it there. After you have studied this chapter, you should be able to: (1) outline the steps that led to "successful controlled, powered, heavier-than-air aircraft flight;" (2) show how the Wright Brothers applied Newton's Laws of Motion and Bernoulli's Principle to their aircraft; and (3) explain why the forces of lift, weight, thrust, and drag are essential to successful flight.

WITH A ROAR and then a steady hum, your flight takes off. The "Fasten Seat Belts" sign goes off, and you relax, secure in the knowledge that your aircraft is being flown well and safely But then you look out the window and see those big engines, representing hundreds of horsepower, propelling your aircraft through the air How do they keep your plane in the air? Why doesn't it fall out of the sky? How (and maybe why) did you get up where you are in the first place?

Sit back, relax, and don't worry Something more than good luck is keeping your aircraft in the air! In one sense, the last five or six hundred years' experience of mankind is holding up your plane. This chapter will take a brief look at aspects of the last five centuries which have led to the smooth and safe flight you're on right now The history of man's attempts to fly under his own power like the birds is an important aid to understanding why man is now able to fly. A short review of man's trials and errors in his attempts to fly may well remove some of your own misconceptions about the nature of flight, certainly, it will show you how earlier man attempted to fly

MAN'S EARLY ATTEMPTS TO FLY

Like so many other things, it all began with the Greeks You have probably heard of read about the legend of Daedalus and Icarus In order to escape from the labyrinth of King Minos of Crete, Daedalus made wings for himself and his son Icarus from feathers and a magic wax Both escaped from the labyrinth, but, so the legend goes, Icarus flew too near the sun, and the sun melted his wings, causing him to plunge to his death in the sea. Like all legends, this one probably has no basis in fact, rather, it arose to explain something that man could explain no other way birds fly and man does not Man had tried, but his nature was such that he didn't succeed.

Archimedes, meanwhile, was performing experiments with water, but his conclusions about the nature of water were also to affect pre-Christian man's notions of flight Archimedes' experiments led him to this conclusion a body will float if it is lighter than a like measure of water, but it will sink if it is heavier Extending this conclusion to one specific case, he concluded that if things lighter than water will float on the sea, then things lighter than air will float "on" the atmosphere The problem, of course, was simply to build an airship lighter than a like volume of air

In this same pre-Christian period of history, the Chinese had solved the problem quite another way they figured out how to harness moving air by means of the kite Old records indicate that some of these early Chinese kites were large enough to lift a man Some of these man-bearing kites were even used in battle for observation Because the Chinese and Greeks were unable to combine their knowledge, it was not until much later that man seriously directed his efforts to solving the problems of flight

Another major thinker on the problem of manned flight was the great Leonardo da Vinci Da Vinci designed both a parachute and an early form (a prototype) of the helicopter, as well as a manpowered ornithopter (a flying machine which used the same principles as birds) But he realized that a power source capable of flying the machine was not available, and so many of his ideas remained in notebook form until

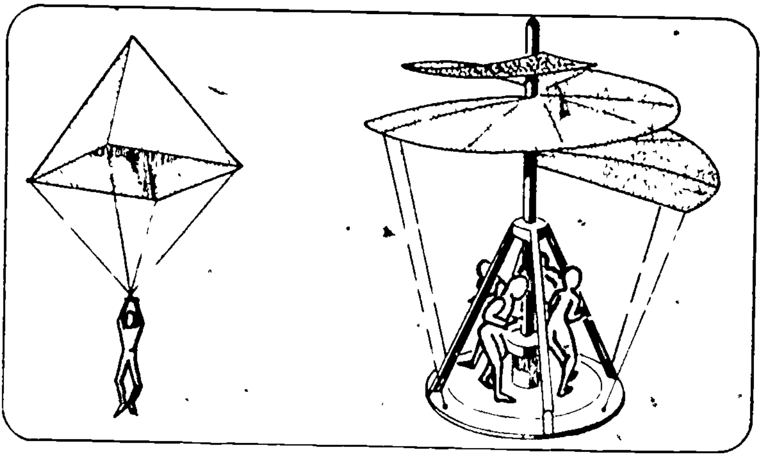


Figure 1 Leonardo da Vinci s Parachute and Helicopter Designs

quite recently A model of da Vinci's helicopter recently built according to his plans was reported to have been successfully flown, although present-day helicopters, of course, far surpass da Vinci's wildest dreams (see Fig 1)

Since heavier-than air craft seemed totally out of the question, man's attention next turned to the possibility of lighter-than-air craft, specifically balloons Joseph and Etienne Montgolfier, eighteenth-century Frenchmen, discovered that smoke (which is really heated air) contained in a silk bag rises, until, of course, the smoke cools off Controlling balloons in the air, however, proved a difficult task, and it was not until the middle of the nineteenth century that man was able to control a balloon with any great degree of success

The next major step in man's conquest of the sky came from simple observation of birds in flight Today, it perhaps seems a bit elementary to us that birds sometimes flap their wings and sometimes do not, because we understand that both the motion and the rigidity of birds' wings are tied in with their ability to fly But the gliding ability of birds was to provide the clue to the secret of flight

The Chinese and Japanese had realized that the gliding ability of birds could be duplicated, to a degree, in a kite Old records and legends would have us believe that men were "flying" in kites as early as the 1600s But this is not really flying, as we understand the term today—it is more like floating or soaring than flying

In the early nineteenth century, the Englishman George Cayley constructed the first true model glider. Cayley's writings indicate that he realized many of the problems about human flight which later experimenters would have to solve Stability and steering were still the primary difficulties man was encountering in the air

Later nineteenth-century experimenters laid the real foundations for the Wright brothers' 1903 flight John Montgomery, an American physics professor, realized that man must understand how to make a controllable glider in order to fly safely Otto Lilienthal, a German experimenter, also began with gliders He realized that an understanding of the glider was essential to an understanding of the true nature of flight. By 1896, he built a powered biplane with movable control surfaces (wingtips), but he was never to fly it because of an accident in one of his gliders. Octave Chanute, an American engineer, finally designed an easily controlled glider which did not require an acrobat to fly it

Meanwhile, the internal combustion engine had emerged as the primary source of power for the twentieth century The exact history of the development of the internal combustion engine is unclear, but it appears that Charles Manly was one of the first to build an internal combustion engine for an aircraft. The engine was installed in an aircraft built by Samuel Langley Langley's big aircraft never actually flew, although a reinforced reproduction of this plane made in the early part of the twentieth century, was successfully flown

Another aeronautical advance took the form of the steerable airship or dirigible. The rigid or nonrigid balloon, eventually of cylindrical shape, was driven by internal combustion engines mounted on a cabin

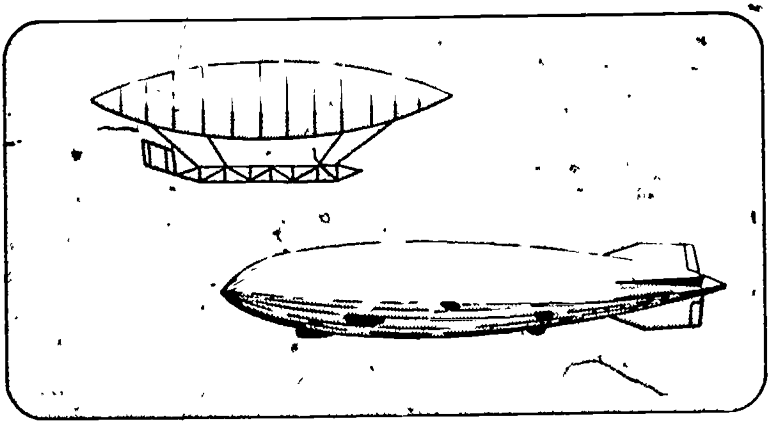


Figure 2 Dumont Dirigible and Zeppelin Rigid Airship

suspended below the craft. These lighter-than-air craft vied with the heavier-than-air machines for superiority in the early part of this century, but the advantages of greater maneuverability and speed of the heavier airplanes greatly outweighed those of the dirigibles (see Fig. 2).

It fell to two bicycle makers from Dayton, Ohio, Orville and Wilbur Wright, to combine all of man's previous knowledge with their technical skill and original contributions to make the first successful controlled, powered, heavier-than-air aircraft flight. Notice all those terms. "controlled," "powered," and "heavier-than-air." When we think of pioneers in aviation today, too often we tend to think that it all began with Orville and Wilbur Wright. This simply is not so. The Wrights studied all the available material on gliders, airships, control systems, and power plants, and only as a result of the study was their successful flight possible.

What did the Wrights study? What did they have to know in order to make their plane fly? They had to know the same basic things you will have to know in order to understand how and why an airplane flies. They did not understand the principles of flight in quite the same terms that we will use, but where they did not understand, they experimented.

How can an aircraft fly? Stated one way, heavier-than-air aircraft fly when the application of power creates thrust greater than drag (the resistance of the air), enabling airfoils to lift and support a given weight in flight That's the whole story in a nutshell. Now let's try to explain what this really means Aerodynamics includes physical laws which have a scientific basis in fact So, we would do well to examine a few of these basic physical laws Sir Isaac Newton (1642-1727) formulated three important basic physical laws. An understanding of his laws of motion is essential to an understanding of aircraft flight

NEWTON'S LAWS OF MOTION

Newton based his laws of motion largely on observation and experimentation Like all theoretical laws, Newton's laws were originally based upon what Newton saw around him and then were expanded to include new phenomena Aircraft flight is a good example of something Newton had never seen (and would never see). It is interesting to note, however, that Newton's laws are substantiated by the fact that aircraft do fly Although you have studied Newton's Laws in earlier texts, they are so important to understanding flight that we should review them before going on.

"A body continues in its state of rest or uniform motion in a straight line unless an unbalanced force acts on it." This is **Newton's First Law of Motion.** Stated more simply, it becomes A body at rest tends to remain at rest, and a body in motion tends to remain in motion, unless an outside force acts on the body This law is sometimes called the Law of Inertia. This is how it works.

Imagine that you are standing up in a crowded train The train is moving forward at about 50 miles per hour when the engineer suddenly applies the brakes. What happens to you? Unless you can grab onto a seat quickly, you'll continue to move forward, even though the train has stopped. You are experiencing Newton's First Law of Motion You are the body in motion, and so you tend to remain in motion The train, too, is a body in motion, but an unbalanced force (the force of the brakes) acts on the train to stop it.

"The acceleration of a body is directly proportional to the force exerted on the body, is inversely proportional to the mass of the body, and is in the same direction as the force" That involved statement is **Newton's Second Law of Motion.** It says three basic things (1) When you hit something, it picks up speed, (2) The heavier the object is, the less rapidly it picks up speed, and (3) The object picks up speed and continues to move in the same direction from which you hit it

Imagine, now, that the train you were taking (the one that slammed on the brakes) was heading for the golf course. It's a beautiful spring day, and you place your golf ball onto the tee You go into your backswing, your club stops at the top of your backswing, you go into your downswing, and at the bottom of your downswing, your club head meets the ball. The ball takes off, and you follow through. It's a perfect shot, straight down the middle of the fairway.

You've just demonstrated Newton's first two laws of motion How? You hit the ball (applied an outside force), making it move (overcoming its inertia). You caused it to pick up speed (accelerate) Since the golf ball is relatively light, it picks up speed rapidly. Finally, since your shot was straight, it accelerated in the same direction as the force

"Whenever one body exerts a force upon a second body, the second exerts an equal and opposite force upon the first body" This is **Newton's Third Law of Motion.** Stated another way "For every action there must be an equal and opposite reaction"

Let's go back to our golf game and see if we can see how this law works When you struck the ball with your club, you performed an action What was the reaction? The golf ball reacted against the club, and this reaction was transferred up the shaft to the club to your hand Then, it went on up your arm to your shoulder, and you "felt" the connection between ball and club

These three laws, then, are important to the student who wants to understand why planes fly You should also be familiar with some terms used in connection with these laws. You will encounter these terms in your study of aerodynamics. It is a good idea, then, to understand them from the start.

NEWTON'S LAW OF MOTION

I. A body at rest tends to remain at rest, and a body in motion tends to remain in motion, unless an outside force acts on the body.

II. The acceleration of a body is directly proportional to the force exerted on the body, is inversely proportional to the mass of the body, and is in the same direction as the force.

III. For every action there must be an equal and opposite reaction

ACCELERATION, VELOCITY, FORCE, AND MASS

In our discussion of Newton's Second Law of Motion, we mentioned the term acceleration. What, exactly, is acceleration? We hear the term all the time: cars accelerate from 0-60 miles per hour in x number of seconds; aircraft accelerate from one speed to another; and so forth. A formal definition of acceleration states. **Acceleration** *is the change in velocity per unit of time*. Acceleration, then, represents a change But a change in what? A change in velocity. What, then, is velocity **Velocity** is, simply, rate of motion in a given direction. In other words, acceleration is change of rate of motion in a given direction per unit of time Remember this definition. you will be using it later in this unit.

Let's take another look at Newton's Second Law of Motion. We've defined acceleration and velocity, how about force and mass? **Force** can be defined as *power or energy exerted against a material body in a given direction*. Perhaps you had already learned that force has both magnitude and direction. Mass is a little more difficult to explain **Mass** is the quantity of material (matter) contained in a body, while weight (which is often erroneously confused with mass) is really an expression of the amount of gravity being exerted on a quantity of matter Let's assume that planet "X" has a gravitational force ("pull") twice that of earth. A person who weighed 150 pounds on earth would weigh 300 pounds on planet "X". The force of gravity on the moon is approximately one sixth that of earth. In the case of the 150 pound person, he would weigh 25 pounds on the moon. On the other hand, if the individual is placed in a weightless condition (no gravity), in effect, he would have no weight Although weight can vary, mass is constant regardless of its location or motion.

Let's substitute our new definitions of terms into the already lengthy statement of Newton's Second Law of Motion and see what happens The rate of change of motion of a body is directly proportional to the power or energy exerted against this body, is inversely proportional to the quantity of matter in this body, and is in the same direction as the power or energy exerted against this body Well, we've added some additional words to our statement of this law of motion, and hopefully, we've gained better understanding of what these words mean.

These laws of motion will figure in a later discussion of aircraft flight. Another factor which is essential to this discussion is called **Bernoulli's Principle.**

Daniel Bernoulli, an eighteenth-century Swiss scientist, discovered that as the velocity of a fluid increases, its pressure decreases. How and why does this work, and what does it have to do with aircraft in flight?

Bernoulli's Principle can be seen most easily through the use of a Venturi tube (see Fig 3). The **Venturi** will be discussed again in the unit on propulsion systems, since a Venturi is an extremely important part of a carburetor. A Venturi tube is simply a tube which is narrower in the middle than it is at the ends. When the fluid passing through the tube reaches the narrow part, it speeds up. According to Bernoulli's Principle, it then should exert less pressure Let's see how this works

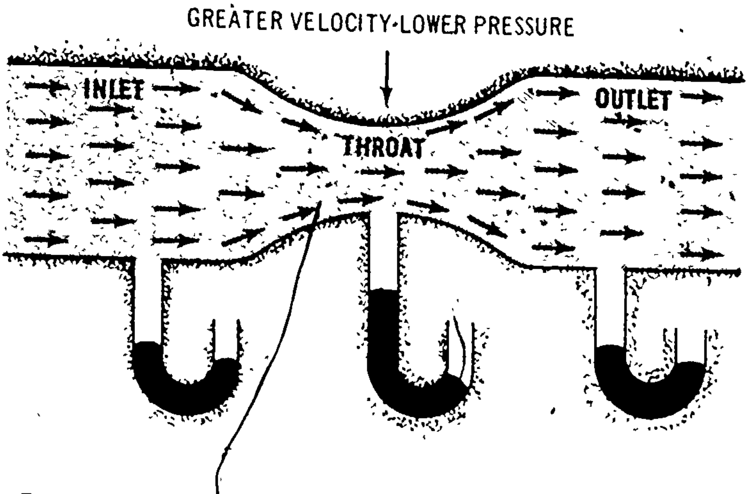


Figure 3 How a Venturi Tube Works Note how the outside air pressure forces the mercury up the center tube because the pressure in the throat is reduced

As the fluid passes over the central part of the tube, shown in Figure 3, more energy is used up as the molecules accelerate. This leaves less energy to exert pressure, and the pressure thus decreases. One way to describe this decrease in pressure is to call it a **differential pressure.** This simply means that the pressure at one point is different from the pressure at another point. For this reason, the principle is sometimes called Bernoulli's Law of Pressure Differential.

We'll be relying on Bernoulli pretty heavily in a later chapter. For the moment, though, let's imagine that we have our plane in the air. We asked you in the preface to this booklet what held it there? It may seem to you that we haven't gotten very far in answering this question, but we're on our way.

THE FORCES OF FLIGHT

Our plane is in the air, and four forces in balance with one another hold it there. These four forces are lift, weight, thrust, and drag. As you can see from Figure 4 these forces operate in pairs: thrust and drag; lift and weight. We will discuss lift and how it works in a later chapter; and you know already that **weight** is a measure of gravity, which is the attraction of the earth for all bodies on or near it. Lift operates to overcome weight, and weight serves to keep the aircraft from continuing to rise any higher than the pilot wants it to go.

How about the other pair, thrust and drag? **Thrust** is a force which gives forward motion to the aircraft. The propeller or the jet engine pro-

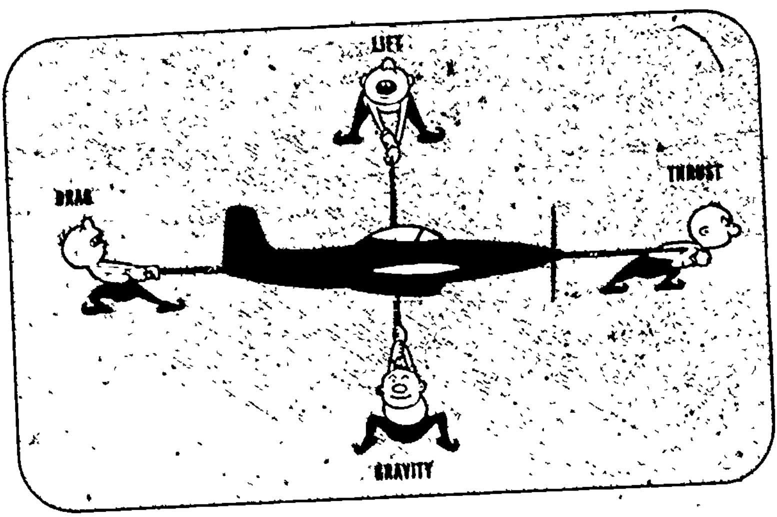


Figure 4 The Forces of Flight

duces the thrust **Drag**, on the other hand, is the force which is opposed to thrust. It opposes the forward motion of the aircraft. It is caused, basically, by the resistance of the air to the aircraft passing through it. Offhand, you may think of two of these forces—lift and thrust—as being helpful to flight, and the other two—weight and drag—as being harmful. But think about it again: if there were no weight to counteract lift, the aircraft would rise—and rise and rise—and the pilot would not be able to control it. If there were no drag to counteract thrust, the aircraft would go faster and faster, and, again, the pilot would not be able to control it. When weight and lift are equal, the aircraft flies level, neither climbing or descending. When thrust and drag are equal, the aircraft flies at a constant rate of speed, neither accelerating nor decelerating.

Newton's Second Law of Motion provides the explanation here: "For every action there must be an equal and opposite reaction." In order for a plane to fly straight and level at a constant speed, lift must be equal and opposite to weight and thrust must be equal and opposite to drag.

Therefore, each of these four forces is both an asset and a liability. They are forces to use and forces to overcome. The thrust of the engine produces the drag of air rushing past the aircraft. Without this drag, an aircraft would be like a car without brakes or steering equipment. Weight, too, can be an asset. It provides stability and control. Fuel capacity and payload (generally, passenger or cargo), which are the very things that make an aircraft a useful machine rather than a piece of sporting equipment, also mean weight.

Thrust and lift, the two helpful forces, must also be kept within the limits of usefulness and safety. An aircraft can be designed with decreased drag, but this decreased drag may also decrease lift. It may also mean that weight must be decreased, as well, so that the plane can get off the ground!

We will be coming back to these basic four forces of flight in later chapters It is important here that you see that they are in balance with one another when an aircraft is in straight and level, unaccelerated flight. Remember, when we say "straight and level," we are referring to the aircraft's path through the air.

To sum up· Man's early attempts to fly were unsuccessful because he did not understand the nature of what he was trying to do. As man's observations became more refined, his understanding increased. Scientific experimentation took the place of wishful thinking, and man finally was able to soar, wobbly at first, but with increasing confidence. Man's success in the air can be explained by describing certain forces which hold his aircraft aloft, but the entire story is somewhat more complicated.

The remaining chapters in this unit will cover other aspects of aircraft in flight.

WORDS AND PHRASES TO REMEMBER

Newton's First Law
Newton's Second Law
Newton's Third Law
acceleration
velocity
force
mass
Bernoulli's Principle
Venturi tube
differential pressure
weight
thrust
drag

THINGS TO DO

1. This chapter deals with basic principles of physics Talk with your physics teacher about experiments you might do to demonstrate Newton's Laws of Motion
2. Fasten an electric fan to roller skates and turn it on. (Have someone stand near the plug so you can stop it). Explain why the contraption worked the way it did
3. Find examples of early aircraft that did not fly Explain to the class why they couldn't fly and the aerodynamic principles involved

SUGGESTIONS FOR FUTURE READING

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REVIEW QUESTIONS

1. Man's early attempts to fly began with the:
- **a. Greeks**
- **b. Germans**
- **c. Americans**
- **d. All of the above**

2. The Daedalus and Icarus legend explains something that man could explain no other way. What was this?

3. ______ is credited with design of the parachute and an early form of the helicopter.

4. Joseph and Etienne Montgolfier discovered that ______ contained in a silk bag, rises until it cools off.

5. During George Cayley's time ______ and ______ were the primary difficulties man was encountering in the air.

6. Name two experimenters who worked with gliders in the 19th century and laid the real foundation for the Wright Brothers 1903 flight.

7. Charles Manley is credited with:
   a. Building the first powered aircraft.
   b. Being one of the first to build an internal combustion engine for an aircraft.
   c. Building a powered biplane with movable control surfaces.
   d. None of the above.

8. What are three advantages heavier-than-air craft have over lighter-than-air craft?

9. True or False. Heavier-than-air craft fly when power is applied to create thrust greater than drag, enabling airfoils to lift and support a given weight in flight.

10. State Newton's three laws of motion in your own words.

11. How much would a 180 pound man weigh on the moon?

12. Define velocity.

13. Why is there less pressure at the smaller part of a Venturi tube?

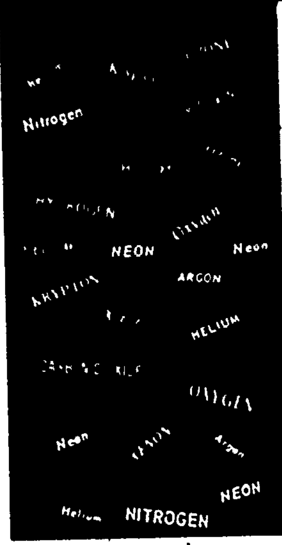
14. True or False. The history of aviation is not important to aviators.

15. List or explain the four forces of flight in your own words.

16. True or False. Each of the four forces of flight is both an asset and a liability.

17. True or False. Man's early attempts to fly were successful because he understood the nature of flying.

Chapter 2



Properties of the Atmosphere

THIS CHAPTER presents the atmosphere as an important factor in flight. Because it is where flight takes place and it makes flight possible, you will read about definitions of the atmosphere and about the composition of the atmosphere. You will also examine several physical properties of the atmosphere. After you have studied this chapter, you should be able to: (1) describe the atmosphere and identify some of the features of its layers, and (2) explain several physical properties of the atmosphere.

WE began this unit by tracing the history of man's attempts to fly and discussing some of the laws governing aircraft in flight In your own reading, you may encounter books which begin with the nature of the atmosphere, the air around us. In this chapter we will review the characteristics of the atmosphere which you studied in earlier units. Certainly the atmosphere and its characteristics are as important as the laws which describe aircraft in flight if we have to give factors relative importance. Actually, the interaction of many things and many principles is really what makes flight possible. Let's look at the atmosphere as one of the things affecting flight.

THE ATMOSPHERE: WHAT IS IT?

The atmosphere has been defined as "the envelope of air that surrounds the earth." But this definition raises certain questions. How high up does this envelope go? What is air made of? There are, of course, many other questions. Another definition describes the atmosphere as "the layer of gases surrounding the earth." This definition is still too general for our purposes.

For a very complete definition we could say the **atmosphere** is the body of air which surrounds the earth. It is usually thought of as consisting of different layers, shells, or spheres. These layers are sometimes called the troposphere, the stratosphere, and the ionosphere, they are sometimes called the lower atmosphere, the middle atmosphere and the upper atmosphere. From a different viewpoint, these spheres may have certain characteristics that make other names seem more logical such as the chemosphere, the isothermal region, the ozonosphere, the exosphere, the esophere, the physiological atmosphere, the mesosphere, and the thermosphere. Quite a mouthful, to describe what we see around us every day.

We really should notice, though, that all of these definitions include the term "air" or "gas." For our purposes, let's define **air** as "the mixture of gases in the atmosphere." Are we going in circles? Let's see.

Air is a mixture, composed of several substances. You probably already know what they are, but let's review them here. Nitrogen accounts for 78.09 percent of air, oxygen accounts for 20.93 percent of it. The oxygen and nitrogen in the air, then, make up over 99 percent of its composition. The remainder is composed of argon, carbon dioxide, neon, helium, krypton, hydrogen, xenon, and ozone—all in extremely minute quantities. Air also contains varying amounts of water vapor, smoke, and dust particles, depending on where you are and how dense the smog is! The water vapor present in the atmosphere takes on varying forms, depending upon related temperatures of the particular portion of the atmosphere it is in. And it is this water vapor, combined with the circulation of air and the action of the sun, that causes most of our weather. You have already examined the how and why of weather in Aerospace Education I; our purpose here is to examine the structure, composition, and properties of the atmosphere as these factors affect how and why aircraft fly.

COMPOSITION OF THE ATMOSPHERE

Our earlier definition of the atmosphere pointed out that the atmosphere is usually divided into various zones or layers. These layers, of course, are really spheres, because they surround the earth on all sides. The composition of the mixture we call the atmosphere varies from layer to layer. What are these layers?

The **troposphere** is the lowest layer of the atmosphere and it is only about 5 to 10 miles thick. This layer extends upward from the ground, but it is not a perfect sphere, being only about 26,000 feet thick (5 miles) at the poles. At the equator it extends upward to about 52,000 feet (10 miles). All earthbound objects are well within the troposphere, even Mt Everest. It is in the troposphere that most aircraft fly As a general rule, propeller-driven aircraft fly in the lower part of the troposphere, while jets fly in the middle and upper portions.

Spacecraft pass quickly through the troposphere in soaring to the far reaches of outer space. Since the troposphere contains over 80 percent of the air molecules, these spacecraft encounter the greatest amount of air resistance in this zone. Similarly, both propeller-driven and jet aircraft constantly encounter this large percentage of air molecules in flying in the troposphere. The effect of this resistance on an aircraft is called drag, as we mentioned in the last chapter.

The **tropopause** is the border between the troposphere and the stratosphere. The jet stream, a high-speed, globe-circling wind, is located at or near the tropopause. The usual speed of this stream of wind is 100-300 miles per hour, but windspeeds as high as 450 miles per hour have been recorded.

The next layer or zone of the atmosphere is called the **stratosphere.** This zone extends from about 52,000 feet to about 264,000 feet (approximately 10-55 miles) above the earth's surface. This portion of the atmosphere has a fairly constant frigid temperature in its lower sections The relatively small change in temperature with height in this region, reported by weather observation instruments, has been attributed to the presence of ozone, a heat-retaining form of oxygen The air is "thinner" in this region of the atmosphere, and aircraft thus encounter less resistance from the air.

The upper atmosphere, often called the **ionosphere,** contains very few particles of air. The distance between these atmospheric particles may vary from several feet to several miles. The individual gas particles break down into the electrical charges from which they are made This breakdown gives the region its name (ion-osphere). These ions form a blanket hundreds of miles thick. It is in this region that we see such electrical manifestations as the Northern Lights (Aurora Borealis)

These layers, taken together, compose the atmosphere. The layer which will concern us most is the troposphere, because most aircraft fly within this zone. When we speak of atmosphere, then, we are normally referring to the troposphere.

PHYSICAL PROPERTIES OF THE ATMOSPHERE

We have pointed out that the atmosphere is not uniform, that it is

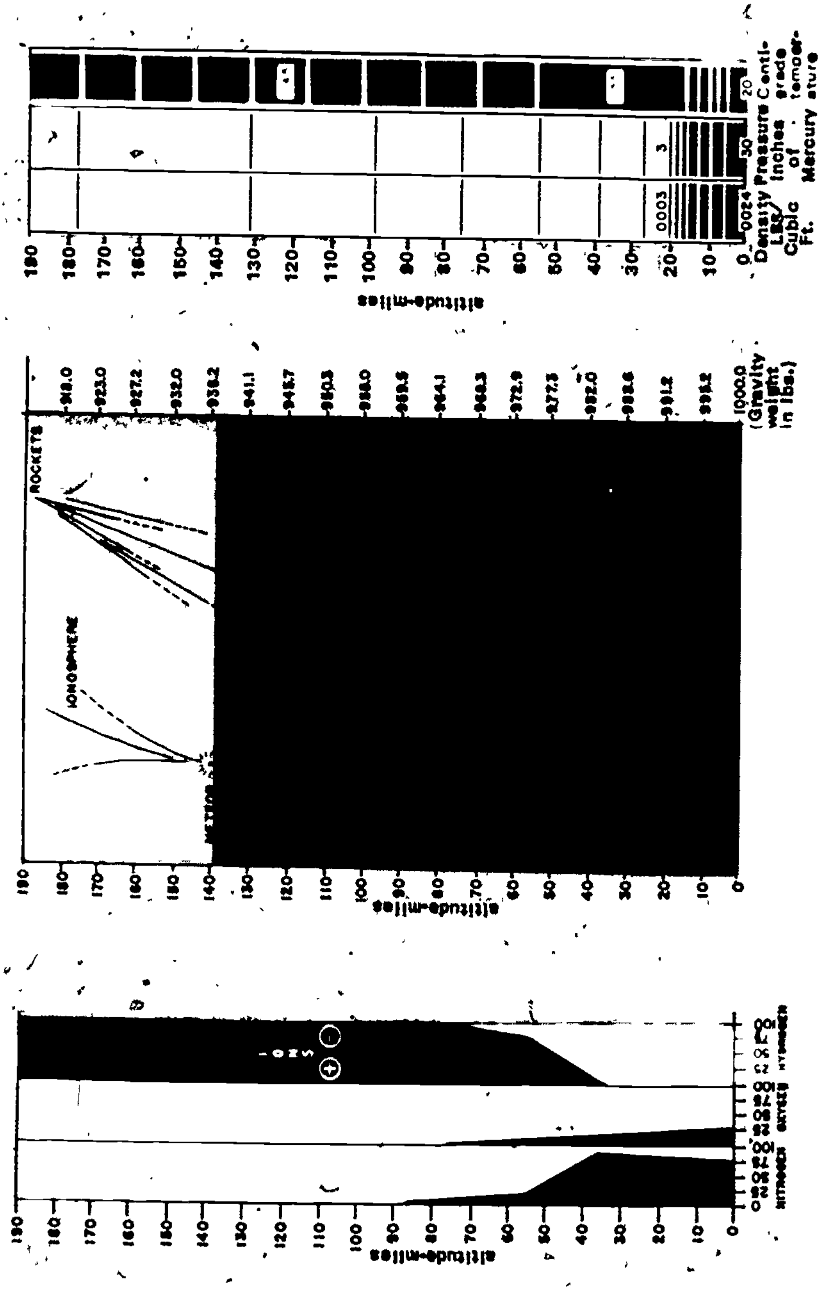

altitude-miles
ROCKETS
IONOSPHERE
Density LBS/ Cubic Ft.
Pressure Inches of Mercury
Centigrade temperature
(Gravity weight in lbs.)

Figure 5

composed of several layers of varying composition. Since aircraft fly primarily within the troposphere, we will concentrate on this lowest level of the atmosphere. But many of the general points about the atmosphere are valid for all levels (see Fig 5.).

For example, the air resting on the open book now before you weighs more than half a ton! This air is in a column, extending for about 200 miles straight up from where you are sitting through all the layers of the atmosphere. This great weight of air, however, crushes neither you nor your book. Imagine what would happen if a half-ton weight pressed directly down on you. Then why doesn't the air crush us? Air is relatively uniformly distributed throughout the lowest portion of the troposphere, so we are, in effect, in the middle of the air, rather than at the bottom of it. We also have air within our bodies, and this air also keeps us from being crushed.

What principles of matter lie behind these observable characteristics? Here they are: Air is matter, air has weight, air is fluid, air is compressible; air exerts pressure. Let's look at these characteristics one at a time.

Air is matter. How is matter defined? Matter is anything that has mass and occupies space. Since this definition includes some of the other characteristics of matter, let's look at them.

Air has weight We've already mentioned this. The vertical column of air extending upward from the earth weighs a great deal

Air occupies space. A vacuum is the absence of air; various suction devices we see around us work on the vacuum principle.

Air is a fluid. Now we're getting somewhere. **Fluids** are substances which may be made to change shape or to flow by applying pressure to them. Both gases and liquids are called fluids, because both substances behave similarly under certain conditions. But even though they share several common characteristics, certain characteristics are true of gases alone. For example, gases may be compressed, while for practical purposes, liquids are incompressible. This brings us to our next characteristic.

Air is **compressible.** What does this mean? It means simply that a given quantity of air may be made to occupy differing amounts of space A given number of molecules of air may be forced into a space smaller than the space they normally occupy

Air exerts pressure. Let's take our quantity of air which we've forced into a smaller container. We've had to expend a force on this air to get it into the smaller container. The air, in turn, exerts a force upon the walls of the container. This force is called pressure, and the air is said to exert pressure. If the air is pumped out of a closed container, creating a partial vacuum, the air molecules on the outside of the container exert a force

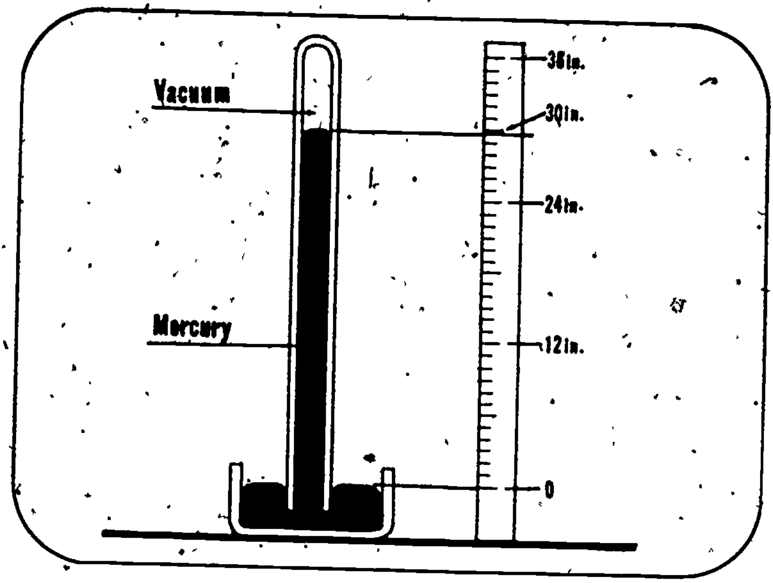


Figure 6 Torricelli's Barometer

on the walls of the container equal to the potential energy lost when the contained air molecules were removed This external pressure may well crush the container, if it is not sturdily made

Pressure is defined as force per unit area Force is measured in pounds, and area may be measured in any desired units. Air pressure is usually measured in pounds (of air pressure) per square inch (of surface area) The seventeenth century Italian physicist Torricelli performed an experiment which led to an easy way to measure air pressure You may be familiar with his experiment, but it bears repeating here (see Fig 6). He filled a glass tube about 36 inches long with liquid mercury He then inverted this filled tube in an open dish containing more mercury When he removed his thumb from the bottom of the filled tube of mercury, he found that it did not all flow out of the tube About 30 inches of the tube remained filled with the mercury What held the mercury up in the tube?

Air, pressing on the mercury in the dish, maintained the level of the mercury in the tube Torricelli also observed that this level fluctuated It rose before a period of good weather; and it fell before a period of stormy weather. He therefore concluded that the pressure exerted by the air had something to do with the weather. Today, we know that pressure alone is not the entire answer to predicting the weather, but we also realize the significance of Torricelli's discovery to an accurate understanding of what air is and how it works

The mercury in Torricelli's tube weighed 0.491 pounds per cubic inch. This means that each cubic inch will exert a pressure of 0.491 pounds per square inch in all directions. The column of mercury in the 30 inch tube, then, will exert a pressure of 0.491 pounds per square inch times 30 inches, which is 14.73 pounds per square inch. Standard pressure is usually defined as the pressure necessary to raise a column of mercury to a height of 29.92 inches. This standard pressure, then, may be conveniently expressed as 14.7 pounds per square inch.

We should also make one other point about air pressure here When air pressure is measured by means of a column of mercury, the resulting pressure is called **absolute pressure,** because the mercury column measures the pressure of the air relative to zero pressure. When you check the air pressure in your automobile tires and get a reading of 30 pounds per square inch, on the other hand, you are really comparing the air pressure inside the tire with the air pressure outside the tire. For this reason, this sort of pressure measurement is called **relative pressure:** you are making a reading of pressure relative to the existing outside air pressure If you wanted to compute the absolute pressure of the air inside the tire, you would simply add the existing outside air pressure to the reading on the tire gauge.

Let's turn now to another characteristic of air. Air has density What, exactly, does this mean? Density is defined as mass per unit volume Mass, we pointed out earlier, refers to the quantity of matter in a given substance. When we combine all these terms, we get this **density** *is the quantity of matter in a given substance per unit of volume of that substance.* The unit of mass used in this country is the slug The weight of the slug is determined by a rather complicated formula involving Newton's Second Law of Motion and the theory of acceleration. For our purposes it's enough to say that one slug would weigh 32.17 pounds. At sea level, a cubic foot of dry air weighs 0.0765 pounds, and this same cubic foot of air, then, has a mass density of 0.002378 slugs

This all boils down to saying that at sea level, the bottom of the column of air over the earth, a given cubic foot of air will weigh 0.0765 pounds and will have a mass density of 0 002378 slugs. However, at any location above sea level, the weight and density of a given cubic foot of air will change (see Fig 7). Imagine a pile of bricks 100 feet high. The brick on the bottom has the weight of all the other 99 bricks pressing on it. This means that it will have a greater amount of pressure on it than will the brick on the top In this respect the column of bricks is like the column of air in the atmosphere

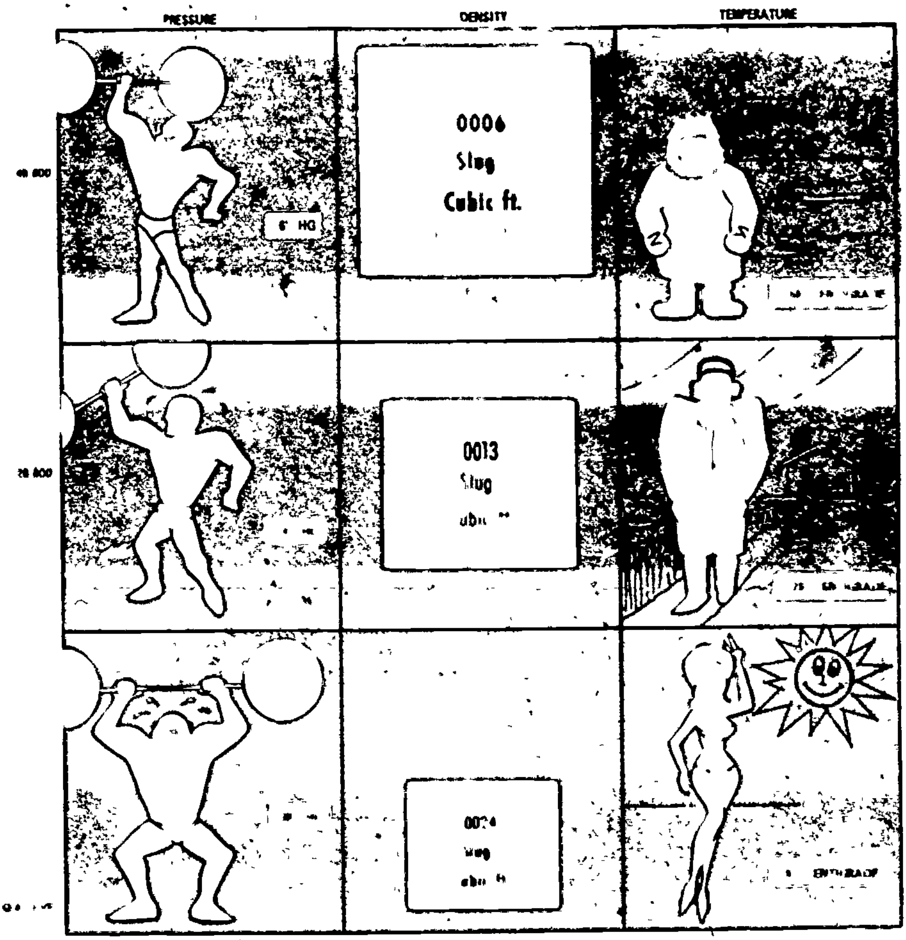


Figure 7 Pressure-Density-Temperature variations with changes in Altitude The Slug is a measure of Air Mass It is used in Horsepower Computations which are discussed in *Propulsion Systems for Aircraft*

But each brick has the same mass—there is the same amount of matter in the bottom brick as in the top brick. The column of air, though, is different. A cubic foot of air at the bottom of the atmosphere simply has more molecules in it than a cubic foot of air at the top of the atmosphere. To describe this, we say that the air at the bottom of the atmosphere has a greater density then the air at the top of the atmosphere

Each intermediate step, between the bottom and the top of the atmosphere, has a gradually lessening number of molecules of air—and so we can say that density decreases as height increases This simply means that the higher you go, the less air there is. This fact is of great significance to pilots, as we will explain a bit further on.

Another characteristic of air is its ability to hold varying amounts of water vapor When we listed the components of air earlier in this chapter, we said that air contains varying amounts of water vapor Let's look at this water vapor now, examine what it does to the atmosphere, and evaluate its effect on aircraft flight.

Which weighs more?—a cubic foot of air or a cubic foot of water? Naturally, the cubic foot of water is much, much heavier than the cubic foot of air. Does it follow, then, that adding water to the air, in the form of water vapor, should make the air much heavier? Oddly enough, adding water vapor to the air makes the air less dense and, consequently, lighter in weight. Let's see how this works.

Water vapor is water in a gaseous state. Its density is 0.001476 slugs per cubic foot. Air, you will remember, has a density of 0 002378 slugs per cubic foot. The water vapor, then, will weigh only about five-eighths as much as a similar amount of air. When a given amount of this water vapor is mixed with air, it displaces a similar quantity of the heavier air. Hence, the same quantity of air with water vapor mixed with it is less dense then dry air and therefore weighs less. It's ironic that on a hot, humid, muggy day we say that the air feels oppressive and heavy, because the air really is lighter. Probably you would run into some trouble convincing people that the air really is lighter, because it "feels" heavy. It "feels" heavy, of course, because perspiration, a cooling process, is not as efficient when water vapor is already present in the air. But this takes us to the realm of weather, covered in last year's work.

Let's move on to another characteristic of air which is important to both weather and aircraft flight—temperature. We have already mentioned that the temperature of the atmosphere varies with height Certain levels of the atmosphere have much lower and more constant temperatures than the troposphere, the lowest level of the atmosphere For the moment, then, let us concern ourselves with a discussion of the relationship between temperature and pressure within the troposphere

Increasing the temperature of air decreases its density Decreasing the temperature of air raises its density. The pressure on the air has to remain constant during these changes in temperature for the density to be affected in this way What this really means is that there is less air per cubic foot when the temperature is high

Let's try to sum up what we've said about the air and its characteristics.

- The atmosphere is composed of several levels of mixed gases
- The troposhere is the lowest of these levels.
- Air, a name conveniently used for atmosphere, has several important physical characteristics it is matter, it is a fluid, it is compressible, it exerts pressure, it can hold varying amounts of water vapor, and it is affected by changes in temperature

All of these properties of the air around us will take on importance in your understanding of why planes fly. In order to understand the airfoil and its role in flight, our next major topic, you'll be relying both on your knowledge of the atmosphere and on your knowledge of the physical principles sketched out in our first chapter.

WORDS AND PHRASES TO REMEMBER

atmosphere
air
troposphere
tropopause
stratosphere
ionosphere
fluids
compressible
pressure
absolute pressure
relative pressure
density

THINGS TO DO

1. Review the *Aerospace Environment* textbook Are there any important properties of the atmosphere which were not covered in this chapter? Report to the class on your findings
2. Water, like air, is a fluid Experiment with different objects to see if they float Measure the amount of water (fluid) they displace Compare the properties of air and water
3. Ask a pilot to explain why an aircraft requires a longer runway for takeoff on hot days or when the runway elevation is high, as in Denver, Colorado
4. Discuss the properties of the atmosphere with your chemistry teacher Are there any experiments he or she can suggest to demonstrate the composition or properties of the atmosphere?

SUGGESTIONS FOR FURTHER READING

Federal Aviation Administration *Private Pilot's Handbook of Aeronautical Knowledge* Washington US Government Printing Office, 1965 (AC 61 23)

McKinley James L and Ralph D Bent *Basic Science for Aerospace Vehicles* 4th ed New York McGraw Hill Book Company 1972

Misenheimer Ted G *Aeroscience* Second Edition Los Angeles Aero Products Research, Inc, 1973

Oxenhorn Joseph M *Oceans of Air And Water* New York Globe Book Company, 1969

Sanderson *Aviation Fundamentals* Denver Colorado Sanderson Times-Mirror, 1972

PROPERTIES OF THE ATMOSPHERE

REVIEW QUESTIONS

1. The body of air which surrounds the earth is called the ________.

2. The layers of the atmosphere are called the ________, the ________, and the ________.

3. Define air.

4. The most important ingredient in air for sustaining human life is ________.

5. The layer of the atmosphere where most aircraft fly is called the ________.

6. What is the name of the border zone between the stratosphere and the troposphere?

7. The stratosphere extends from approximately ________ to ________ miles above the earth's surface.

8. The layer that contains very few particles of air is called the ________ or the ________.

9. True or False. Air is matter and has weight.

10. Air:
    a. exerts pressure
    b. is a fluid
    c. is compressible
    d. all of the above

11. Define fluids.

12. "Force per unit area" defines ________.

13. Why didn't all of the mercury flow out of Torricelli's tube? How much stayed?

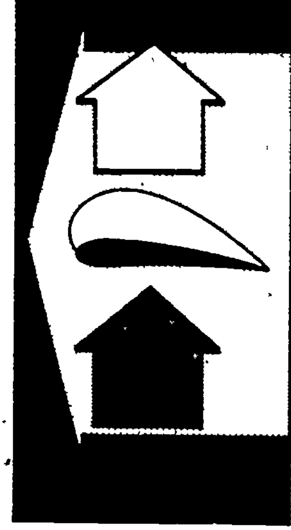
14. True or False. When you check the air pressure in your tires you are measuring the absolute pressure.

15. When you climb to higher altitude the air becomes (more/less) dense.

16. Adding water vapor makes air (more/less) dense and (heavier/lighter) in weight.

17. If we keep pressure constant, decreasing the temperature of air (increases/decreases) its density.

Chapter **3**



Airfoils and Flight

THIS CHAPTER is perhaps the most critical section of the entire unit. It explains exactly why aircraft can fly. First, you will examine the airfoil and learn its parts and its role in generating lift. Next, you will see how airflow and wing interact to produce lift. You will examine the Venturi tube and see how it, too, helps to explain lift. Finally, you will look at several ways that lift can be changed. After you have studied this chapter, you should be able to: (1) discuss the parts of an airfoil and tell how each part helps to create lift; (2) differentiate between pressure differential and impact lift; (3) show how lift can be varied and explain what happens as a result; and (4) relate the concept of lift to what you learned in the first two chapters about physical principles and the atmosphere.

NOW we are getting into the real meat of this complicated business of aircraft flight. A balloon "flies" because the gas inside it is lighter than air. A heavier than-air aircraft must depend upon something entirely different to sustain flight. "Heavier-than-air aircraft fly because, through the application of power to the resistance of air, airfoils create lift, and this lift sustains a given weight in flight." Remember that statement? We cited it back in the first chapter, when we were discussing the physical laws that lie behind the science of flight. Since then, we have looked at some of the physical properties of air that you must understand to begin to see the total impact of this statement. Now let's see how these things tie together.

AIRFOILS

The term airfoil will occur again and again in our discussion of aircraft flight. An **airfoil** may be defined as any part of the aircraft that is designed to produce lift. Although the wing is the primary airfoil on an aircraft, other airfoils may be the propeller blades, the tail surfaces, or, in some cases the fuselage itself.

AIRFOIL DESIGN

In this definition, we point out that an airfoil is designed to produce lift. Part of the Wright brothers' achievement was their realization that the scientific study of how an airfoil (a wing) behaves in a moving stream of air is essential to determining whether or not the airfoil will sustain flight. They realized, in other words, that you have to experiment with a wing first, before you build an entire aircraft. This realization, while not new, is just as important today as it was then.

The Wrights' wind tunnel was simply a tunnel with a large fan at one end to blow air past a suspended section of wing. Modern wind tunnels are much more complex, but they are made essentially the same way

It is important to note here that the air flowing past an airfoil suspended in a wind tunnel behaves in the same way as the air flowing over an airfoil in flight. We'll discuss this wind flowing past an airfoil a little later on, but remember that the air moving past the stationary airfoil is the same as the airfoil moving through the air.

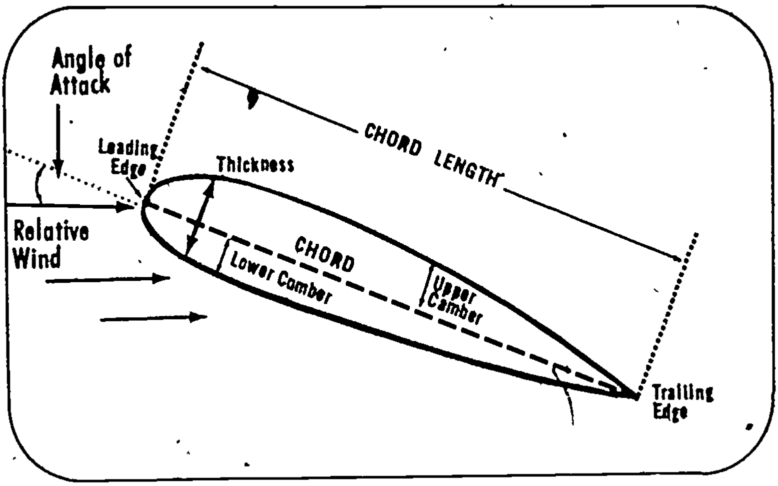


Figure 8 Elements of an Airfoil

An airfoil has a leading edge, a trailing edge, a chord, and camber, as shown in Figure 8. An understanding of these terms is essential to an understanding of airfoil design, so we will discuss each term individually

Leading Edge

This is the "front" of the airfoil, the portion that meets the air first. The shape of the **leading edge** depends upon the function of the airfoil If the airfoil is designed to operate at high speed with a minimum amount of lift, its leading edge may be very sharp, as on most current fighter aircraft. If the airfoil is designed to produce a greater amount of lift at a relatively low rate of speed, as in a Cessna 150 or a Cherokee 140, the leading edge may be thick and fat. Actually, the supersonic fighter aircraft and the light propeller-driven aircraft are virtually two ends of a spectrum. Most other aircraft lie between these two. The leading edges of their airfoils may have a compromise shape, designed to provide a moderate amount of lift at relatively high speeds. The A-7 Corsair is a good example. Bear in mind, though, that the purpose of the airfoil will determine the characteristic shape of its leading edge.

Trailing Edge

The **trailing edge** is the "back" of the airfoil, the portion at which the airflow over the upper surface joins the airflow over the lower surface. The design of this portion of the airfoil is just as important as the design of the leading edge. This is because the air flowing over the upper and lower surfaces of the airfoil must be directed to meet with as little turbulence as possible, regardless of the position of the airfoil in the air.

Chord

The **chord** of an airfoil is an imaginary straight line drawn through the airfoil from its leading edge to its trailing edge When you look at an airfoil, you can see its leading edge and its trailing edge, but you can't see its chord, because this line is imaginary. If it is an imaginary straight line, why, then, is it important? It is important to an understanding of relative wind, our next major subject area, and it is important to an understanding of our next definition, camber.

Camber

The **camber** of an airfoil is the characteristic curve of its upper or lower surface This characteristic curve is measured by how much it departs from the chord (a straight line) of the airfoil A high-speed, low lift airfoil, the type found on the F-4, has very little camber A low-speed, high-lift airfoil, like that on the Cessna 150, has a very pronounced camber.

You may also encounter the terms **upper camber** and **lower camber.** Upper camber refers to the curve of the upper surface of the airfoil, while lower camber refers to the curve of the lower surface of the airfoil. In the great majority of airfoils, upper and lower cambers differ from one another. When the curve is away from the chord, the camber is said to be positive When the curve is toward the chord, the camber is said to be negative.

Once again we need to refer to Bernoulli's Principle. As the velocity of a fluid increases, its pressure decreases. The camber of an airfoil causes an increase in velocity and a consequent decrease in pressure of the stream of air moving over it. But more on that later.

RELATIVE WIND

Have you ever held your flattened hand out of the window of a moving automobile? When you held your hand level with the road, you were able to hold your hand there with very little effort. Because the car had to keep its' wheels on the road, the air flowing over your hand always paralleled the road. An aircraft, however, is not restricted to one fixed plane of flight But similar to the case of the automobile, the air flows parallel to the aircraft's *path of flight*. This flow of air is called the **relative wind.** The relative wind is created by the movement of the aircraft through the air, thus the flight path and relative wind are parallel, but act in opposite directions (see Fig 9).

If that were the only factor, flying would be very simple. Let's get back to your hand out of the moving car window. Picture your hand as an airfoil with the chord line running from your fingertips to your wrist. When you lowered or raised your fingers, your hand tried to climb or descend What you did, was to change the angle of attack. Had your

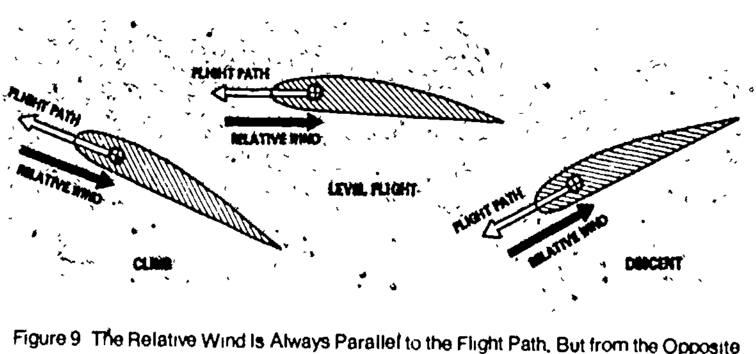


Figure 9 The Relative Wind Is Always Parallel to the Flight Path, But from the Opposite Direction

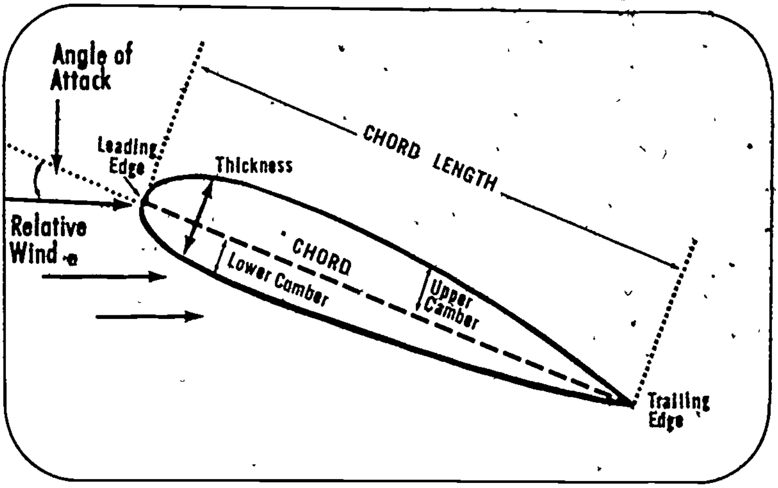


Figure 10. Angle of attack and Relative Wind.

hand been an actual airfoil (you're the pilot), this change in angle of attack would probably have changed the flight path, thereby changing the direction of the relative wind (see Fig 10).

That's what the term relative wind means. It is the wind which is moving past the airfoil, and the direction of this wind is parallel to the flight path and relative to the attitude or position of the airfoil. Who controls the position of the airfoil? The pilot, of course, consequently, the pilot controls the direction of the relative wind. What controls the velocity of the relative wind? The speed of the airfoil through the air, of course. The pilot controls this too.

ANGLE OF ATTACK

We mentioned the term angle of attack in our discussion of relative wind. From the example of your hand out a car window, you may have already decided that angle of attack is the angle at which relative wind meets the airfoil. But my hand has an unusual shape, what part of the airfoil forms the angle involved?

Here's where we use the chord of the airfoil, that imaginary line we drew from leading edge to trailing edge of the airfoil. To sharpen up our definition, the **angle of attack** is the angle formed by the chord of the airfoil and the direction of the relative wind or between the chord line and the flight path. The angle of attack is not a constant during a flight, rather, it changes as the pilot changes the attitude of the aircraft. The

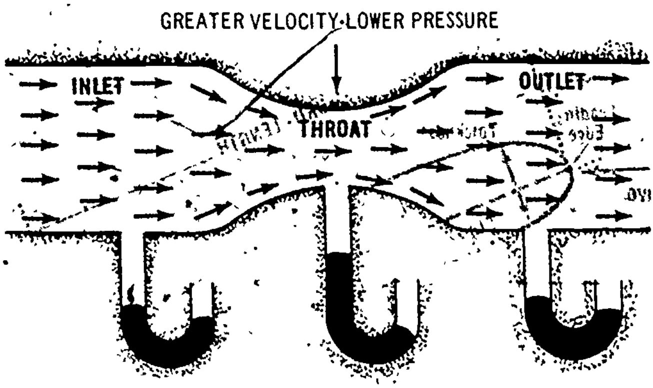


Figure 11 How a Venturi Tube Works. Note how the outside air pressure forces the mercury up the center tube because the pressure in the throat is reduced

angle of attack is one of the factors which determines the aircraft's rate of speed through the air.

Don't confuse angle of attack with angle of incidence. The **angle of incidence is** the angle at which the wing is fixed to the aircraft's fuselage, or body. Strictly speaking, the angle of incidence is the angle formed by our old friend the chord of the airfoil and the longitudinal axis of the aircraft. This longitudinal axis of the aircraft is an imaginary line drawn through the fuselage from the front of the aircraft to the rear of the aircraft—but we'll have more on the axes of flight in a later section. Right now, the important thing to remember is that angle of attack is the angle formed between the chord of the wing and the relative wind, and this has a great deal to do with lift, our next major subject.

Also do not confuse the aircraft attitude with angle of attack. **Attitude** is normally considered to be the aircraft position in relation to the horizon. A nosehigh attitude might mean the aircraft is climbing or it could be flying "straight and level" unaccelerating or it might even be descending in this attitude. As we progress through our explanations of lift, this will become more clear.

LIFT

Once again we need to review Bernoulli's Principle and how it applies to lift. Let's begin with the diagram we showed you earlier of a Venturi tube (Fig 11), which illustrates Bernoulli's Principle. As the velocity of a fluid increases, its pressure decreases, or to put it another way, as the velocity of a fluid increases past an object, the less sidewise pressure the fluid exerts on the object.

Imagine, now, that we remove the upper part of the Venturi tube. Figure 12 is what we get:

Figure 12.

Notice the air flow, it continues to increase in velocity at the point of the bulge, which is really the point of maximum camber. Now, if we bring the other part of the Venturi back but put it underneath, we get Figure 13.

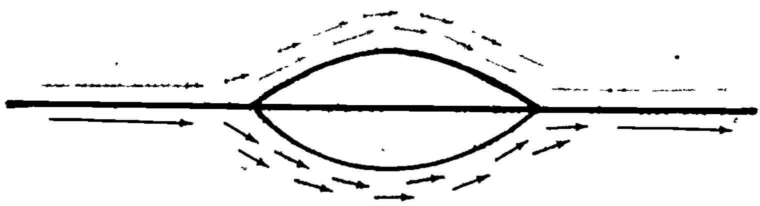


Figure 13

This looks suspiciously like the section of an airfoil, doesn't it? Let's just change a curve or two (we're actually adjusting the camber), Figure 14 is what we get:

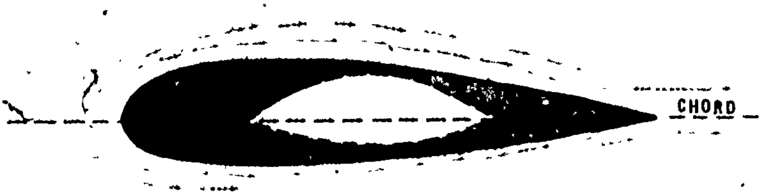


Figure 14

The changing of the curve is really a redesigning of the camber of the airfoil We've taken advantage of Bernoulli's Principle, too. The pressure generated by the moving stream of air on the lower surface of the airfoil is greater than the pressure generated by the moving stream of air on the upper surface of the airfoil. What will happen? The airfoil will be raised, or lifted, by this difference in pressure. This is **lift.** The airfoil is literally lifted by the difference in pressure, or pressure differential, between the upper and lower surfaces of the airfoil. This kind of lift is called **pressure-differential** lift.

It may interest you to know, at this point, that lift can also be created by an airfoil without any camber at all. This lift, however, is completely different from the lift we have been talking about. It is caused by the pressure of impact air against the lower surface of the airfoil.

A kite flying on a balmy spring day is an excellent example of an airfoil without camber being sustained in flight by impact air against its lower surface. Similar to the airfoil in the wind tunnel it makes no difference to the kite whether it is moving forward through the air or the air is moving past it. It simply goes on and hangs up there in the spring sky. If you have flown a kite, however, you know there's a difference. You know that when the wind is light, you have to run your legs off at times to get the kite airborne.

The same kind of lift also helps hold the aircraft in the air. Think back to Newton's Third Law of Motion. For every action, there is an equal and opposite reaction. This law explains the second kind of lift, **impact lift,** which helps sustain aircraft in flight.

We've pointed out that air is a fluid. The passing of the airfoil through the air is an action. We can expect, then, that the air will act upon the wing. This is the reaction. The lower surface of the wing meets the air at a slight angle (the angle of attack, which we've already covered). The air flowing past the lower surface is deflected slightly. The wing exerts a force on the air in order to do this—while the air, meanwhile, exerts an equal and opposite force on the wing. This force of the air (the reaction force) causes lift. The amount of lift generated by this action-reaction process usually amounts to only about 15 percent of the total lifting force necessary to sustain aircraft flight. However, it can create a much greater percentage as was the case when you put your hand out the car window.

Adding impact lift to pressure differential lift gives us total lift. Figure 15 will help us to visualize this.

Let's sum up. Think back to the opening paragraph of this chapter. Heavier than air aircraft fly because, through the application of power to the resistance of air, airfoils create lift, and this lift sustains a given weight in flight. Remember that capsule statement? We've concentrated on how airfoils create lift in this section. How *do* airfoils create lift?

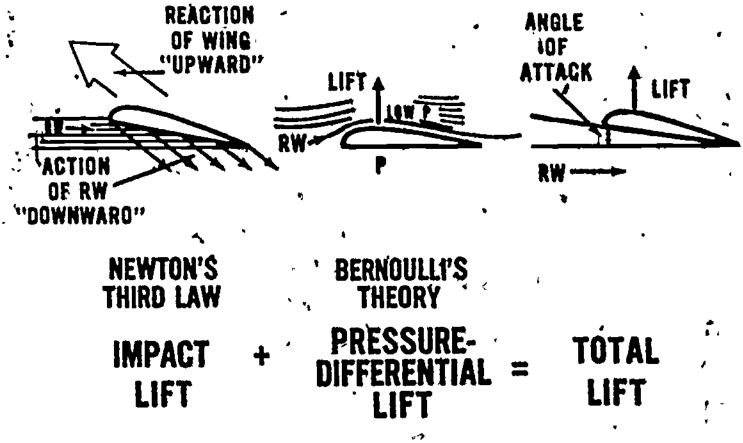


Figure 15 The Forces Making Up Total Lift.

They make use of Bernoulli's Principle and Newton's Third Law of Motion. Airfoils move through the air, creating an interaction between air and airfoils. This interaction takes the form of a difference in pressure between upper and lower surfaces of the airfoil, and the decreased pressure on the upper surface of the airfoil causes lift. Additional lift comes from the force of the impact air on the airfoil moving through the air.

LIFT VARIABLES

Now we know how lift is generated. The next step is to tell you how lift is controlled. The pilot must have at his disposal some way to control the amount of lift which the airfoils generate. If he didn't, the aircraft would either constantly stall or climb. Here are some of the variables acting on the amount of lift generated. angle of attack, velocity of relative wind (speed of the aircraft), air density, airfoil shape, wing area, airfoil planforms, and high-lift devices. Let's look at these, one at a time.

Angle of Attack Again

Looking first at angle of attack, remember that it is the angle formed by the chord of the airfoil and the direction of the relative wind. Remember that the angle of attack of an aircraft is not a constant during a given flight, rather, it is one of the things over which the pilot has control and which he can change.

Changing the angle of attack can change the amount of lift generated as the airfoil moves through the air. Let's see how this works.

Airflow over an airfoil is normally smooth, with no burbling or turbulence. Burbling breaks the flow of air, causing a loss of lift. In the case of an airfoil with a flat or approximately flat undersurface, when the lower surface is parallel to the relative wind, there is no impact pressure on the lower surface. The whole lift force, then, comes from reduced pressure along the upper surface (pressure differential lift). When the wing is tipped up so that the lower surface makes an angle of 5 degrees with the relative wind, the impact pressure on the under surface contributes about 25 percent of the total lift. When it is tipped up to 10 degrees, the impact pressure on the lower surface produces about 30 percent of the total lift.

A small force acts on each tiny portion of the wing. This force is different in magnitude (size) and direction from the force acting on other small areas of the surface which are farther forward or rearward. It is possible to add mathematically all of these small forces, taking into account their magnitude, direction, and location. The sum of all the tiny forces over the surface of the wing is called the **resultant**, since it results

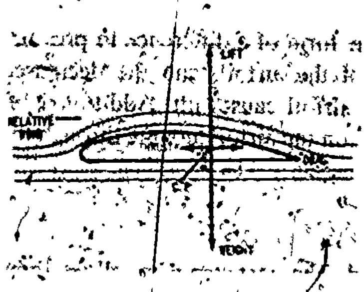


Figure 16. Straight and Level Unaccelerated Flight.

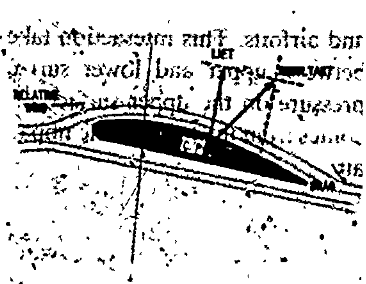


Figure 17. Low Angle of Attack.

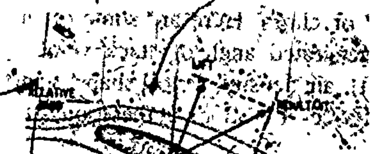


Figure 18. Approaching Stall

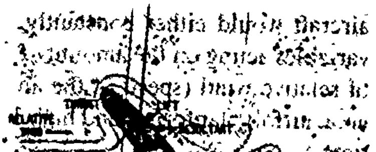


Figure 19 Full Stall

from adding all the forces together. This resultant has magnitude, direction, and location. The point of intersection of the resultant with the chord of the wing is called the **center of pressure** (C/P).

Figure 16 shows the four forces acting on an aircraft in straight and level unaccelerated flight in balance. Let's see what happens when the pilot increases the angle of attack of the wing. Figure 17 shows the wing at a low angle of attack. The center of pressure (C/P) is in about the same place as in Figure 16 The resultant is upward and back from the vertical, and we can assume that the aircraft will climb. Notice Figure 18 now. The angle of attack of the wing is greater. The center of pressure has moved forward, and the resultant is somewhat larger, which means that the aircraft will climb more quickly.

The angle at which lift stops increasing and begins to decrease is called the **burble point.** You may also find this angle called the stalling angle or the angle of maximum lift. When the angle of attack is increased beyond the burble point, the resultant decreases in magnitude and its angle back from the vertical becomes bigger (see Figure 19).

Note that at the various angles just described, the direction of the resultant has had an upward and backward direction. If, then, it is broken up into components or parts, the vertical component will be upward, and the horizontal component will be backward. You can see now that lift is the component of the resultant force, which is perpendicular to the chord of the airfoil. It should also be noted that as the angle of attack increases, the center of pressure moves forward, when the angle of attack decreases, the center of pressure moves backward.

Now let's see what the pilot can do with angle of attack. As the angle of attack is increased, more and more lift is generated. This increase in amount of lift continues up to a certain angle of attack (the burble point, mentioned above) which depends on the type of wing design. Most aircraft wings have a burble point of somewhere between 15 and 20 degrees, but, again, this is built into the aircraft. What happens when the aircraft reaches this high angle of attack? The air no longer flows smoothly over the top surface of the airfoil. Instead, it breaks away from the surface and forms violent eddies. This is called **burbling.** When burbling is taking place on a surface, there can be no decrease in pressure below atmospheric pressure. Why not? The turbulence of the air doesn't allow for a smooth increase in air velocity which produces the reduced pressure. Hence, there can be no lift. From this point on, then, as the angle of attack is increased, the amount of lift generated is decreased. The pilot, then, does well to know exactly the maximum angle of attack in which his aircraft can be placed to prevent loss of lift!

The point at which the amount of lift generated is no longer sufficient to support the aircraft in the air is called the **stalling point**, and the maneuver in which the pilot does this is called the **stall**. If you should hear of a pilot who stalled his aircraft, you will know that he's referring to something he did with the lifting surfaces, rather than something involving his engine! The stall is a useful maneuver, however. When an aircraft lands, the pilot often deliberately stalls it. How does he do this? He simply gradually increases the angle of attack until the aircraft no longer has any lifting forces. Meanwhile, the aircraft is going forward—and when all goes well, the airfoils stall just as the aircraft hits the runway.

Another Lift Variable—Velocity of Relative Wind

Changes in angle of attack, then, can increase or decrease the amount of lift generated. The velocity of the airfoil through the air is another important factor in determining the amount of lift generated. Let's see how this works.

If an airfoil is made to travel faster through the air, a greater pressure difference between the lower and upper surfaces of the airfoil results. The impact pressure on the lower surface is greater, and the decrease in pressure on the upper surface is also greater. So, as the speed increases, the lift increases, within practical limitations, of course. This increase in lift, though, is not a directly proportional increase (that is, there isn't a one-for-one gain of lift for velocity). Actually, the lift increases as the square of the velocity.

For example, an aircraft traveling 100 mph has four times as much lift as the same aircraft traveling at 50 mph., because the square of 100 (100x100 = 10,000) is four times the square of 50 (50x50 = 2,500). This increase assumes, of course, that the angle of attack stays the same.

You probably have been water skiing or have watched someone water ski at one time or another. You may have noticed that a larger engine is needed to get a larger skier up on his skis in the water. It's the same principle there as here: the faster the skis are pulled over the water, the greater the weight they can support.

Air Density and Lift

Air density is another variable factor which can influence lift. In chapter 2 we discussed air density and how it varies with altitude. We pointed out that air density is important in flight. Here's why.

The first thing we should note is that lift varies directly with density. For instance, at 18,000 feet, where the density is about half that at sea level, an aircraft will need to travel 1.414 times as fast as it would at sea level to maintain altitude. The figure 1.414 is the square root of 2. We said in the last section that lift varies as the square of the speed. It follows, then, if something reduces the lift by half, we have to increase the speed so that the square of the new velocity is twice the square of the original velocity. If the original velocity is Vo and the new velocity is Vn, then Vn^2 must equal $2Vo^2$. This is simply a mathematical statement of the velocity-density relationship.

For example, assume that Vo is 50 mph. Then Vn must be 70.7 mph (50x1.414 = 70.700). The square of 50 is 2,500, and the square of 70 7 is 4,998.5, or about 5,000, which is twice as much. In chapter 2 of this unit, we pointed out that air density is decreased not only by altitude but also by an increase in temperature and by an increase in humidity It is important to bear this in mind, because even at sea level, the aircraft must go faster to stay in the air on a warm humid day than on a dry and cool day.

Airfoil Shape as a Variable

In the section on camber, we stated that the camber of an airfoil is fixed Strictly speaking, this isn't quite true. Up to a certain point, the greater the camber, the greater the lift. Hence, it becomes extremely important, once an airfoil has been designed, to preserve the characteristic curve the designers build into the airfoil. Otherwise, the aircraft will not perform as it should Dents, mud, and ice are three common things that can spoil the built-in shape of the airfoil and hence interfere with the performance of the entire aircraft.

Wing Area and Lift

When we discussed lift, we pointed out that differences in pressure between the upper and the lower surfaces of the airfoil were the main source of lift in most aircraft. It is interesting to note how increases in the wing area affect the effective lifting force.

If the pressure differential is only 2½ ounces per square inch (a very small amount of differential pressure), this pressure differential will produce a lifting force of more than 20 pounds per square foot (144 square inches/square foot × 2½ ounces/square inch). In general, the greater the surface area of the wing, the greater the amount of lift that will be generated, within practical limitations if the proportions of the wing and the airfoil section stay the same

Gliders or sailplanes are very good examples of how a large wing surface generates lift Advances in technology are making possible lift potentials which would have staggered the Wright brothers Lighter, stronger materials are being developed, so that today's aircraft can be built to withstand tremendous strains and yet not be heavy.

Although it is not something the pilot can control, wing area certainly does vary from aircraft to aircraft, and more importantly, wing area differences provide great variations in the amount of lift generated

Planform of an Airfoil

We've been looking, for the most part, at airfoil sections—side views of airfoils—in our discussion of lift. Another way to look at an aircraft wing is from the top. This is called the planform of the wing. The **planform** is simply the shape of the wing as seen from directly above or below. We'll have more to say later on planforms, but you should note here that the planform of the wing provides us another way to measure the efficiency of the lifting force.

Aspect ratio is a statement of the relationship between the length and the width of a wing. It can be computed by dividing the **span** (the distance from wing tip to wing tip) by the average chord (distance from leading edge to trailing edge) of the wing. In the case of tapered wings, it is sometimes difficult to find average chord It is usually simpler to com

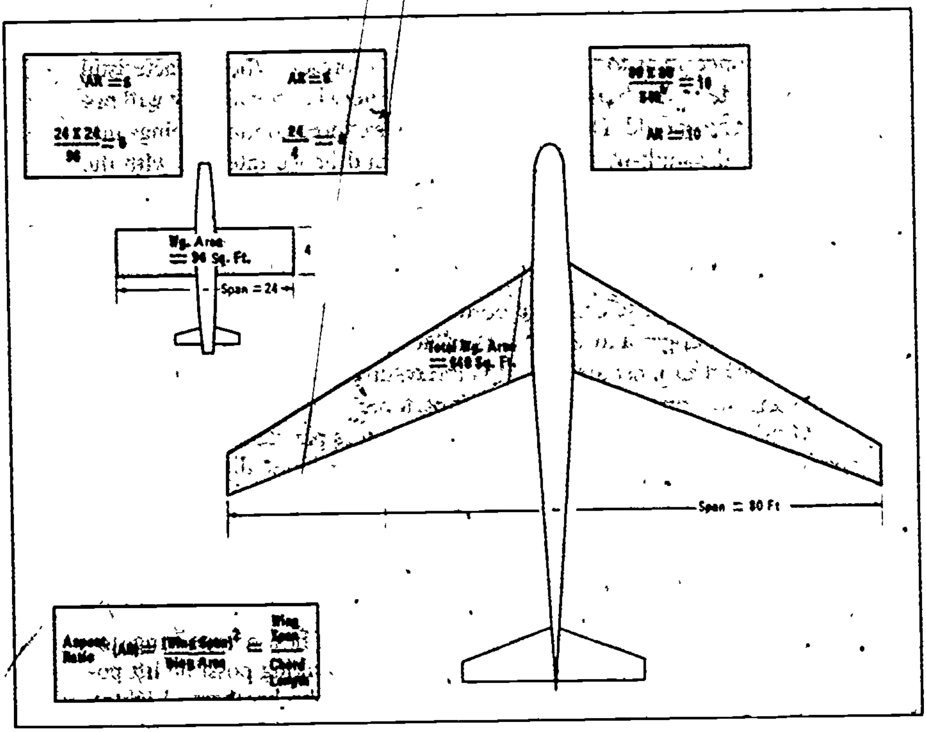


Figure 20 Aspect Ratio Varies with the Planform of an Airfoil

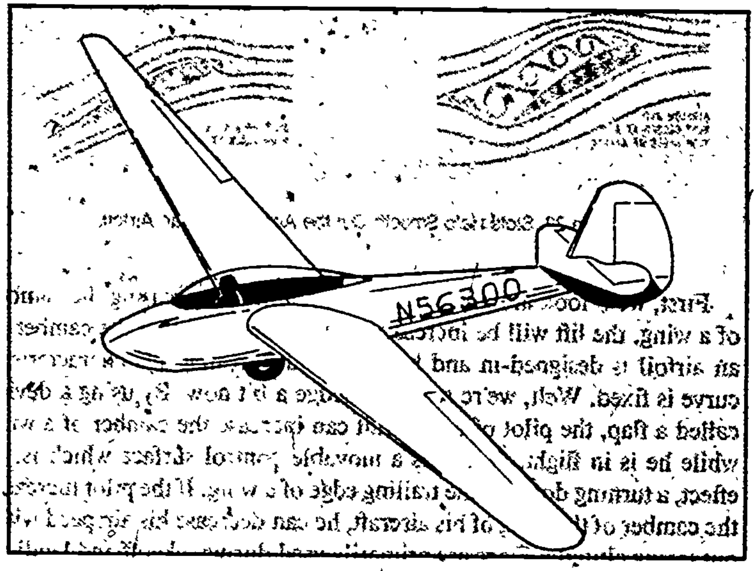


Figure 21 Gliders Have Very High Aspect Ratios Due to Their Long Narrow Wings.

pute aspect ratio (AR) by squaring the span and dividing this by the total wing area. Referring to Figure 20, we note that with the small square-winged aircraft, AR can easily be computed using either average chord length or the wing area, but in the large aircraft wing area is much simpler to use.

In general, the higher the aspect ratio, the more efficient the wing. A long narrow wing will create much better lift per square foot of area than a short wide wing Some gliders have an aspect ratio as high as 20 (see Fig 21) The longer the wing, then, in proportion to its width, the more efficient the lifting force it will generate. Why is this so? The wing tip is the least efficient portion of the wing, because the air under the wing, which is at atmospheric pressure, or even higher, rolls over the wing tip into the low pressure area above the upper surface of the wing. This air then causes a swirl, or vortex, at the tip of the wing and decreases the amount of smooth air flow which creates lift. So, a long narrow wing is more efficient than a short wide wing. We'll see more about aspect ratio a bit later on in this unit when we discuss drag.

Flaps, Slots, and Spoilers

These three devices also affect the generation of lift. Let's look at them, one at a time, and see how they fit in.

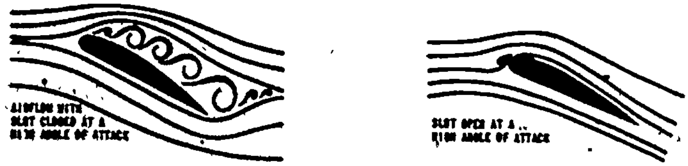


Figure 22. Slots Help Smooth Out the Airflow Over an Airfoil.

First, we'll look at flaps. We have said that by increasing the camber of a wing, the lift will be increased. We pointed out that the camber of an airfoil is designed in and built in, and also that this characteristic curve is fixed. Well, we're going to hedge a bit now. By using a device called a flap, the pilot of an aircraft can increase the camber of a wing while he is in flight. A **flap** is a movable control surface which is, in effect, a turning down of the trailing edge of a wing. If the pilot increases the camber of the wing of his aircraft, he can decrease his airspeed without losing altitude. Flaps are primarily used during takeoff and landing. They give added lift at low airspeeds and provide better aircraft stability for these critical phases of flight.

Slots, too, can affect lift by changing camber. **Slots** are either movable or fixed sections of the leading edge of an airfoil. They are installed on an airfoil to help control the airflow over its upper surface. We mentioned earlier that burbling of the flow of air is caused by eddies over the top surface of the wing. The slots on an aircraft reduce or eliminate burbling. The burble point, you'll remember, is the point at which the flow of air begins to break up into currents and eddies. Since we already know that the burble point is reached at relatively high angles of attack, it naturally follows that if we can do anything to smooth the flow of air,

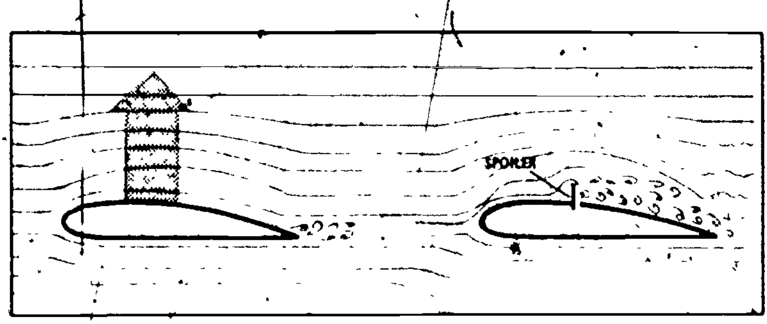


Figure 23 Spoilers Reduce the Amount of Lift Generated

the airfoil will allow a higher angle of attack before stalling. Changing the characteristic shape of the leading edge of the airfoil by opening the slots and allowing a smoother flow of air across the upper surface of the airfoil diminishes both burbling and the airfoil's stalling characteristics (see Fig 22).

Spoilers are small surfaces, recessed into the upper surface of the airfoil. The name just about tells you what they do. when they are raised, they "spoil" the smooth flow of the air over the airfoil and, thus, reduce the amount of lift generated (see Fig 23). You might also say that the spoilers change the upper camber of the airfoil and thereby reduce the amount of lift generated.

Flaps and slots, then, serve to increase camber and thus increase lift. Spoilers serve to decrease camber and thus decrease lift.

Let's sum up again, this time reviewing where we've been and pointing out where we're going from here. Lift is generated by the interaction of air and airfoils. Bernoulli's Principle and Newton's Third Law of Motion help explain how the lifting force is generated. Although airfoils are specifically designed to generate lift, the amount of lift generated can be varied by the pilot in flight, by the characteristics of the air through which the aircraft is passing, and by built in flexibilities in the airfoil itself. Now, we're going to move on to a brief look at the other forces affecting an aircraft in flight. thrust, drag, and weight, with some glances back at lift. We'll then know better what holds the aircraft in the air. Once we have it up there, we'll look at how it behaves.

WORDS AND PHRASES TO REMEMBER

airfoil
leading edge
trailing edge
chord
camber
upper camber
lower camber
relative wind
angle of attack
angle of incidence
attitude
lift
pressure-differential lift
impact lift
resultant
center of pressure
burble point
burbling
stalling point
stall
planform
aspect ratio
span
flap
slots
spoilers

THINGS TO DO

1 Tape one end of a piece of paper flat to the other end so that it looks like an airfoil

from the side Put a pencil along the inside of the leading edge. Hold the leading edge below your lower lip and blow. Explain what happens.

2. Have a kite or paper airplane flying contest. See who can fly his kite the highest or have a paper airplane stay airborne for the longest time. Discuss the different kinds of lift involved
3. Talk to a racing car driver. Report back to the class on why racing cars use airfoils on the back
4. Build a wind tunnel. (Your instructor has the plans).
5. If you are close to an Air Force facility that has a wind tunnel (such as Arnold Engineering Center in Tullahoma, Tennessee), go visit it.
6. Do some research to find out about different kinds of flaps, slots, or spoilers.
7. Discuss why some aircraft require longer runways than others
8. When riding in a car with no obstructions or trees along the road, perform the experiment we discussed of putting your hand out of the window.

SUGGESTIONS FOR FURTHER READING

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REVIEW QUESTIONS

1. **A part of an aircraft that is designed to produce lift is called a/an _______.**
2. **True or False. Tail surfaces, propeller blades, and fuselages are not considered to be airfoils.**
3. **True or False. Air flowing past an airfoil suspended in a wind tunnel behaves in the same way as air flowing over an airfoil in flight.**
4. **Name four major parts of an airfoil.**
5. **A thick and fat leading edge would produce (more/less) lift at low speeds than a sharp one.**
6. **The portion of the airfoil where the upper surface airflow rejoins the lower surface airflow is called the _______.**
7. **An imaginary straight line drawn through the airfoil from its leading edge to its trailing edge is called the ______________.**

8. Define camber.

9. The _______________ is created by the motion of the aircraft through the air and is parallel to the flight path.

10. True or False. The angle of attack remains constant in flight.

11. The aircraft position in relation to the horizon is called the:
   a. relative wind
   b. angle of incidence
   c. angle of attack
   d. attitude

12. Define lift.

13. The pressure of moving air against the lower surface of an airfoil causes (pressure differential/impact) lift.

14. Pressure differential lift plus impact lift gives _______________.

15. True or False. The pilot must be able to control the amount of lift generated by the airfoils.

16. Which of the following affects the amount of lift generated?
   a. airfoil shape
   b. relative wind speed
   c. angle of attack
   d. all of the above

17. As the airfoil moves through the air, changing the angle of attack can change the amount of _______.

18. A resultant has _______, _______, _______.

19. Define center of pressure.

20. The angle at which lift stops increasing and starts decreasing is called the:
   a. burble point
   b. stalling angle
   c. angle of maximum lift
   d. all of the above

21. When the angle of attack increases the center of pressure moves (forward/backward).

22. What happens to the amount of lift generated as the angle of attack is increased past the stalling angle?

23. The point at which the amount of lift generated is no longer enough to support the aircraft in the air is called the _______________.

24. Lift varies (directly/indirectly) with density.

25. The greater the camber the (greater/less) the lift.

26. For the most part, the greater the wing area, the (greater/less) the lift.

27. The shape of the wing as seen from above or below is the ________.

28. Define aspect ratio.

29. True or False. In general, the lower the aspect ratio, the more efficient the wing.

30. Match the lift device to its position on the wing:

a. flaps	1. upper surface
b. slots	2. trailing edge
c. spoilers	3. leading edge

Chapter 4

Weight, Thrust, and Drag

THIS CHAPTER explains the other three forces acting on an aircraft in straight and level unaccelerated flight. Essentially, the chapter defines these forces: weight, thrust, and drag. You will read a description of each of these terms and then read about how these factors influence aircraft design and performance. After you have studied this chapter, you should be able to: (1) discuss the "balance of forces" which keeps an aircraft in the air; (2) explain how Newton's Third Law accounts for thrust; (3) differentiate between induced drag and parasite drag; (4) explain how designers reduce turbulent flow drag; (5) define supercritical wing; and (6) show how the four forces relate to helicopter flight.

IN THE FIRST CHAPTER, we stated that four forces in balance maintain an aircraft in straight and level unaccelerated flight. These four forces, we said, are lift, weight, thrust, and drag. We've just looked at lift in some detail; now we'll examine the other three forces.

WEIGHT

Since weight opposes lift, we'll start here. Gravity is the force which pulls the aircraft toward the center of the earth. The pull of gravity is responsible for the total weight of the aircraft and its contents. For our purposes we will consider weight to be constant within the atmosphere. You should realize, though, that gravity is not always equal. For example, you would weigh slightly less on a high mountain peak than you would at sea level.

The point at which the total weight of the aircraft and its contents appear to be centered or concentrated is called the **center of gravity.** On a model airplane you can find the center of gravity by suspending it using a thread. When it's level, the thread will be in line with the center of gravity. What would happen to the center of gravity if all the passengers on an airliner suddenly decided to meet at the rear of the aircraft? You can see that the center of gravity can be changed (even in flight) and is important to the pilot—more on this later. All in all, weight is not too complicated, but the next force is a bit more complex.

THRUST

Thrust is the force which drives the aircraft forward. A formal definition of thrust might read something like this. *Thrust is a force imparted to move a body in a desired direction. It is obtained by the application of an equivalent force applied in a direction directly opposed to the desired direction of motion.* If this hefty mouthful sounds like something you've read already in this unit, it's no accident. Do you remember Newton's Third Law of Motion? Here it is again. "For every action, there is an equal and opposite reaction." How does this statement explain thrust?

The two types of aircraft propulsion systems in general use today, reciprocating engines and jet engines, both operate on this principle to create thrust. The unit on propulsion systems for aircraft will cover the operation of these systems in some detail, our purpose here is simply to point out that the principle behind these two systems is exactly the same. They are both reaction engines. This simply means that they both depend upon Newton's Third Law of Motion to produce thrust. Let's see how this works.

In a reciprocating engine, an explosion inside the cylinder(s) causes an action. This action is transmitted, ultimately, to the propeller(s). The action of the propeller(s) then propels a mass of air to the rear. In so doing, the aircraft is propelled forward. At this point do not concern yourself with how a propeller operates since this will be discussed in *Propulsion Systems for Aircraft.*

The operation of a jet engine is even simpler. Compressed air is mixed with vaporized fuel and ignited. The hot burning gases then are exhausted from the rear of the combustion chamber, producing an equal and opposite reaction on the interior walls of the combustion chamber which moves the aircraft forward. The "equal and opposite reaction," then, is thrust.

The essential difference, for our purposes, between reciprocating engines and jet engines is the action of the burning gases. In a reciprocating engine, these burning gases drive a complex system which, through the turning of a propeller, results in the movement of a mass of air opposite to the direction of desired travel. In a jet engine, the burning gases act rather more directly to produce the equal and opposite reaction which propels the aircraft. In both engines, thrust is the result.

DRAG

Drag is the force which opposes thrust. It is caused, purely and simply, by the resistance of air. Air, you will remember, is a fluid and has mass When you stick your hand out of the window of a moving automobile, you do several things. First, you may violate the law in some sections of the country—in addition to possibly getting your hand clipped off by a tree! Secondly, you experience (or feel) the relative wind created by the car's forward movement. Remember the relative wind? It is the wind moving past an object—and the object, in this case, is the car Your hand, in effect, becomes an extension of the car in experiencing the relative wind. Third, you may possibly create lift. If you arch your hand slightly (you're really giving it some camber, your hand may tend to rise If you place your hand at a slight angle to the relative wind, the impact air will cause your hand to rise. But fourth and for sure, you will encounter air resistance and experience *drag*. This drag will tend, then, to push your hand backwards.

Aircraft in flight encounter the same force as your hand, but aircraft are designed to fly, rather than to do all the things that your hand can do Aeronautical engineers realize that drag, like the other forces acting on an aircraft in flight, is made up of a number of components. One way to look at the total drag is to divide it up into two fairly broad divisions, induced drag and parasite drag. Let's look at these two, one at a time.

Induced drag is an unavoidable result of lift. It is caused by the change in direction of the airflow. As the aircraft speeds forward through the air, the air which creates the lifting force creates a retarding force Here's how it works. Air from the higher pressure area below the wings tends to move into the lower pressure area above the wings both at the wing tips and at the trailing edges (see Fig 24).

Air flowing over and under the wing creates different pressure differentials at different points on the wing. An aircraft wing is usually thicker at its root (where it is attached to the body of the aircraft) than at its tip This means that the pressure differential caused by the relative wind is greatest at the root, gradually decreasing along the length of the wing and least at the tip This means that the air molecules at the root of the wing have a greater amount of kinetic (motion) energy than the air

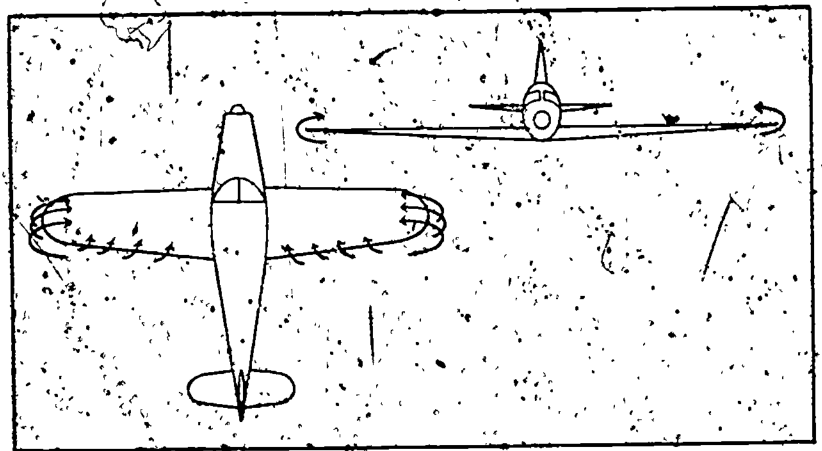

Figure 24. The Higher Pressure Air Under the Wings Seeks to Flow to the Lower Pressure Area Above

molecules at the tip of the wing. This means that air molecule kinetic energy gradually decreases from the wing root to the wing tip. What's the effect of all this? A pressure wave is created along the surface of the wing, forcing the air molecules at the tip of the wing to be pushed off, as nature tries to equalize pressure.

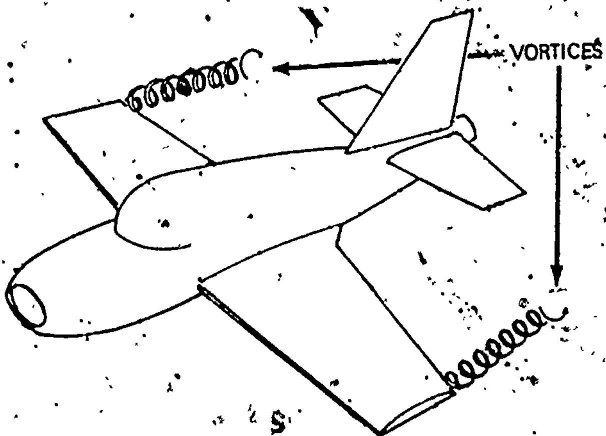

Figure 25. Induced Drag

The violent interaction of these two pressure movements and the forward motion of the aircraft result in trailing **vortices** or whirlpools at the wing tips (see Fig 25), these tip vortices tend to retard the forward motion of the aircraft by absorbing energy. Also, lift is reduced at the wing tips due to the turbulent airflow.

Induced drag, then, comes from lift. Does this mean that in order to get lift, we can do nothing about drag? Not at all. Both the designer and the pilot of the aircraft can exercise some control over the amount of induced drag generated. Here's how.

By reducing the area of the wing affected by the wing tip vortices, the designer can reduce induced drag. He has two ways to do this If the wing is longer or if it is narrower, the percentage of the wing area will be reduced Does this sound familiar? Remember aspect ratio? It's the relationship between the span (length) of a wing and its average chord If other things remain constant lengthening the wing or reducing the average chord increases the aspect ratio, which reduces induced drag

What can the pilot do about this kind of drag? He can change his angle of attack. Angle of attack, you will recall, is the angle at which the relative wind meets the airfoil Just as increasing the angle of attack increases the amount of lift generated, decreasing the angle of attack decreases the amount of lift generated Induced drag works exactly the same way An increase in angle of attack increases the amount of induced drag; and a decrease in angle of attack decreases the amount of induced drag, all other factors remaining equal.

Let's move on to parasite drag **Parasite drag** includes all drag components except those causing induced drag Skin friction and turbulent flow are two of the components of parasite drag **Skin friction drag** is caused by the friction between the outer surfaces of the aircraft and the air through which it moves **Turbulent flow drag** is caused by whatever interferes with the streamline flow of air about the aircraft We'll have to go a bit deeper to examine what causes skin friction drag and turbulent flow drag, we'll look at boundary layer air

Boundary layer air is a layer of air very close to the surface of a moving airfoil It is caused by the friction between the wing and the air. In this layer of air, only a few thousandths of an inch thick, impact pressure is reduced because of the air's viscosity This simply means that this microscopically small layer of air resists the tendency to flow What happens? The air particles which are flowing smoothly at the leading edge of the airfoil gradually flow with more and more turbulence as they approach the trailing edge of the airfoil

How is boundary layer air related to skin friction drag? We've learned that turbulence can cause drag The more turbulent the boundary layer air, then, the more skin friction drag will be created Why? Because the already turbulent boundary layer air will be passing over a surface which is rough—and this roughness will cause additional turbulence. Skin friction drag is difficult to reduce, but keeping the aircraft clean and well polished helps. Removing surface irregularities, such as those caused by protruding rivet heads, also makes the surface smoother and, hence, less likely to generate additional turbulence in the boundary layer air.

What about turbulent flow drag? We've already stated that it is the drag which is caused by anything which interferes with the streamline flow of air about the aircraft What causes this kind of drag? It is caused by our old friend turbulence, which creates low pressure areas which tend to retard the forward motion of the aircraft This turbulence forms eddies, or burbles, which are simply descriptive names for the motion of the air in these areas of lowered pressure

How can turbulent flow drag be reduced? Aeronautical engineers have discovered that the best way to reduce it is to streamline the aircraft This simply means that designs for an aircraft (and for specific portions of an aircraft) approach the shape of a teardrop The reason? This particular shape is the best adapted to flowing through the air Taking their clue from nature, then, aeronautical engineers have realized that this particular shape encounters the least resistance to the air because it best disposes of the turbulence around it Hence, they design exposed aircraft parts in as close an approximation of the teardrop as possible See Figure 26

Not all parts of an aircraft can be given this particular shape, though What then? The engineers enclose the particular part in a cover which has a streamlined shape This auxiliary structure, called a **fairing**, reduces the amount of turbulent flow drag generated by the part to which it is fitted Some of these fairings are not complete covers, they may only fill out a portion of the aircraft in order to make it more streamlined.

Let's try to pull these aspects of drag together The two primary components of aircraft drag are induced drag and parasite drag Both types of drag are a result of air turbulence induced drag is the result of air turbulence associated with lifting surfaces, parasite drag is the result of air turbulence associated with nonlifting surfaces Both pilot and designer have some control over the amount of drag generated by the aircraft, but drag is as much a consequence of flight as lift Let's briefly look at the latest development in aerodynamics which very clearly shows the important relationship between drag and lift

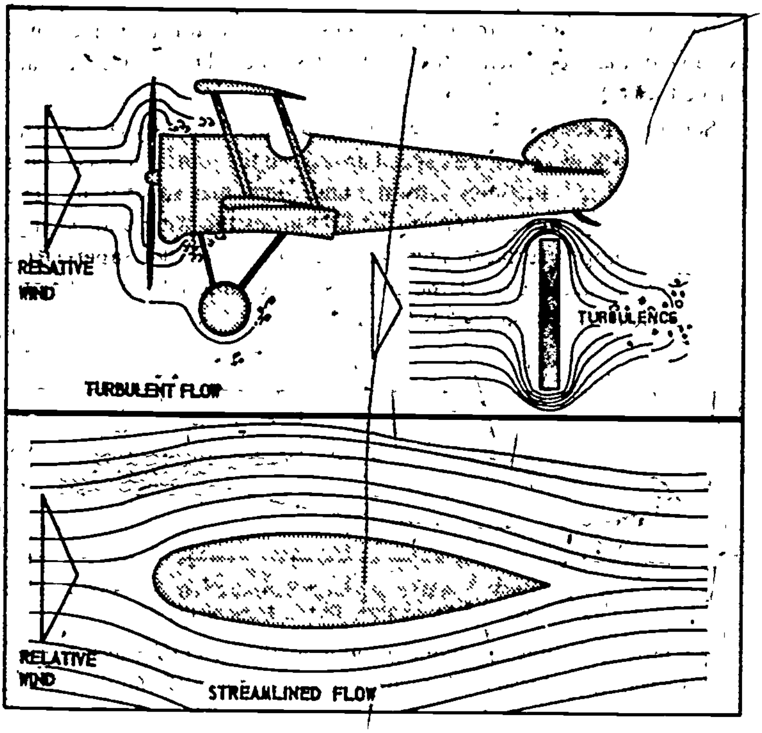

Figure 26 Turbulent Flow and Streamlined Flow

If you've watched any science fiction movies, you know that sometimes things happen just the opposite of the way they're supposed to happen The supercritical wing is something like that It seems to violate some of the principles we've been discussing

First, let's extend our discussion of boundary layer As the air flows

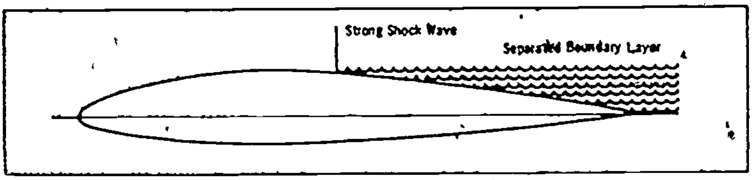

Figure 27 Airflow Over a Typical Airfoil at Transonic Speeds

over the airfoil, it tends to separate, creating turbulence and drag. The farther forward on the airfoil it separates, the more drag there is created. As an aircraft approaches the speed of sound, shock waves are also formed (See Fig 27).

Scientists have found that they can reduce the boundary layer separation and shock wave for high speed aircraft in the transonic speed range (where speed is sometimes subsonic and sometimes supersonic). They do it by putting the camber on the bottom of the wing and having a nearly flat upper surface. This new design, called the **supercritical wing,** overcomes many of the problems encountered when flying at these critical transition speeds (see Fig 28).

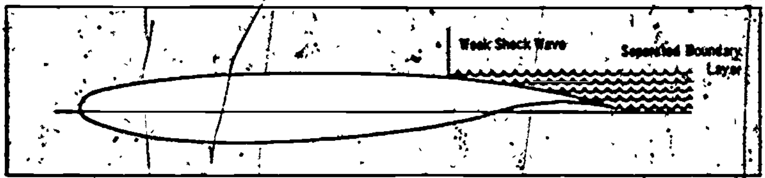

Figure 28 Supercritical Wing. The Boundary Layer Separation and Shock Wave Effects Are Reduced by Moving Them Farther Back on the Wing

By now you may be wondering how the aircraft stays airborne because the wing doesn't create any lift according to Bernoulli's Principle You're right, the lift comes from impact lift which means the aircraft must maintain higher speeds or it will stall

With this wing, an aircraft could operate approximately 15 percent more efficiently, meaning that an aircraft equipped with a supercritical wing could go farther and faster with the same engines and weight. This proves that an understanding of the forces of flight is important to both the designer and the pilot.

Let's look one more place to insure our understanding of the forces of flight Shifting from the transonic speed range, we'll see how the four forces affect helicopter aerodynamics

HELICOPTERS

Up to now, no discussion has been made of the forces involved in helicopter flight. There was really no reason to, since the same laws of aerodynamics apply to both helicopter and aircraft flight. Lift counteracts weight and thrust overcomes drag resulting in flight in the desired direction.

The unique thing about a helicopter is that it does not just fly straight up and down or remain stationary, it also can fly in any direction As if this weren't enough, it can fly any direction regardless of the direction

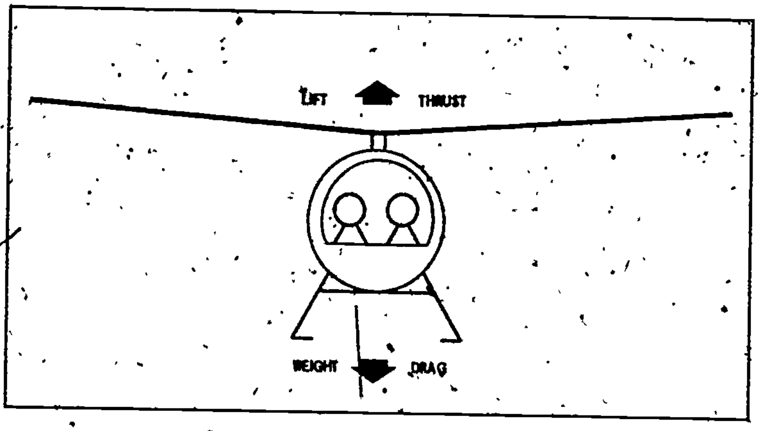

Figure 29 Hovering Lift Equals Weight and Thrust equals Drag

the helicopter is headed, for example, it can be headed north and be flying south or headed east and flying north.

In order to best understand helicopter flight, let's first examine what happens when a helicopter hovers Because there is no forward, rearward, upward, or downward movement, the four forces are in balance Drag and weight operate parallel to and opposite of lift and thrust (see Fig 29) If we decide to climb, we merely increase thrust which increases lift overcoming both weight and drag.

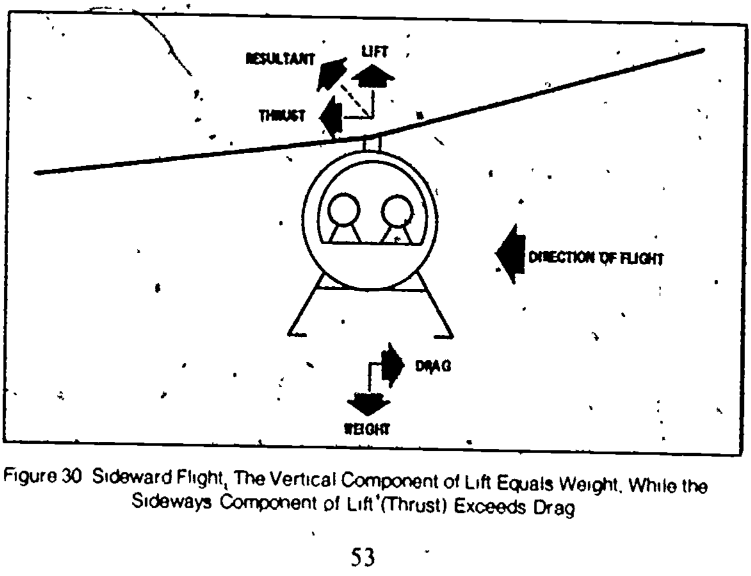

Figure 30 Sideward Flight, The Vertical Component of Lift Equals Weight, While the Sideways Component of Lift (Thrust) Exceeds Drag

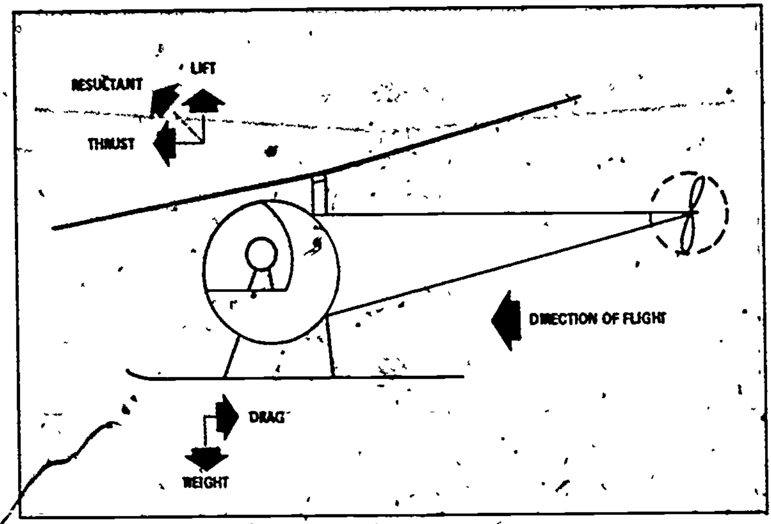

Figure 31 Forward Flight

Assume now that the pilot wants to go to the right. He moves his control to the right causing the rotor to tip toward the desired direction of flight. Now thrust and lift are no longer parallel Thrust is moving the helicopter to the side overcoming drag, while effective lift is operating in a vertical direction overcoming weight (see Fig 30)

By changing the tilt of the rotor, the pilot can fly in any desired horizontal direction (see Fig 31). Thrust always acts in the direction of flight, drag always acts in the opposite direction. Lift and weight always act in the vertical direction.

How does all this add up? In straight and level, unaccelerated flight, lift equals weight and thrust equals drag. If lift exceeds weight, the helicopter will climb, if lift is less than weight, it will descend If thrust exceeds drag, the helicopter will speed up and if thrust is less than drag it will slow down.

We will not discuss helicopters again until the unit on propulsion systems However, you should remember that the aerodynamic principles applying to the aircraft also apply to helicopters

In summary. lift, weight, thrust, and drag are the four forces which act upon any aircraft in flight Each of these forces has an explainable cause, and each one (except gravity) can be controlled to a certain extent by the men who design and build aircraft and by the men who fly them

When these four forces are in balance with one another, the aircraft flies straight and level at a constant speed.

Aircraft don't always fly straight and level, you may say; aircraft climb; they descend, they take off, they land, they fly upsidedown; they roll; and so forth Precisely. Aircraft fly in a three-dimensional environment, the air. This is the subject of our next chapter.

WORDS AND PHRASES TO REMEMBER

center of gravity
thrust
drag
induced drag
vortices
parasite drag
skin friction drag
turbulent flow drag
boundary layer air
fairing
supercritical wing

THINGS TO DO

1 If your physics teacher has the equipment, perform this experiment for the class Show how a feather falls in a vacuum
2 Report on how and why we use streamlining for things other than airplanes
3 Take two ropes and tie them together in the middle so that there are four free ends. Have four people of approximately equal strength have a tug-of-war simulating the four forces of flight What does the point where the ropes are connected represent?
4 Research wingtip vortices Explain the effect of a 747's or DC-10's vortices on a light aircraft Explain to the class what a light aircraft would do on takeoff and landing to avoid these vortices
5 Go waterskiing. What aerodynamic principles are involved?
6 Have an aeronautical engineer visit your class. Perhaps he could explain how the supercritical wing operates
7 Perform wind tunnel experiments in the wind tunnel you are building for the class Demonstrate to the class how unstreamlined bodies create more drag.
8 Make and fly a paper autogyro (Your instructor has the plans)

SUGGESTIONS FOR FURTHER READING

BRYAN LESLIE A *Fundamentals of Aviation and Space Technology* Urbana, Ill · Institute of Aviation. University of Illinois, 1973

Federal Aviation Agency *Basic Helicopter Handbook* Washington US Government Printing Office. 1965 (AC 61-13)

MISENHEIMER TED G *Aeroscience* 2nd ed Los Angeles Aero Products Research. Inc. 1973.

VAN DEVENTER C N *An Introduction to General Aeronautics* Chicago American Technical Society. 1968.

History of Flight New York American Heritage Publishing Co . Inc . 1962

VON KARMAN THEODORE *Aerodynamics* New York McGraw-Hill Book Co . 1963

REVIEW QUESTIONS

1. The force which pulls an aircraft toward the center of the earth is called ______.

2. The point at which the total weight of the aircraft appears to be centered is called the:
   a. center of pressure
   b. center of gravity
   c. centrifugal force
   d. centripetal force

3. Define thrust.

4. What two types of aircraft propulsion systems are in general use today?

5. Define drag.

6. What causes induced drag?

7. Wingtip vortices tend to (aid/retard) the forward motion of the aircraft by (contributing/absorbing) energy.

8. How can a designer reduce induced drag?

9. How can a pilot reduce induced drag?

10. Define parasite drag.

11. What are the two primary components of parasite drag?

12. The air very close to the surface of a moving airfoil is called ________________ ________________ ________________.

13. The more turbulent the boundary layer air, the (more/less) skin friction drag will be created.

14. How do we reduce skin friction drag?

15. The best way to reduce turbulent flow drag is through ________.

16. What shape is best adapted to flowing through the air?

17. An airfoil with a nearly flat upper surface and camber on the bottom is called a ________________.

18. Most of the lift supplied by a supercritical wing is in the form of (pressure-differential/impact) lift.

19. True or False. The same aerodynamic laws apply to both helicopters and conventional aircraft.

20. How does a helicopter pilot change his horizontal flight direction?

Chapter 5

Aircraft Motion and Control

THIS CHAPTER examines the aircraft in motion. You will read about the axes of rotation and the movement around these axes which the aircraft makes when it flies. Studying the axes of rotation leads to the concept of stability, which is very important to an aircraft in flight. You will read about various kinds of stability. The chapter then discusses aircraft control and explains which controls the pilot of an aircraft uses to perform various maneuvers. The chapter concludes by showing the relationship between the physical principles involved in stability and the ways in which the pilot controls the aircraft. After you have studied this chapter, you should be able to: (1) describe various conditions of stability; (2) explain how varying stability factors will affect an aircraft in flight; (3) discuss the concept of aircraft control and list several control surfaces; (4) explain rate of climb and angle of climb; and (5) point out which control surfaces affect which aircraft motions.

WE POINTED OUT earlier that aircraft are able to sustain flight because of a balance among the four forces we've just discussed: lift, weight, thrust, and drag. When the aircraft is in the air and flying straight and level, we can assume that these four forces are in balance. But the aircraft has to get there somehow, you may say; what other types of aircraft motion are there, besides straight, level, unaccelerated flight?

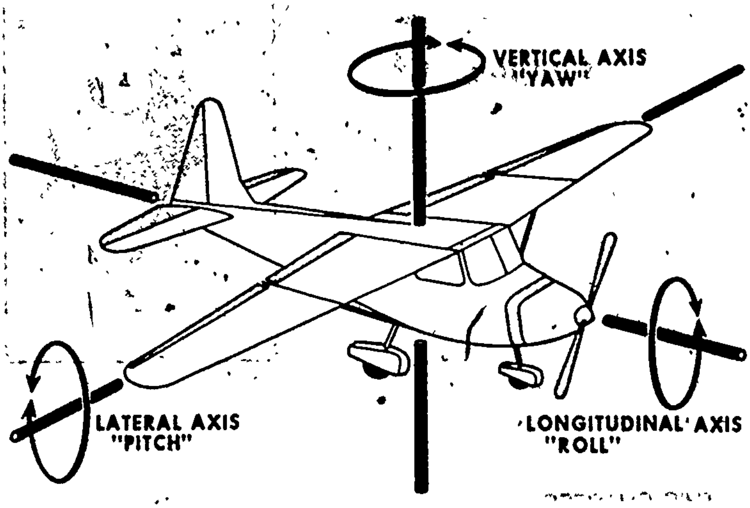

Figure 32 The Axes of Rotation

Aircraft fly in three dimensions. Aircraft are three-dimensional objects, and they move in directions other than straight and level.

THE AXES OF ROTATION

In order to examine these other directions, we have to take another look at our aircraft. In addition to moving forward, an aircraft in flight may move about three axes. See Figure 32 and you will understand what we mean The simplest way to understand the axes is to think of them as long rods passing through the center of gravity, where each will intersect the other two. At this point of intersection, each of these axes is also perpendicular to the other two. This relationship is a bit difficult to sketch out, your best bet for getting this concept of axes straight is to have your instructor show you a model plane and point out each axis.

The axis that extends lengthwise (nose through tail) is called the **longitudinal axis**, and rotation about this axis is called **roll**. The axis that extends crosswise (wing tip through wing tip) is called the **lateral axis**, and rotation about this axis is called **pitch**. The axis that passes vertically through the center of gravity (when the aircraft is in level flight) is called the **vertical axis**, and rotation about this axis is called **yaw**. There is apparently no real rationale for these names, you simply have to memorize them Longitudinal axis—roll, lateral axis—pitch, and vertical axis—yaw.

You can demonstrate them for yourself by means of a model airplane. Hold the airplane from above at about the middle (somewhere near where you imagine the center of gravity to be). Tip one wing down. You've moved the airplane about its longitudinal axis, and the airplane has rolled. Bring the wing back up, now, and the airplane has returned to a stable configuration. Now pivot the whole airplane to the left. You've just moved the airplane about its vertical axis, and the airplane has yawed. These movements are not always this simple in the air, often they are combined with one another, but more on that later.

If the aircraft rotates about any one axis, the other two axes are considered to be moving with the aircraft. For example, if the aircraft dips one wing, it is rolling—but it is *not* yawing or pitching. However, as we mentioned above, the aircraft can rotate about all three axes at the same time, as it does in the beginning of a climbing turn.

STABILITY

Stability is an important central concept behind aircraft design, operation, and control. We'll discuss stability in general first, and then we'll move on to show how aircraft stability works. The axes of flight, discussed above, will provide convenient reference points for our discussion of aircraft stability.

First off, what is stability? A body is said to be in equilibrium when all the forces acting on it balance one another. **Stability,** then, is that property of a body which causes it to return to its original condition when its equilibrium is disturbed. This tendency of a displaced object to return to its original position is also called **static stability.**

Let's examine static stability more closely. We can divide it into three types positive, neutral, and negative. We can demonstrate these with a small ball and a piece of posterboard. First, lay the posterboard on a flat surface. Place the ball on it so that it's perfectly still (in equilibrium). If we push the ball, it doesn't try to return to its original position nor does it try to move further away This is **neutral stability.** See ball A in Figure 33 Next, bend the ends of the posterboard up slightly and put the ball in the middle (ball B in Figure 33). Now when we push the ball up the sides (disturb its equilibrium) it always tends to return to its original state—**positive stability.** Now for the hard part. Curve the edges of the posterboard down as for ball C in Figure 33 It's very obvious that if you're able to balance the ball on the top, once you disturb its equilibrium, it tends *not* to return to its original state—**negative stability.** In fact, it tends to accelerate away from the point of origin. Sometimes we simply say that ball B is stable and ball C is unstable.

An unstable aircraft tends constantly to change from normal flight into abnormal flight, and it must just as constantly be restrained from

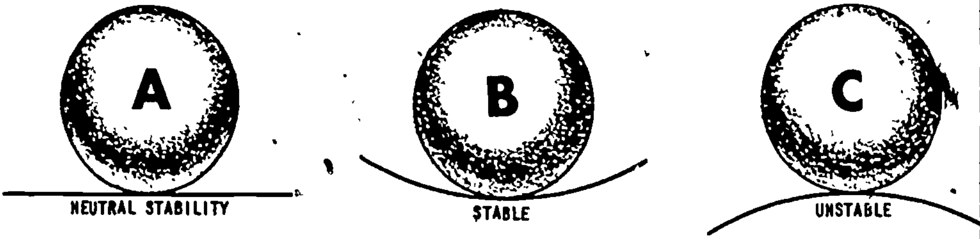

Figure 33 Types of Stability

doing so by proper use of the controls. Obviously, unstable aircraft are extremely dangerous and aircraft designers are careful to build at least some stability into all aircraft

Another division of the concept of stability is into static stability and dynamic stability As we discussed earlier, if the body has static stability, it has a tendency to return to its original position If an aircraft tends to return to level flight without effort on the part of the pilot after it has been put into a climb or a dive, the aircraft is statically stable However, the force that tends to restore the aircraft to normal flight might be so great that it would carry the aircraft too far in the opposite direction If the aircraft is put into a dive, the restoring forces would move it first into a climb, then into a steeper dive, then into a steeper climb, then into a steeper dive, and so on until the aircraft finally stalled or crashed. In such a case, the aircraft would be statically stable (it would tend to return to its original position), but it would be dynamically unstable **Dynamic stability,** then, is a tendency to return to the original position with a minimum of oscillations

Refer again to Figure 33 If we released ball B so that it rolled up and down the side of the posterboard, it would gradually come to a stop in the middle As it rolls back and forth until it stops, it is demonstrating dynamic stability The steeper the sides of the posterboard, the greater the dynamic stability

Sometimes stability is really a type of instability It is possible to design an aircraft so that it's stable when flying in an abnormal attitude In the early days of flight, for example, some aircraft were stable when they were flying upside down This is all well and good, if you happen to wind up flying upside down The trouble is that the aircraft will constantly tend toward this condition of stability—and taking off or landing upside down is not a particularly safe maneuver! Even today, an improperly loaded aircraft will be inherently unstable. Perhaps you've wondered why you could only carry hand luggage with you on a commercial flight. Overloading the plane, of course, is the primary reason, but an important secondary reason is linked to the problem of distributing this weight properly.

So much for stability in general. The question naturally arises as to how and why an aircraft maintains stability, particularly since it must be stable about all three axes. Let's assume that our aircraft is stable. If the aircraft noses down, there should be a tendency for the nose to come back up, if the nose swings to the right or to the left, it should have a tendency to resume its original direction, and if one wing drops, there should be a tendency for the wing to come back up to normal position.

Longitudinal Axis Stability

If an aircraft is stable along its longitudinal axis, it will not pitch unless some force raises or lowers the nose of the aircraft. This movement is sometimes called "nosing up" or "nosing down." If the aircraft is statically stable along its longitudinal axis, it will resist any force which might cause it to pitch, and it will return to straight and level flight when the force is removed. Of the three types of stability of an aircraft in flight, this type is the most important.

To obtain longitudinal axis stability, the aircraft is deliberately balanced so that it is slightly noseheavy. In our discussion of the forces of flight, we mentioned the terms center of pressure and center of gravity. Aircraft designers deliberately locate the center of gravity ahead of the center of pressure in a given aircraft. This means, then, that the aircraft in normal flight has a continuous slight tendency to dive. Why? The center of pressure, you will remember, is the point at which all the forces acting on an aircraft in flight are assumed to be concentrated. The center of gravity is the point at which the weight of the aircraft is considered to be concentrated. Obviously, then, the center of weight will be ahead of the center of the other forces—and the aircraft will have a slight tendency to dive The correction for this tendency is simple, and we'll explain a bit further on why this tendency is built into the aircraft.

Think back to the section on lift. The relative wind passing over the airfoil is given a slight downward movement, and this movement is called **downwash.** The horizontal tail surfaces are usually set at a negative angle of attack, which simply means that when they meet the relative air, they produce a sort of downward or negative lift. Why? When the aircraft is flying at a given speed, the downward force on the tail exactly offsets the nose heaviness. The aircraft, then, maintains level flight without effort from the pilot (see Figure 34).

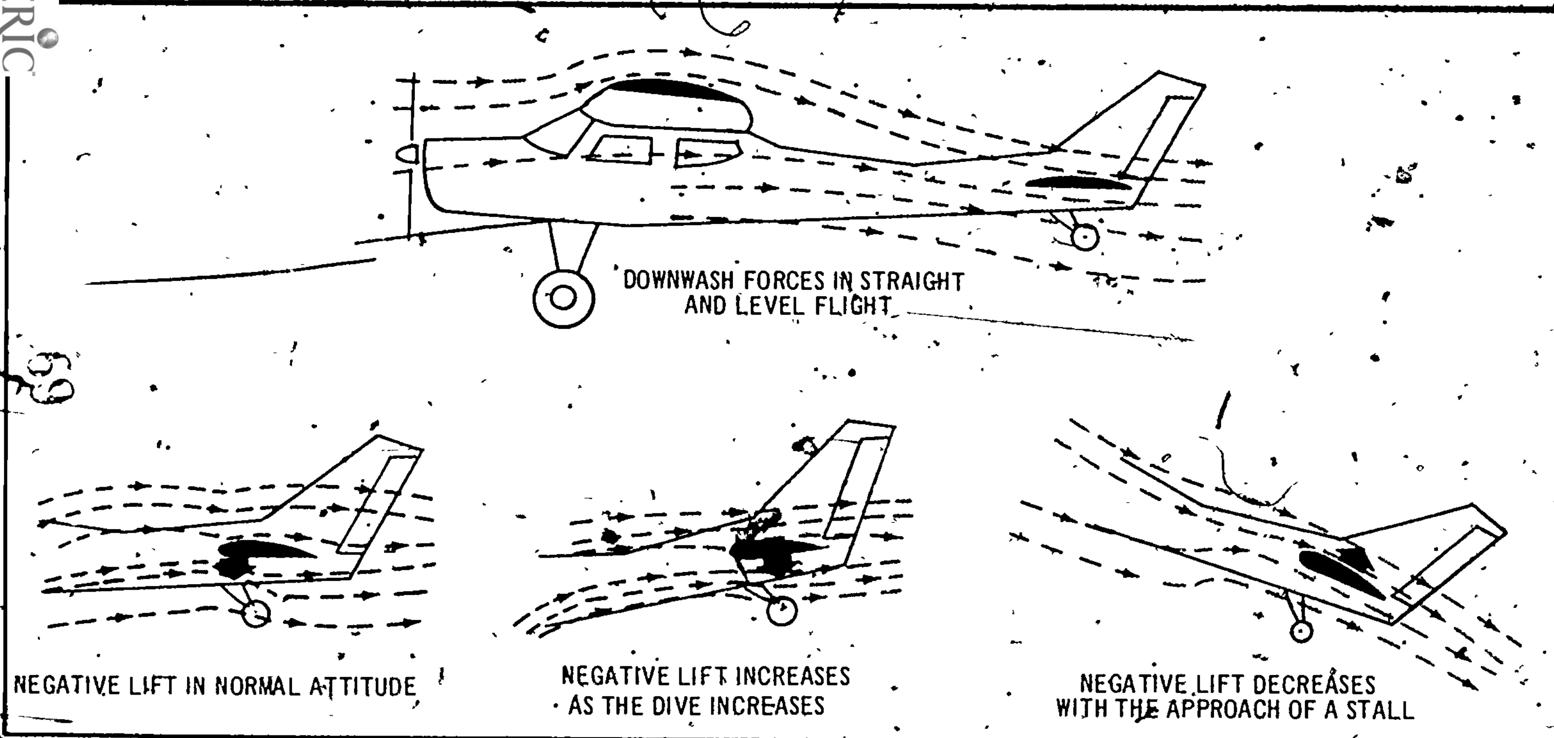

Figure 34. Longitudinal Axis Stability

If the engine "conks out," two things decrease the speed of the air over the tail surfaces The first is a loss of speed which is due to lack of thrust. The second is the elimination of the **slipstream.** The slipstream is the stream of air driven rearward by the propulsion system Since the speed of the air over the tail of the aircraft decreases, the downward force on the tail also decreases What happens then? The aircraft becomes noseheavy, the nose drops, and the aircraft goes into a glide or a dive As the aircraft dives, its airspeed increases In turn, the downward force on the tail increases, since the negative lift becomes greater. This increase of the downward force on the tail of the aircraft forces the tail down and the nose up, and the aircraft goes into a climb As the climb continues, the speed again decreases, and the downward force on the tail becomes gradually less until the nose drops once more This time, if the aircraft is dynamically stable, the nose does not drop as far as it did the first time The aircraft then has a much shallower dive The speed then increases until the aircraft again goes into a shallower climb, as before After several such oscillations, the aircraft will finally settle down to a speed at which the downward force on the tail exactly offsets the tendency of the aircraft to dive The aircraft then can make a smooth glide down, regardless of whether the power is on or off

What happens when an aircraft is balanced so that the center of gravity is *behind* the center of pressure? Such an aircraft is tailheavy, hence, it has a tendency to climb This climbing tendency may be offset only by increasing the lift on the horizontal tail surfaces so as to get a positive lift or upward force What happens when the engine conks out on an aircraft balanced this way? Because the lifting force developed by the tail is decreased due to the loss of thrust, the aircraft becomes tailheavy and starts to climb Since there is nothing to check this climbing tendency, the aircraft continues to climb until it stalls and falls off into a spin If the aircraft is put into a dive with the controls released, the lift on the tail becomes greater and greater as the speed increases This, in turn, forces the nose of the aircraft down and causes the aircraft to dive more and more steeply, until it finally may go partly onto its back

We'll discuss aircraft control in more detail later, right now, let's look at lateral axis stability

Lateral Axis Stability

If the lateral axis of an aircraft is stable, the wings will not pivot about the longitudinal axis What does this mean? To say it another way the wing tips will hold their positions in flight unless some force is applied to change their position If the lateral axis is statically stable, any force applied to cause the wings to change position will be resisted, and the

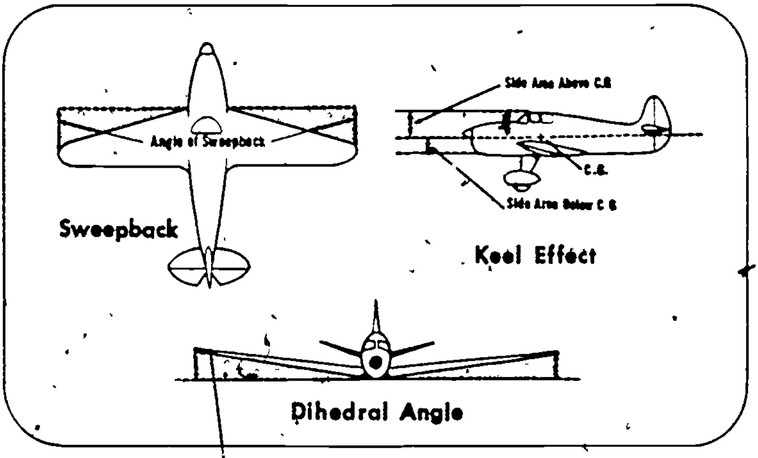

Figure 35 Dihedral Keel Effect and Sweepback

wings will return to straight and level flight once the force is removed This type of stability is comparatively easy to obtain Three factors help make an aircraft stable along its lateral axis (1) the dihedral angle of the wings, (2) keel effect, and (3) sweepback Study Figure 35 briefly, and then we'll look at these three design characteristics one at a time

Dihedral is the angle produced when the outer ends of the wings are higher than the inner ends Actually, you should view this as an upward inclination of the wings The angle at which the wing slants upward from an imaginary line parallel to the ground is the **dihedral angle.**

Here's how the dihedral figures in maintaining the aircraft's lateral axis stability When an aircraft with dihedral rolls so that one wing is lower than the other, the aircraft immediately begins to sideslip (go slightly sideways through the air) The result of this slip is that the angle of attack of the lower wing is greater than the angle of attack of the higher wing What happens? The greater angle of attack produces a greater amount of lift, and the aircraft tends to return to straight and level flight

Keel effect, the second lateral axis stabilizing factor, can also help return the aircraft to a level attitude When more of the aircraft's side surface is above the center of gravity than below it the resistance of the air to the downward and sideward movements of the aircraft tends to return the aircraft to a stable position (see Fig 36) A large vertical tail surface is often used to increase the side surface

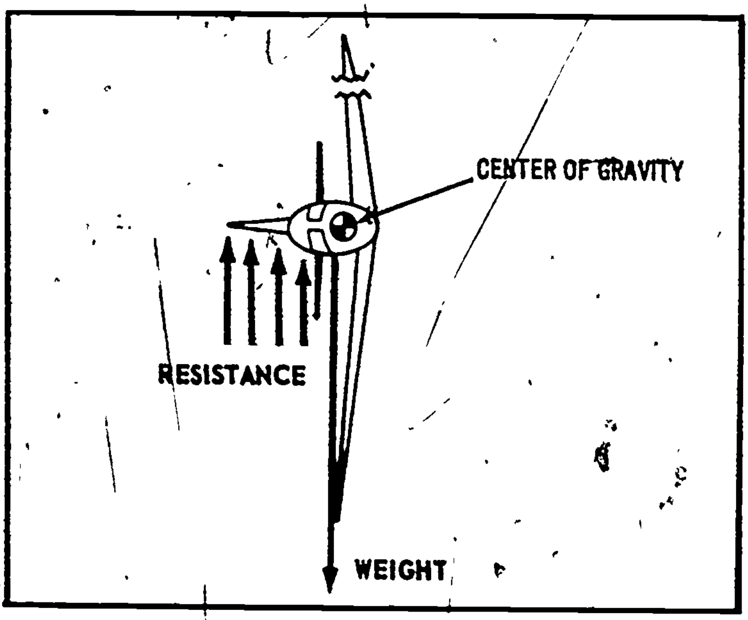

Figure 36 Keel Effect Tends to Right Sideslipping Aircraft

Sweepback produces lateral axis stability in almost the same manner as dihedral, although sweepback is not so effective Here's how it works

When an aircraft with sweptback wings begins to slip, the angle of attack of the lower wing is greater than the angle of attack of the higher wing Hence, while it is not as effective, the same kind of additional lifting force generated by the dihedral effect is produced and the aircraft tends to fly laterally stable However, this is not the primary reason for building sweepback into aircraft wings Rather, it is more commonly used to locate the center of pressure in the desired position It often happens, in designing an aircraft, that the wings must be attached to the fuselage at a certain point for structural reasons In some cases, if straight wings were used, the center of pressure would be too far forward, and the aircraft would be too noseheavy Hence, when the designer builds in sweepback, he helps both lateral and directional stability, and he also locates the center of pressure where he wants it

Directional Stability

This type of stability tends to keep the aircraft flying in a given direc-

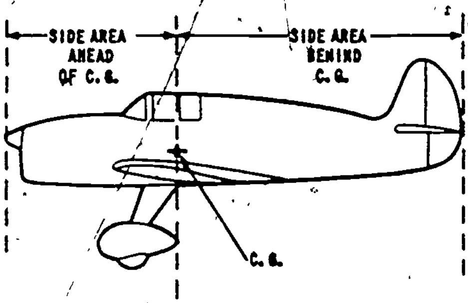

Figure 37 Directional Stability

tion Aircraft design is the key to this type of stability Movement about the vertical axis of the aircraft, you'll recall, is called yaw Aircraft can be designed so that they will tend to correct any tendency to yaw Here's how .

An aircraft acts something like a weathervane If it swings away from its course by rotating about its vertical axis (yawing), the force of the air on the vertical tail surfaces tends to swing it back to its original line of

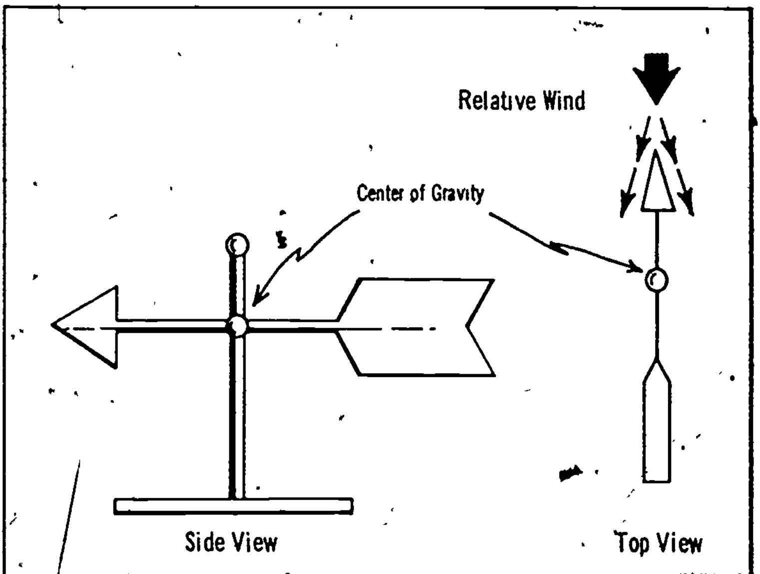

Figure 38 A Weatherwave Has Directional Stability

flight Here again, the location of the center of gravity is important The side area *behind* the center of gravity must be greater than the side area in front of the center of gravity in order to prevent yaw Why? Obviously, if there were more side area in front of the center of gravity, any tendency of the aircraft to rotate about its vertical axis would, then, tend to turn the aircraft around (see Fig 37).

Visualize a weathervane and you'll see what we mean (see Fig 38). The point at which the arrow is joined to the vertical upright is *ahead* of the center of the arrow This means that there is more side area *behind* the center of gravity than ahead of it—and the weathervane tends to face into the relative wind.

Directional stability, again, is the result of aircraft design. Adequate rear fin surface provides the necessary directional stability.

Let's sum up An aircraft is considered to be stable if it tends to resist any force which changes its flight attitude and if it also tends to return to its original position if this position is disturbed. A stable aircraft, for example, will maintain straight and level flight at a given speed without the pilot touching the controls. While it is important for the aircraft to be stable, it is also important that the pilot be able to control the attitude of the aircraft without exerting too much physical effort An aircraft can be so stable that it is difficult to maneuver Stability and control, then, are interdependent, which brings us to our next major topic area, control.

Let's start with some definitions. **Controls** in an aircraft are those devices by which a pilot regulates the speed, direction of flight, altitude, and power of an aircraft **Control surfaces** are movable airfoils designed to be rotated or otherwise moved by the pilot of an aircraft in order to change the attitude of the aircraft *Control* itself is the name given to the central concept behind these operations See Figure 39

The problem of control of an aircraft about its three axes was one of the first major problems encountered by the pioneers of aviation The Wrights recognized that one of the obstacles they must overcome was how to control their aircraft, once they got it in the air Wilbur Wright, so the story goes, observed how birds maintain lateral balance by twisting their wingtips down when they hit a gust of wind He reasoned that this twisting increased the angle of attack and hence increased the amount of lift generated This changing of the wing shape is called **wing-warping**, and it was among the first control devices built into aircraft

Ailerons soon replaced wing-warping as a more effective means of

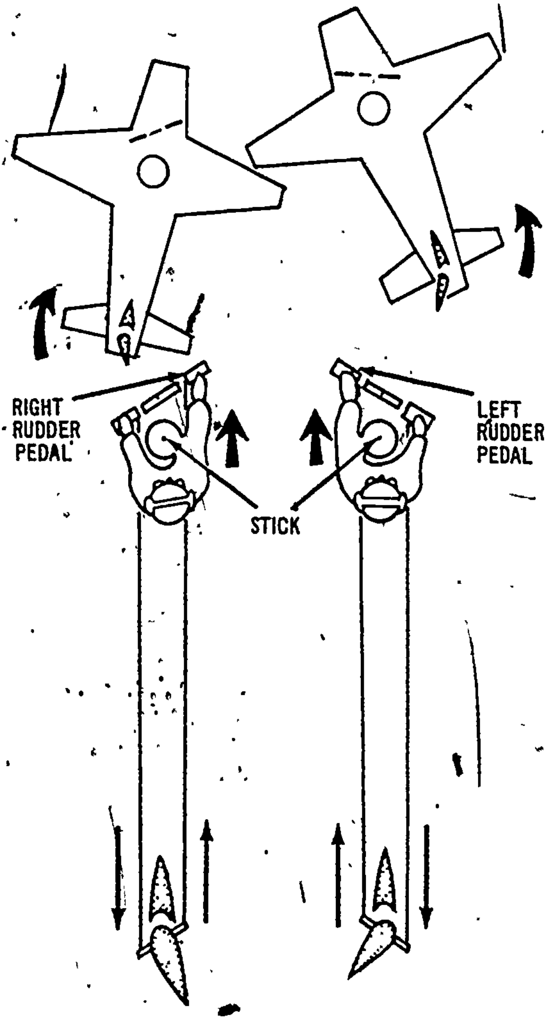

Figure 39 Operation of the Rudder

controlling the aircraft's tendency to roll **Ailerons** are movable segments of the airfoil located on the trailing edge of the wing, and they control movement of the aircraft about its longitudinal axis—roll The pilot of the aircraft moves his **stick** (wheel) to the right or to the left to control roll Moving the stick to the left raises the left aileron and

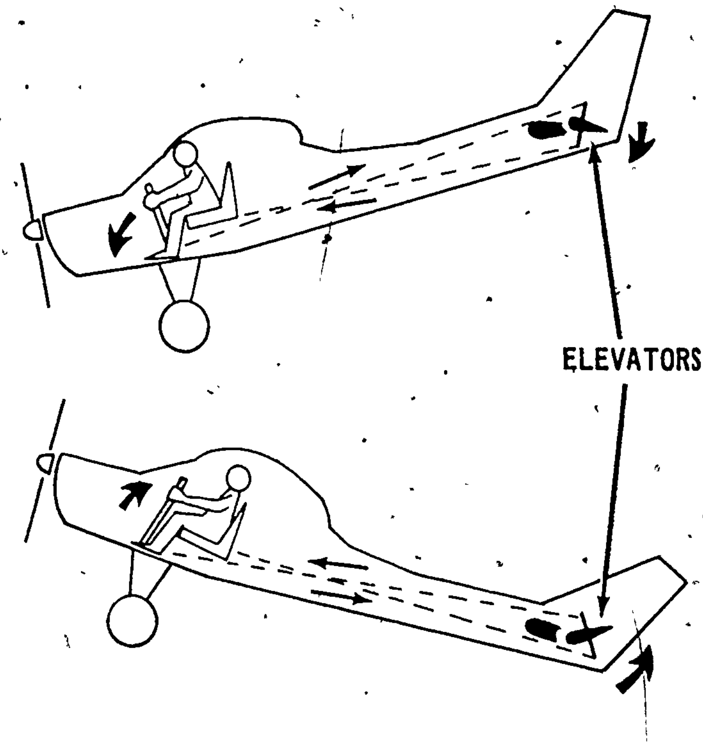

Figure 40 Operation of the Elevators

lowers the right aileron (see Fig 40) What happens? The right wing then develops more lift than the left wing, and the aircraft banks left This simply means that the aircraft turns counterclockwise

Once the ailerons have been properly positioned, the pilot returns his controls to a neutral position The aircraft then continues to bank until the pilot applies opposite control pressure to take the aircraft out of the bank

Increasing the lift, though, also increases the drag The wing with the lowered aileron will generate both greater lift and greater drag What happens then? The aircraft will yaw in the direction of the wing with the lowered aileron, which is the direction opposite the turn being performed

This yawing tendency can be corrected in two ways the ailerons themselves can be so designed that the drag on the wing with the lowered

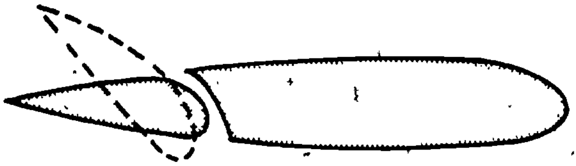

Figure 41 The Frise Aileron

aileron is decreased or the rudder can be used to offset the tendency to yaw. The **Frise aileron** (Fig 41) is designed so that the leading edge of the aileron protrudes below the lower surface of the wing. This projection, then, increases the drag on this wing, and the yawing tendency is overcome.

However, the rudder is the primary device used to overcome the tendency of the aircraft to yaw. The **rudder** is a movable control surface attached to the vertical fin of the tail assembly By pressing the proper rudder pedal, the pilot moves the rudder of the aircraft in the direction of the pedal he presses (right pedal moves the rudder to the right, and left pedal moves the rudder to the left). What happens then? When the pilot pushes the left rudder pedal, he then sets the rudder so that it deflects the relative air to the left. This then creates a force on the tail, causing it to move to the right and the nose of the aircraft, then, to yaw to the left This yawing to the left, though, is deliberate—because it overcomes the tendency of the aircraft to yaw to the right in a left-banked turn What the pilot is really doing, then, is setting up a force to counter the adverse effect which occurs when the ailerons are adjusted

At this point, it is probably well to point out that the rudder does not steer the aircraft in normal flight The rudder does not turn the aircraft, rather, its primary purpose is to offset the drag produced by the lowered aileron Clear? Let's look now at the elevators

The **elevators** are hinged sections of the horizontal stabilizer They control the pitching movements about the aircraft's lateral (wingtip to wingtip) axis Like the ailerons, the elevators are controlled by means of the stick Unlike the ailerons, though, the elevators are controlled by forward and backward movements of the stick Here's what happens when you pull back on the stick the elevators are raised so that they intersect the flow of the relative wind The impact air causes the aircraft to rotate in a taildown position about the lateral axis (which amounts to the same thing as saying that the nose is raised), and the aircraft climbs When you push forward on the stick, the opposite thing happens, the elevators are lowered so that they intersect the relative wind The impact air causes the aircraft to rotate to a tail-up position (which amounts to the same thing as saying that the nose is lowered), and the aircraft dives

These are the three basic control surfaces, then ailerons, rudder, and elevators. Although all aircraft do not have all these surfaces, we should point out that virtually all aircraft are flown by the movement of stick (wheel) and rudder pedals, which we have described Certain aircraft which do not have elevators, for example, have sections of the wing which serve much the same purpose. Hence the pilot performs the same operations in the cockpit, and the aircraft performs the same maneuvers, but for different reasons. You may have ridden in cars which have the engine mounted in the front and other cars which have the engine mounted in the rear. The controls for the driver of both autos are the same, but different things happen when the driver presses down on the accelerator pedal. Nonetheless, the car performs the same maneuvers, regardless of exactly how the controls are related to the engine

The three basic control surfaces may also have secondary control surfaces attached directly to them These additional control surfaces, called **trim tabs** may be controlled by the pilot or may be fixed. He uses these surfaces when the inherent stability of the aircraft has been disturbed by unusual loading, such as passengers in a commercial aircraft moving around inside the cabin

You may encounter some writers on aeronautics who discuss another group of control devices, flaps, slots, and spoilers We've already discussed these in the chapter on lift, and we prefer to look at these devices as lift (or antilift) devices A control device is one which controls the attitude of the aircraft in the air as its primary function, and the devices we've just finished discussing all do this The flaps, slots, and spoilers all affect the attitude of the aircraft in the air, but this is actually incidental to their primary function generating or retarding lift.

Now that you have some idea of the control surfaces and how they work, let's take a look at how these controls work in flight You still will have to learn a few more terms, but we'll include these as we go along

Climbing Flight

Climb requires power If all the available power of the engine is being used to keep the aircraft in the air, there is no power left for climbing In other words, when all the power is all being used for forward motion, none is left for vertical motion

You may be interested in knowing how to calculate the rate of climb in feet per minute This is actually very simple One horse-power is equal to 33,000 foot pounds per minute (see the unit on aircraft propul sion systems for a full discussion of the concept of horsepower). The **reserve horsepower** in an aircraft engine is the horsepower over and above that necessary just to keep the aircraft in the air in straight and level flight. If we multiply the reserve horsepower by 33,000, we then get the total number of foot-pounds per minute which can be used to climb the aircraft. If we then divide this figure by the total weight of the aircraft in pounds, we get the rate of climb in feet per minute The formula is

$$\frac{\text{Excess Horsepower} \times 33{,}000}{\text{Weight}} = \text{Rate of Climb}$$

For example, in a light aircraft weighing 2,000 pounds and having 20 excess horsepower, what would be the rate of climb?

$$\frac{20 \times 33{,}000}{2{,}000} = 330 \text{ feet per minute}$$

What about a C-5 weighing 660,000 pounds and having 20,000 excess horsepower? (For this comparison we have converted the pounds of thrust of the C-5's jet engines to horsepower)

$$\frac{20{,}000 \times 33{,}000}{660{,}000} = 1\,000 \text{ feet per minute}$$

All of these calculations, of course, are based on sea level figures. The horsepower decreases with altitude, and other factors enter into the calculations which make them somewhat more complicated. The principle, however, is the same regardless of altitude.

Another term you may encounter, **power loading,** is simply the weight of the aircraft in pounds divided by the horsepower of the aircraft.

The best speed for climbing is somewhere between the stalling speed and the maximum speed of the aircraft The best climbing speed varies with various types of aircraft The one which should be used is that given in the Aircraft Operating Manual for the specific aircraft being flown

Another thing to remember climbing angle and rate of climb do not necessarily go together An aircraft may be flying at such a high angle of attack that the reserve horsepower is very low, but it may be climbing at a very steep angle because of its low forward speed On the other hand, the speed and angle of attack that give the best rate of climb in feet per minute usually do not give the best angle of climb, since the aircraft is going farther forward for each foot of altitude it gains Here's the difference between the steepest climbing angle and the angle for the maximum rate of climb Climbing flight is flight in which the aircraft is gaining altitude. When the aircraft operates at the **best angle of climb,** it

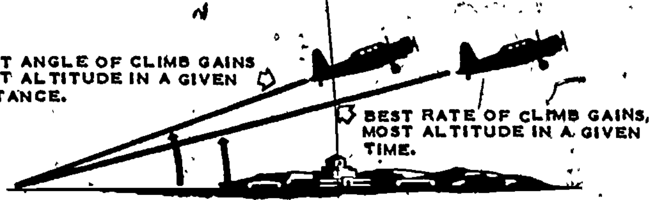

Figure 42 Angle of Climb and Rate of Climb

gains the most altitude in a given distance. When the aircraft operates at the **best rate of climb,** it gains the most altitude in a given time. (See Fig 42).

Some other terms you may encounter which deal with climbing flight are important, too **Service ceiling** is the altitude at which the maximum rate of climb is 100 feet per minute. **Absolute ceiling** is the altitude at which the aircraft stops climbing entirely, even though the throttle is wide open At the absolute ceiling, the stalling speed and the maximum speed are the same. This simply means that the density of the air is so low that the angle of attack must be increased to the maximum in order to support the aircraft, and full throttle is required to maintain level flight at that angle. A side effect of this high altitude is a dropping off in horsepower of the engine, because of the decrease in density of the air. This means that less horsepower is available at high altitude than at sea level, unless, of course, the aircraft is equipped with a supercharger (see the unit on propulsion systems for a fuller discussion).

Forces in Turns

Before we discuss forces in turns, we need to look at lift again. Lift can be divided into two components vertical (effective) and horizontal. If the aircraft wings are not straight and level, the wing lift does not act in a strictly vertical plane (see Fig 43) In addition to the vertical component there is a sideways or horizontal component with the actual lift being the resultant of these two forces. **Effective lift** is the vertical component which acts to overcome weight As you can see in Figure 43, the resultant is the actual lift, but not all of it goes toward overcoming weight Figure 44 may help you to better understand why there is less vertical component or effective lift when the aircraft is not straight and level.

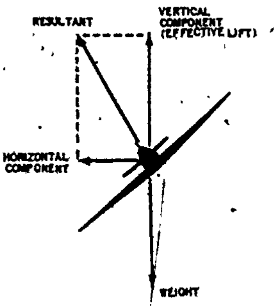

Figure 43 Components of Lift Effective Lift Equals Weight When a Constant Altitude Is Maintained.

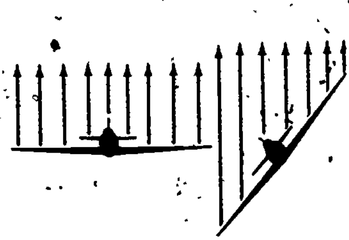

Figure 44. A Banked Aircraft Has Less Effective Wing Area Directly Opposing Weight.

Let's look now at what happens when an aircraft turns. When an aircraft is maintaining constant altitude but is not flying in a straight line, an additional force—**centrifugal force**—acts upon it. This is a force which tends to move the aircraft away from the center of the curve which it is following. Two factors influence the size of the centrifugal force. the airspeed of the aircraft and its weight. A third highly important factor is the sharpness of the turn. These forces are combined to form a resultant force. This force acts downward and outward. If the aircraft is not banked, it will skid sideways. See Figures 43-48 for examples of the various types of forces in turns in this discussion.

The angle between the aircraft wings and the horizontal (horizon) is called the **angle of bank.** When the pilot is flying correctly, this angle of bank must be numerically equal to the angle that the resultant force (combination of the weight and the centrifugal force) makes with the vertical. In other words, the upper and lower resultant forces must form a straight line. The lift must equal the lower resultant force in magnitude. If the angle of bank is correct and if the lift equals the resultant, the aircraft executes a correct turn.

If the angle of bank is too small the lift will not be acting in a direction exactly opposite to the resultant of the weight and centrifugal force. In effect, the horizontal component of centrifugal force is greater than the compensating horizontal component of lift. Then, regardless of the amount of lift, the aircraft will tend to move outward, or **skid** (see Fig 45).

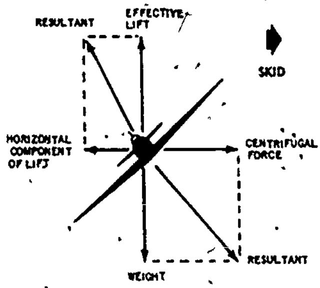

Figure 45 Skid, Aircraft Moves Toward the Outside of the Turn

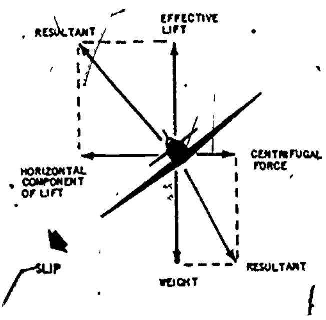

Figure 46 Slip, Aircraft Moves Toward the Inside of the Turn

Take a look, now, at Figure 46. Here, the angle of bank is too great. The lift force and the resultant of weight and the centrifugal force combine to produce a force acting inward and downward. In this example the horizontal component of lift is greater than centrifugal force and the aircraft will **slip** to the inside of the turn.

In Figure 47, the bank is right, but the lift is too low. Since the resultant is greater than the lift, the aircraft will settle or descend.

The opposite holds true in Figure 48. Here, the lift is greater than the resultant In this case, the aircraft will climb, and the net result will be a climbing turn This particular maneuver requires a great deal of extra power, simply because the aircraft is overcoming, simultaneously, the forces of weight, drag, and centrifugal force. Under ordinary circumstances, a truly vertical bank can't be made without slipping occurring.

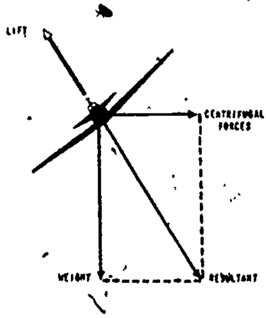

Figure 47 Lift Less Than Resultant

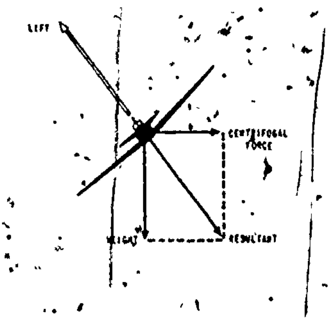

Figure 48, Lift Greater than Resultant

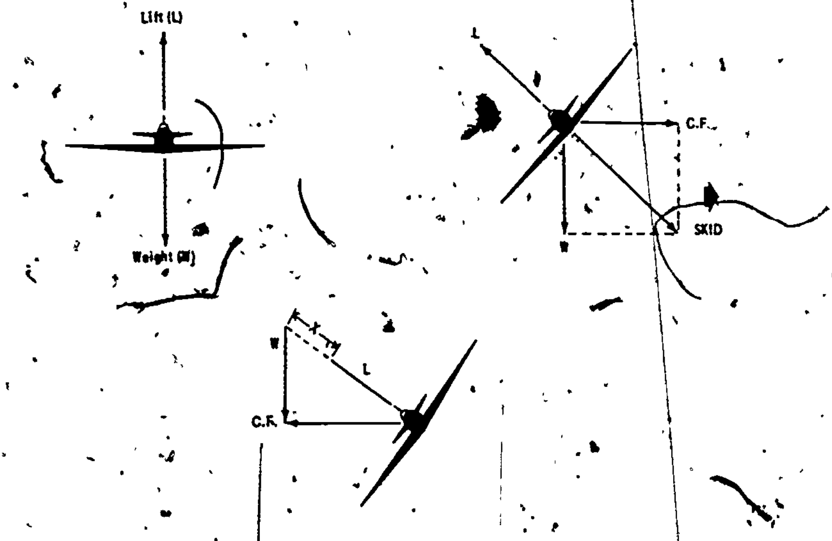

Figure 49 Effect of Centrifugal Force on a Turning Aircraft Lift Must Be Increased to Maintain Altitude

Obviously, it is almost impossible to maintain a true vertical bank in a conventional aircraft, because no matter how great centrifugal force may be, weight is always acting, so the resultant will have a downward component

To review in oversimplified terms, too much centrifugal force results in a skid while too much weight or horizontal lift results in a slip An imbalance in lift means that the aircraft will either climb or descend

Let's take another look at turns, only this time we'll use a different approach Take a look at Figure 49 In section A, the aircraft is shown in level flight, and the lift and the weight (L and W) are equal In section B, the aircraft is in a bank with the same amount of lift (L) and weight (W) But now, we have centrifugal force (CF) as well Hence, we have to compute a resultant, and the resultant is greater than the lift. Now, take a look at section C We have moved the forces so that the difference may be more readily appreciated The centrifugal force is moved to the inside of the bank, and the weight force is also drawn on the inside In order for the aircraft to maintain altitude, the lift force must extend to the point where the weight force begins In other words, we're missing

"X" amount of lift and will lose altitude if we don't change something Thus, if altitude is to be maintained in a turn, lift must equal weight plus the resultant centrifugal force caused by the turn.

Some way or other, this deficiency in lift must be made up This may be done by either increasing power or increasing the angle of attack The only way that you can increase the angle of attack is to raise the nose by the use of the elevators. That's why we said that in any turn, it is the elevators that really do the work.

Take another look at Figure 49. What will the rudder do in turning flight? The rudder controls movement about the vertical axis, therefore, moving the rudder will have no effect except to cause the nose of the aircraft to drop along a line parallel to the wing—that is, on a diagonal line. The ailerons, likewise, can have no effect other than to hold the aircraft at the proper bank, if that is necessary As a matter of fact, as we'll discuss shortly, a slight amount of opposite aileron is usually necessary in executing a proper turn. With respect to the rudder, however, once the turn has begun and the drag of the lowered aileron has been overcome, the pilot can remove his feet entirely from the rudder pedals and still continue to make a perfect turn. When he decides to come out of the turn, he uses opposite aileron (the aileron which is not in the direction of the turn he is making), and he has to use opposite rudder For example, if the pilot is coming out of a right turn he applies left rudder and left aileron.

Now, let's go back to the use of left aileron in a right turn and right aileron in a left turn When the aircraft is turning, it is moving in a circle (see Fig 50) It may not move around a complete circle, but it is still moving in a circular motion The wing tips, then, describe concentric circles This means that the outer wing moves farther, in the same period of time, than the inner wing. If it is moving farther in the same period of time, it is then moving faster than the inner wing Since it is moving faster and is at the same angle of attack as the inner wing, it generates slightly more lift than the inner wing Do you see the problem developing? Here's what happens next

To offset this additional lift, the pilot has to exert a slight pressure on the stick toward the outside of the turn This pressure, of course, slightly lowers the aileron on the inside of the turn, and this lowering compensates for the increased lift on the outer wing and makes the lift of the inner and outer wings the same If you've been following closely, you realize that the pressure on the stick also raises the aileron on the outside wing, which decreases its lift Both actions tend to equalize the lift If the pilot did not do this, the aircraft would bank more and more steeply as

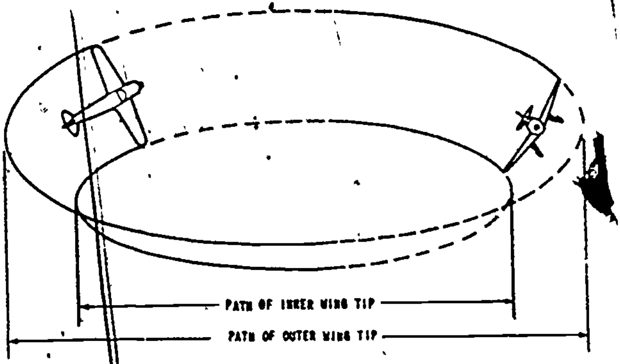

Figure 50 Ailerons and Turns

long as the turn was continued This effect is called the over-banking tendency

A final point about forces in turns since the pilot is increasing his aircraft's angle of attack to maintain altitude during a turn, he has to increase his power to maintain a constant airspeed If he does not, the airspeed will decrease in a steep bank This combination of increased power and increased angle of attack may produce severe stresses on the wings, but we'll discuss this more later.

AIRCRAFT MOTION AND CONTROL

Do you really know how an aircraft flies? Most people do not know, even though they think they understand it Ask yourself these questions What is the up and-down control of an aircraft? The elevators, you say? You are wrong—it is the throttle. What in the world is the speed control, then? The throttle? Wrong again—it is the elevators What turns the aircraft in the air? Well, we tipped you off a little while back that it is not the rudder. After the ailerons start the turn, the wings lift the aircraft around. How does this work? Simple—the pilot holds the stick back, which increases the angle of attack and produces more lift

Don't take our word for it, though. Let's get an aircraft into the air and adjust the controls so that the aircraft flies straight and level We'll assume that this is a propeller-driven aircraft The propeller interacts with the air, and the aircraft moves forward This is thrust The air moving over the wing causes a decrease in pressure above the wing, producing lift. The resistance of the air to the wing's moving through it is called drag. The force which attracts the aircraft to the earth is called gravity, and it measures the aircraft's weight. So far, so good, this is all old stuff to you. All the forces acting on the aircraft are in balance.

Now, we push the throttle forward, the propeller turns faster and produces more thrust, the wing moves faster, generating more lift, and the aircraft climbs The more lift generated by the wing, the greater the drag of the wing The additional drag balances the additional thrust, but the additional lift makes the aircraft climb. Now, if we pull out on the throttle (reducing power), the nose will drop. The throttle, then, is the up and down control.

Surprised? If the throttle is the up and down control of the aircraft, what controls the speed? We said it was the elevators. Here is how it works As we cruise along, the airspeed indicator shows 80 mph. Now, we pull back on the stick, and the airspeed drops to 60 mph. Now, we push the stick forward, and the airspeed increases until it reaches 100 mph This shows that the elevators really are the aircraft's speed control. The elevators control the speed of the aircraft because they control its angle of attack, and you remember that angle of attack is the angle formed by the relative wind and the chord of the airfoil, or wing.

We've talked about speed, let's look, for a moment, at speed in a bit more detail. The important thing for an aircraft is its airspeed. Airspeed is the speed of the aircraft through the air, while the speed of the aircraft over the ground is called, logically enough, groundspeed. A pilot learns to "feel" a stall coming When his aircraft is approaching a stall, the pilot can feel a shudder in the aircraft's wings, and he finds that the ailerons are so sluggish that they have little, if any, effect on the wings

Stall speed changes with the aircraft configuration It increases in a turn It decreases with the flaps down. The aircraft can stall in level flight and in a turn, even with full power on.

How does an aircraft turn? Certainly not by the rudder! Some aircraft don't even have rudders An aircraft is turned by first lowering one wing with the ailerons and then lifting the aircraft around using the elevators. When the aircraft makes a turn, centrifugal force tries to pull it away from the center of the turn If you whirl a stone on a string, centrifugal force tends to pull the stone and the string out of your hand The same is true of an aircraft in a turn (See Fig 51) The aircraft, then, must oppose this pulling force, and this requires extra lift.

Right about now, you are probably wondering why an aircraft has a rudder at all, if it is not used for turning Here's why Let's put the aircraft in a right turn In the right turn, the right wing is lowered, and the left wing is raised The left wing develops more lift, and it also develops more drag This increased drag tends to pull the aircraft around in a direction opposite to the turn This tendency is called ad-

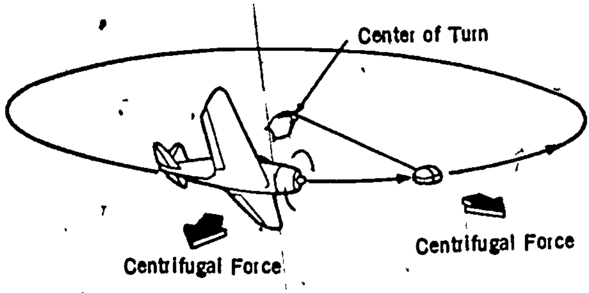

Figure 51 Centrifugal Force in Turns

verse yaw. To correct for adverse yaw, the pilot applies pressure to the right rudder pedal This moves the rudder to the right and consequently moves the tail to the left This keeps the plane from yawing That is the rudder's main job to correct for adverse yaw

Now you should have a better idea of how the controls of an aircraft really work Experienced pilots often say there is one rule that will be the greatest help to the amateur pilot "Get that stick forward!" Why? If the aircraft's turn is too tight, it will stall The stick is your speed control, and your aircraft must have speed to stay in the air

Let's try to sum up this lengthy chapter Aircraft fly in three dimensions, and pilots can control the aircraft's performance in all three Stability in an aircraft in flight comes from both design and operation, and the controls in an aircraft enable the pilot both to maintain straight and level flight and to perform various maneuvers Flight controls are almost unnecessary in a properly trimmed aircraft to maintain straight and level flight They are used under all conditions of aircraft motion taxiing, takeoff, climb, straight and level, turning, descending, and landing When the aircraft is properly trimmed for a particular maneuver, it may be flown in that maneuver with very little need for manual control

WORDS AND PHRASES TO REMEMBER

longitudinal axis	control surfaces
roll	wing-warping
lateral axis	ailerons
pitch	stick
vertical axis	Frise aileron
yaw	rudder
stability	elevators

static stability
neutral stability
positive stability
negative stability
dynamic stability
downwash
slip stream
dihedral
dihedral angle
keel effect
sweepback
controls
trim tabs
reserve horsepower
power loading
best angle of climb
best rate of climb
service ceiling
absolute ceiling
effective lift
centrifugal force
angle of bank
skid
slip
adverse yaw

THINGS TO DO

1. Build a model airplane with movable control surfaces as a shop project. (Your instructor has a set of plans).
2. Perform the experiment on stability described in the text.
3. Discuss flight controls on a balloon.
4. Demonstrate how elevators and ailerons work by flying paper airplanes. If any class members have controllable model airplanes, have them put on a class demonstration. Be sure they explain the principles involved in each maneuver.
5. If you look closely at the wings on a light aircraft, you will see they are not exactly the same. One appears slightly twisted. Find out why.
6. Suppose a multiengine jet aircraft with engines near the wing tips was flying at supersonic speeds and an outboard engine suddenly quit. Discuss what might happen and suggest what aircraft designers could do to aid a pilot in this situation. If you are stumped, ask your instructor for help.

SUGGESTIONS FOR FURTHER READING

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MANDER JERRY and GEORGE DIPPEL and HOWARD GOSSAGE *The Great International Paper Airplane Book*. New York Simon and Schuster, 1967

SANDERSON *Aviation Fundamentals*. Denver, Colorado Sanderson Times-Mirrow, 1972

STOVER H GUYFORD and JAMES J HAGERTY *Flight* New York Time Incorporated, 1965.

REVIEW QUESTIONS

1. What can we assume about the four forces of flight when the aircraft is flying straight and level?

2. Match the aircraft axis with the description of its location:
   a. longitudinal — 1. wing tip to wing tip
   b. lateral — 2. nose to tail
   c. vertical — 3. top to bottom

3. Match the aircraft axis with its direction of rotation:
   a. longitudinal axis — 1. roll
   b. lateral axis — 2. yaw
   c. vertical axis — 3. pitch

4. True or False. An aircraft cannot rotate around all three axes at once.

5. The property of a body which causes it to return to its original condition when disturbed is called ______.

6. Match the following conditions of static stability with appropriate descriptions.
   a. positive stability — 1. neither returns nor accelerates away when displaced
   b. neutral stability — 2. accelerates away when displaced
   c. negative stability — 3. returns when displaced

7. Define dynamic stability.

8. Stability along which axis is the most important?
   a. vertical
   b. lateral
   c. longitudinal

9. The center of pressure is deliberately located (ahead of/behind) the center of gravity of an aircraft.

10. Define downwash.

11. The stream of air driven rearward by the propulsion system is called the ______.

12. The wings of an aircraft will not pivot readily about the longitudinal axis if which axis is stable?

13. Which of the following factors help to make an aircraft stable along its lateral axis?
    a. keel effect
    b. sweepback
    c. dihedral angle
    d. all of the above

14. True or False. The primary reason for building sweepback into wings is to promote lateral stability.

15. The larger the rear fin surface, the (more/less) directional stability an aircraft will have.

16. Match the following subjects to appropriate definitions.
    a. controls — 1. name of central concept
    b. control surfaces — 2. name of moveable airfoils
    c. control — 3. name of regulating devices

17. Ailerons are (more/less) effective than wing-warping.

18. True or False. Ailerons are moveable segments of the airfoil located on the trailing edge of the horizontal stabilizer.

19. Moving the stick to the right lowers which aileron?
 a. right
 b. left
 c. both ailerons
 d. none of the above

20. What control surface design automatically corrects the yawing tendency in a roll?

21. Define rudder.

22. True or False. The rudder steers the aircraft in normal flight.

23. True or False. Elevators control the pitching movements about the aircraft's vertical axis.

24. What is the rate of climb in feet per minute of a 3,000 lb. aircraft with 20 reserve horsepower?
 a. 100
 b. 220
 c. 330
 d. 990

25. The best speed for climbing lies somewhere between the _______ speed and the _______ speed of the aircraft.

26. When an aircraft operates at the best rate of climb, it gains the most altitude in a given (distance/time).

27. The altitude at which the maximum rate of climb is 100 feet per minute is called the (service/absolute) ceiling.

28. Which of the following factors has the greatest influence on the size of the centrifugal force?
 a. altitude
 b. density
 c. wing span
 d. weight

29. Define angle of bank.

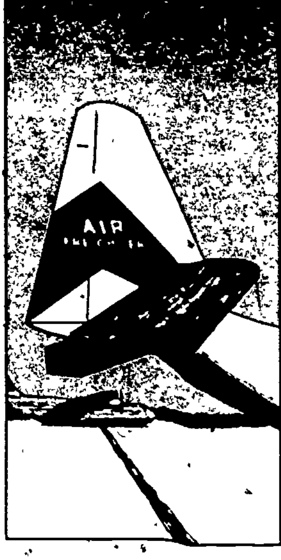
30. If the forces on a banking aircraft are not in balance and the plane is moving to the inside of the turn, it is said to be (skidding/slipping).

31. Match the aircraft motion with the appropriate control:

a. up and down	1. throttle
b. speed	2. elevators
c. turns	3. ailerons and elevators

32. What is the rudder's main job?

33. What rule is probably the greatest help to an amateur pilot?



Chapter 6

Aircraft Structure

THIS CHAPTER examines the aircraft itself and how the various parts are built and why they are built that way. First, you will read about the power plant, then the fuselage and the way in which it is built. A brief discussion of stresses and how they affect aircraft construction will follow. We will also look, in some detail, at wing and tail construction, control surfaces, hydraulic and electrical systems, and the landing gear. After you have studied this chapter, you should be able to: (1) discuss the five types of stress which act on an aircraft in flight; (2) explain how aircraft construction counteracts these stresses; (3) discuss the various types of fuselage and wing construction and point out some advantages of each; (4) describe the principal parts of the empennage; (5) list applications of hydraulic and electrical systems in the aircraft; and (6) explain how today's aircraft landing gear works.

WE'VE LOOKED at many things, from man's first desire to fly to controlled powered flight. We've discussed the theories underlying flight, and we've talked about how an aircraft maneuvers in the air. Next, let's take a closer look at the aircraft itself. You may remember from last year the various parts of the aircraft that were mentioned. Here, we plan to show you how all the structures of an aircraft fit together in light of what you now know about why the aircraft flies.

We're including a diagram of a conventional propeller-driven aircraft (Fig 52) This diagram will help you to see where aircraft parts

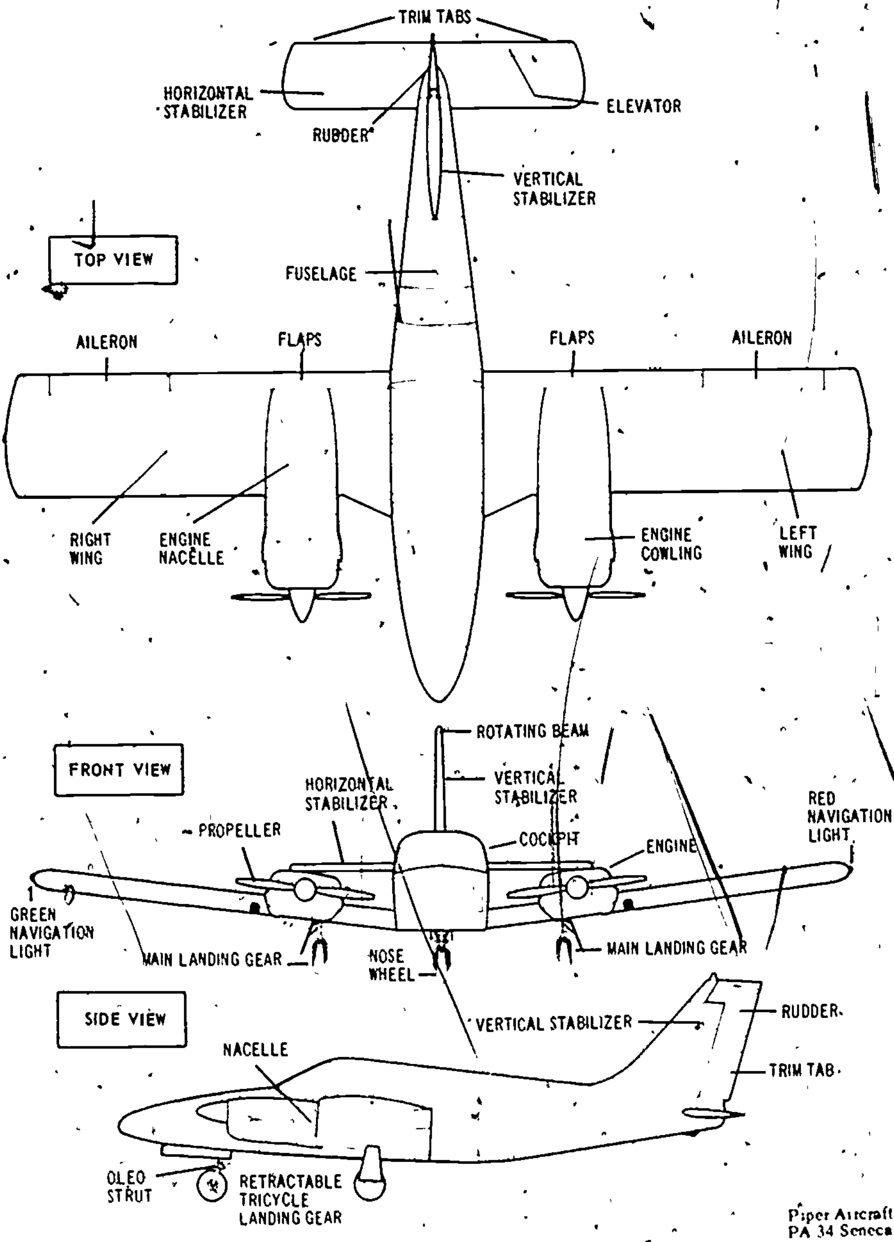


Figure 52 Structural Elements of an Aircraft

are located as we discuss them. Except for the propellers, a jet aircraft would consist of the same basic structures.

POWER PLANT

Because an aircraft is a functionally designed piece of equipment, it's hard to say if any one component is more important than any other. However, many people will say that the power plant is one of the most essential components for normal flight. You'll soon be covering propulsion systems for aircraft in another unit, so we won't go into much detail on how the various propulsion systems operate. We will merely tell you what the power plant does, what it looks like, and where it is located.

In Figure 52, you can see the propeller, the engine nacelles, and the engine cowlings. The propeller, as we noted earlier, is essentially a curved airfoil. It provides the thrust which helps sustain the aircraft in flight. It operates because of Newton's Third Law of Motion (the action-reaction law we've studied). The action here comes from the relationship between the moving propeller and the air, and the reaction is the forward movement of the aircraft. The unit on propulsion systems will examine the propeller at some length.

Behind the propeller, you'll notice the **engine cowling.** This is simply a cover for the engine. It protects the engine and directs cooling air onto the engine itself.

The **engine nacelles** are streamlined containers for auxiliary engine systems. Notice in the side view shown in Figure 52 how the engine nacelles continue the streamlining begun by the engine cowlings. Other aircraft have nacelles adapted for other purposes. If you see an aircraft with "tip tanks", note the shape of the fuel tanks, they, too, are nacelles. Some aircraft have had passenger nacelles, such as the C-119 "Flying Boxcar." It had, in effect, two greatly extended engine nacelles with a passenger nacelle in between. Single-engine aircraft do not have engine nacelles. This is because the engine is attached directly to the fuselage, our next major structural element.

FUSELAGE

The **fuselage** is the main or body part of the aircraft. It carries the crew, passengers, cargo, instruments, and most other essential equipment or payload. Fuselages are usually classified according to the way the structure has been built to withstand all of the stresses that it will have to meet. The two main types of construction are the welded steel truss and the semimonocoque. The truss type of construction is made of steel tubing, and the semimonocoque type of construction is made from internally braced metal skin. In order to understand these two types of

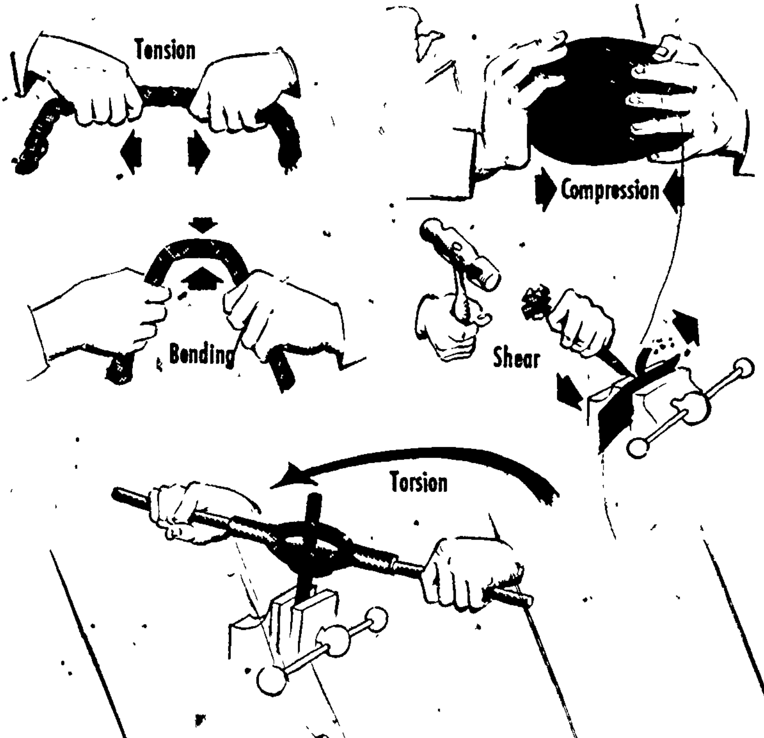


Figure 53 Types of Stress

construction better, you need to know something about the stresses which act on an aircraft in flight. First we'll look at the types of stress, and then we'll return to the types of fuselage in order to show you how the fuselage is designed to bear these stresses.

Take a stick in your hands and start to break it Up to the breaking point, the stick has internal forces which resist the force you apply These internal forces are called **stresses,** and they are measured in terms of force per unit of area. Stresses are expressed in pounds per unit of area (often in square inches) If you exert a force of 50 pounds on an area of one-half square inch, the stress is 100 pounds per square inch

Five types of stress act on an aircraft in flight tension, compression, bending, shear, and torsion. Let's look at each one individually (see Fig 53)

Tension. When you try to break a length of rope, you exert a type of stress which is called tension Tension is the stress which tends to pull members apart A **member** is any part of an aircraft that carries a stress

When you pull on the control cables of an aircraft, you're exerting tension.

Compression. Compression is the opposite of tension. Compression is the stress which tends to push materials together. When you grasp a football at both ends and push, the ball is subject to compression. The landing gear struts of an aircraft are also subject to compression.

Bending. This type of stress combines tension and compression. You put a bending stress on a bar when you grasp it with both hands and push the ends together, or when you bend a paper clip. The wing spars (interior structural members) are subjected to bending while the aircraft is in flight. The lower side of the spar is subjected to tension, while the upper side is subjected to compression. Obviously, some materials will break before they bend and often are unacceptable for aircraft construction.

Shear. This is the stress that is placed on a piece of wood, clamped in a vise, when you chip away at it with a hammer and chisel. This type of stress is also exerted when two pieces of metal, bolted together, are pulled apart by sliding, one over the other or when you sharpen a pencil with a knife. The rivets in an aircraft are intended to carry only shear. Bolts, as a rule, carry only shear, but sometimes they carry both shear and tension.

Torsion. Torsion is the stress which tends to distort by twisting. You produce a torsional force when you tighten a nut on a bolt. The aircraft engine exerts a torsional force on the crankshaft or turbine axis.

All the members (or major portions) of an aircraft are subjected to one or more of these stresses. Sometimes a member has alternate stresses, such as compression one instant and tension the next. Some members can carry only one type of stress. Wire and cables, for example, normally carry only tension.

Since any member is stronger in compression or tension than in bending, members carry end loads better than side loads. In order to do this, designers arrange the members in the form of a **truss**, or rigid framework. In order for a truss to be rigid, it must be composed entirely of triangles. We'll eliminate many of the technical terms associated with trusses, it's enough that you realize that the fuselage is designed so that the various types of stress are distributed throughout the fuselage. Most aircraft which have trussed fuselages use the **Warren truss** (Fig 54). The members in this type of truss can carry either tension or compression. When the load acts in one direction, every alternate member carries tension while the other members carry compression. When the load is reversed, the members which were carrying compression now are subjected to tension, and those which were carrying tension are under com-

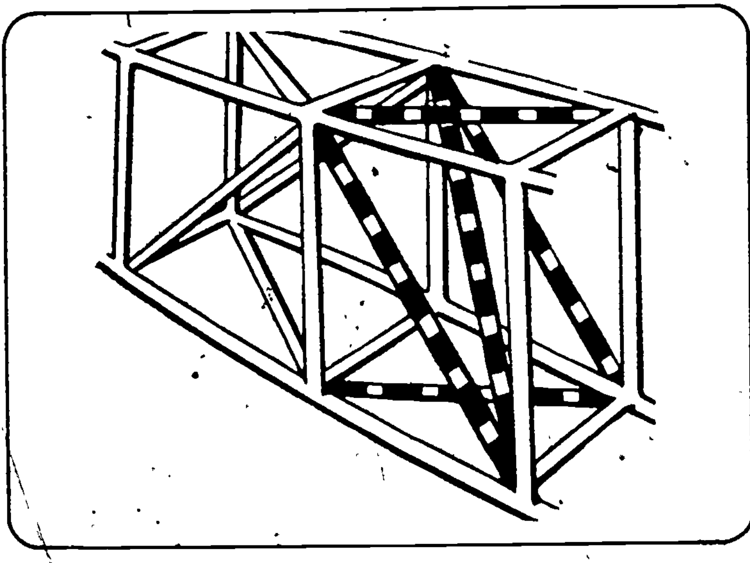


Figure 54. The Warren Truss.

pression. The truss itself consists of a welded tubular steel structure with **longerons** (horizontal members) and diagonal braces. These features make it rigid, strong, and light.

The truss can be covered with a metal or fabric cover. Since we're building our own plane, we'll use fabric. We want a smooth external surface so that less drag will be generated. To produce a smooth surface, the fabric cover is put on **fairing strips,** which are thin flat strips of wood or metal. These fairing strips run the length of the fuselage in line with the direction of flight. The top of the fuselage usually has several such members arranged in the form of a curve, or it may have a single curved sheet of a light metal, such as aluminum. This curved upper portion (called a **turtle back**) is simply a fairing, and its purpose is to cut down air resistance (see Fig 55).

The semimonocoque type of fuselage is used in most military aircraft. The word monocoque is French, and it means single shell. In the true monocoque fuselage, which few aircraft use, all the stresses are carried by the shell or skin itself. The de Havilland Mosquito, one of the triumphs of World War II British aircraft design, was one of the last really notable aircraft to use this type of construction.

As its name implies, the **semimonocoque** type of construction allows for both the skin of the aircraft and the internal bracing to carry the

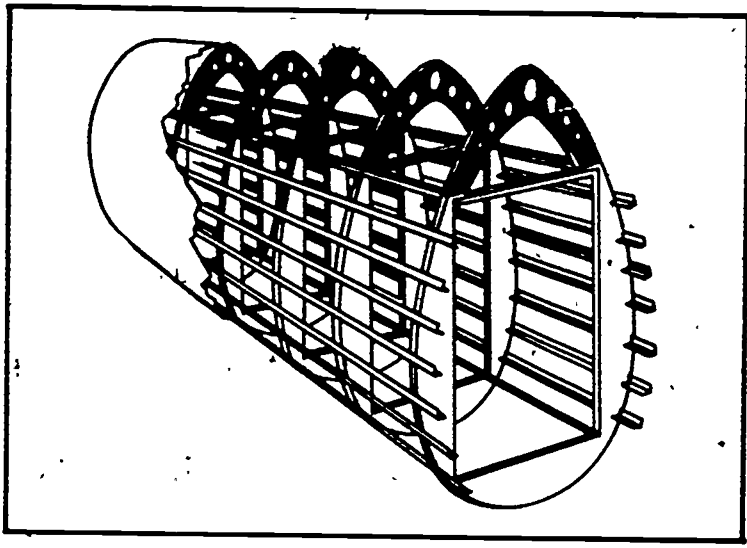


Figure 55. The Turtle-Back Fairing.

stress The internal bracing is made up of longitudinal members, called **stringers** and vertical members called frames (sometimes called **bulkheads**) The stringers are attached to **rings** or formers which run around the fuselage and serve chiefly to give the fuselage its shape (see Fig 56).

The semimonocoque type of fuselage is easy to build in streamlined

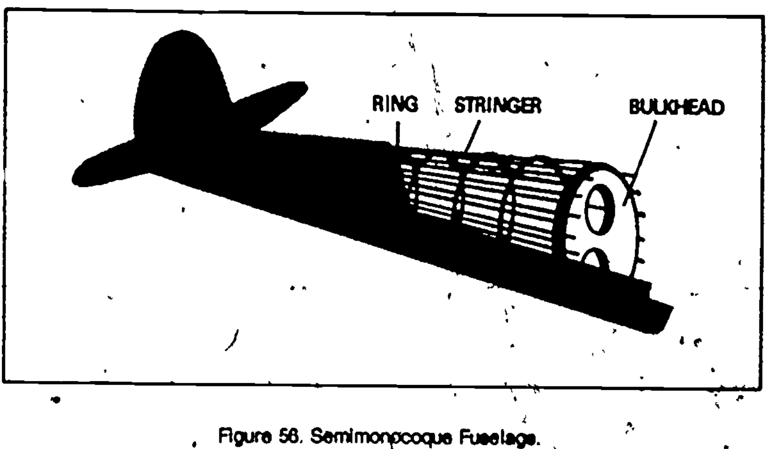


Figure 56. Semimonocoque Fuselage.

form and, as you've already learned, the streamlined form is the most efficient shape for moving through the air. If it is built with flush rivets, it becomes a highly streamlined body all-metal, fireproof, and with proper protective coatings unaffected by climatic conditions For this reason, the semimonocoque fuselage can take considerable punishment and still hold together.

The skin itself is usually made of sheets of aluminum alloy, although plywood has been used. In the future, we may develop plastics and other synthetics which will replace metal alloys as efficient, rigid, strong, and safe skins.

You may encounter the term load factor in your study of aircraft structure. **Load factor** simply means the load placed upon the aircraft under various conditions of flight. When an aircraft is flying straight and level, the wing load is equal to the weight of the aircraft If the pilot pushes the controls forward or pulls them back, additional forces are exerted which change the load on the aircraft. Rough air has the same effect, although it generally is not so great as pushing forward or back on the controls.

Aircraft must be designed, then, to carry not only the loads of normal flight but also those loads developed in reasonable maneuvers and in gusts. To save weight, most aircraft parts are made of extremely thin, high quality material. Corrosion, rust, scratches, or nicks may weaken them and cause structural failure or collapse of the part in flight

In keeping structural weight to a minimum, aircraft designers always take ultimate load into account. **Ultimate load** is the load that causes structural failure. If ultimate load is exceeded, the aircraft will come apart. Ultimate load is customarily fixed at about one and a half times the maximum applied load. The **maximum applied load** is the greatest load to which the structure will be subjected in flight The ratio between the maximum applied load and the ultimate load is called the **safety factor.**

Regardless of the altitude or position of an aircraft, whether it is parked, taking off, flying straight and level, turning, performing acrobatic maneuvers, descending, or landing, stresses occur on the fuselage structure. The truss type assembly acts like the structure of a bridge, since loads are distributed by the parts to the entire fuselage The semimonocoque type of construction gets its strength from the metal skin or shell, which is, in turn, reinforced by the internal rings and stringers.

WINGS

Wing construction is basically the same in all types of aircraft The

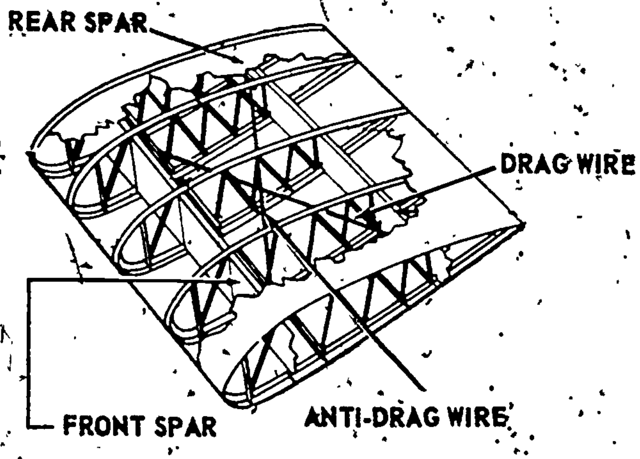


Figure 57. Construction of a Cloth Covered Wing.

Terms used to describe the elements of wing construction will look familiar to you, since many of them are the same terms we've just discussed in fuselage construction. The two basic materials used in wing construction are wood and metal.

The main structure of a wood and fabric wing consists of two long spars (longitudinal members) running outward from the fuselage toward the wing tip. Curved ribs are secured to the spars, and they are then braced and covered with special cloth which gives the wing its familiar curved shape. The fabric is then painted (or "doped") to make it tough, strong, and weather resistant (see Fig 57).

Metal wings are constructed along the same general lines, except that the ribs are generally made of light metal, and thin sheets of metal replace the fabric. The metal wing is obviously much stronger, therefore, it is used most often for military aircraft and large commercial aircraft. However, its increased weight and cost make it undesirable for the average light transport or sport aircraft (see Fig 58).

In order to maintain its all important aerodynamic shape, a wing must be designed and built to hold this shape even under extreme stresses. To understand and appreciate the aircraft's design and strength, you'll need to know about the several types of wing construction.

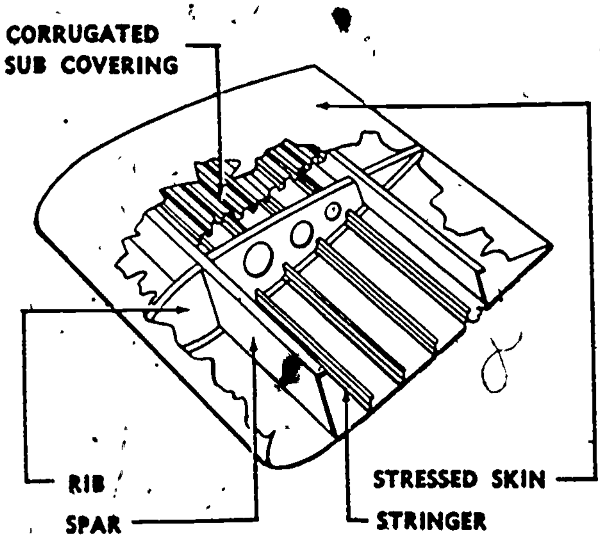


Figure 58 Construction of a Stressed Skin Type of Wing

In its simplest form, the wing is simply a framework composed chiefly of spars and ribs. **Spars,** you'll remember, are the main members of the wing. They extend lengthwise of the wing (crosswise of the fuselage). All the load carried by the wing is ultimately taken by the spars. In flight, the force of the air acts against the skin. From the skin, this force is transmitted to the ribs, and then it is finally borne by the spars.

Most conventional wings, particularly those which are covered with fabric have two spars. one near the leading edge and one about two-thirds the distance to the trailing edge. Some metal-covered wings may have as many as five spars. In this type of wing, the ribs are either omitted entirely or are made up of short sections fitted between the spars. In addition to the main spars, some wings also have what is called a false spar. The **false spar** carries the aileron, rather than carrying stresses.

The **ribs** are the parts that support the covering and maintain the shape of the wing. The main ribs, which give the wing its shape and carry the lift loads transmitted by the skin, are called form ribs These ribs normally do not carry any of the drag load. Nose ribs serve to maintain the shape of the nose section of the wing, since the force of the air on this section is much greater than on other sections of the wing. In addition to these nose ribs, plywood or metal coverings help maintain the contour of the leading edge of the wing.

A drag truss, composed of compression ribs, keeps the wing rigid in a fore-and-aft direction. Often these ribs are simply round tubes. The compression rib at the inner end of the wing is called the root-rib. Two types of bracing wires are often used to strengthen the structure. **Drag wires** run from the inner front to the outer rear of the wing, and **anti-drag wires** run from the inner rear to the outer front of the wing. In some wings, a diagonal strut replaces these two wires, since this strut may carry either tension or compression.

If the wing is covered with metal, the drag truss is usually eliminated entirely, and the metal covering keeps the wing from losing its shape. In the metal wing, the covering itself also bears some of the stress, and this is why it is called **stressed skin.**

So much for the wings themselves. Let's see how they're attached to the aircraft fuselage. Three systems are used to attach the wings to the fuselage. full cantilever, semicantilever, and externally braced. The **full cantilever** wing features an extremely strong wing structure. This structure is so strong that the wings can be attached directly to the aircraft without any external bracing.

In the **semicantilever** wing, the internal structure of the wing is lighter and less expensive than in the full cantilever wing. Small streamlined wires or tie rods supply strength and rigidity to the connection between wing and fuselage. Sometimes, the wires or tie rods may be attached to the landing gear, if the landing gear is of the fixed type.

The third type of wing structure is the **externally braced** wing. Heavy struts or spars extend from the wing to the fuselage and the landing gear. This type of wing is even lighter than the semicantilever type of wing, but of course the external struts increase the amount of drag the aircraft develops in flight. This increase in drag, you'll remember, will decrease the top speed of the aircraft considerably. Fast military aircraft can't use this type of wing construction, but relatively slower and less expensive types of sport aircraft use it extensively. Figure 59 is an example of an externally braced wing. Then what kind of a wing does a swing wing aircraft like the F-111 have? If you think about it, you will realize it must be a full cantilever due to the extra stresses placed on the movable wing (see Fig 60).

EMPENNAGE

This imposing French term means **tail assembly.** Its derivation, though, is quite interesting. The French verb empenner means "to feather an arrow." Why are arrows feathered? To give them greater

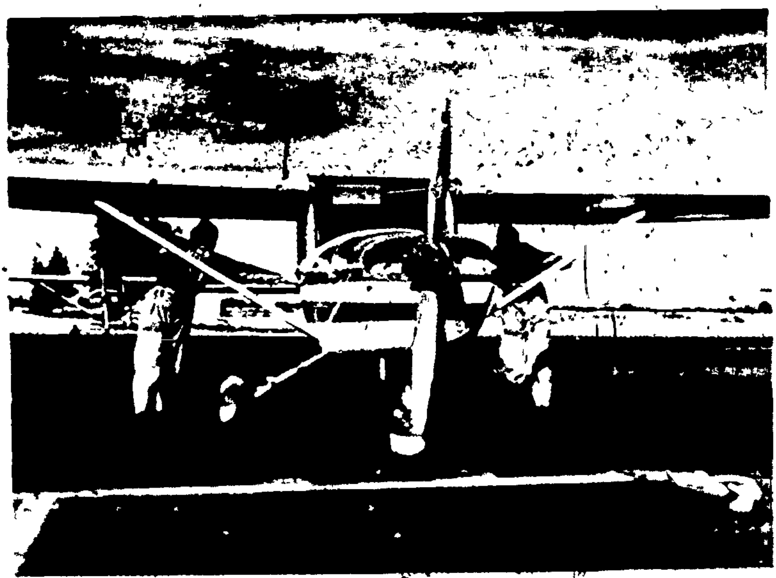


Figure 59. An Externally Braced Wing.

stability in the air, of course. This is also the primary function of the tail assembly. We've also discussed how the control surfaces of the empennage operate in the last chapter, all we want to do here is to point out where on the aircraft these surfaces are located and also to describe the noncontrol surface portion of the empennage.

If you've seen pictures of very early aircraft, perhaps you've noticed that many don't have tail assemblies. This is because the very early aviation pioneers didn't understand stability as we do, today. An aircraft without a tail assembly is just about as unstable as a boat without a keel! Virtually all modern aircraft have some sort of tail assembly. But tail assemblies, like wings, are designed with specific performance characteristics in mind.

When you stand behind an aircraft and look at it, you'll usually see at least two small winglike structures extending to the right and to the left and one vertical structure which extends upward from the fuselage. Look more closely, and you'll see that these structures are each divided in half (see Fig 61). Let's look at the horizontal structure first.

The front fixed section is called the **horizontal stabilizer.** You can probably figure out from its name that its purpose is to help provide longitudinal stability. In most aircraft, it is a fixed section, however in

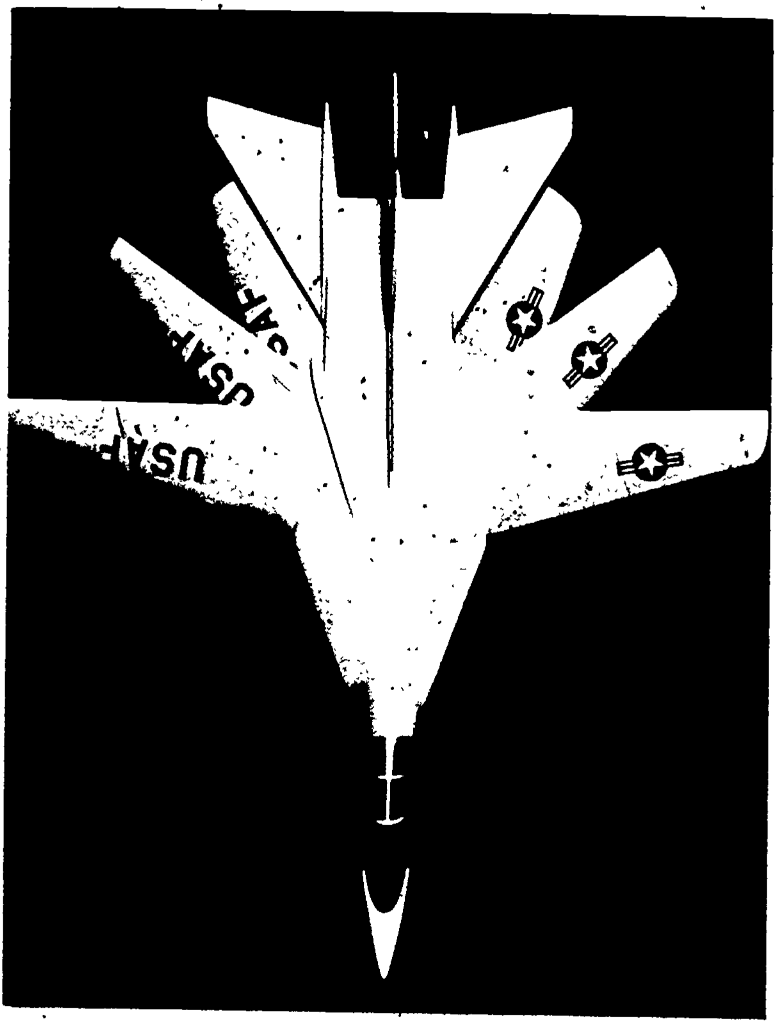


Figure 60. F-111 Swing Wing Positions

some aircraft it can be adjusted so that its angle can be changed to correct errors in longitudinal balance or trim. This adjustment is called the **stabilizer control,** and it is another of the "fine tuning" devices used to balance an aircraft in flight.

The rear section is called the elevator, and we've already discussed what the elevator does it controls the angle of attack of the aircraft, therefore it controls its speed.

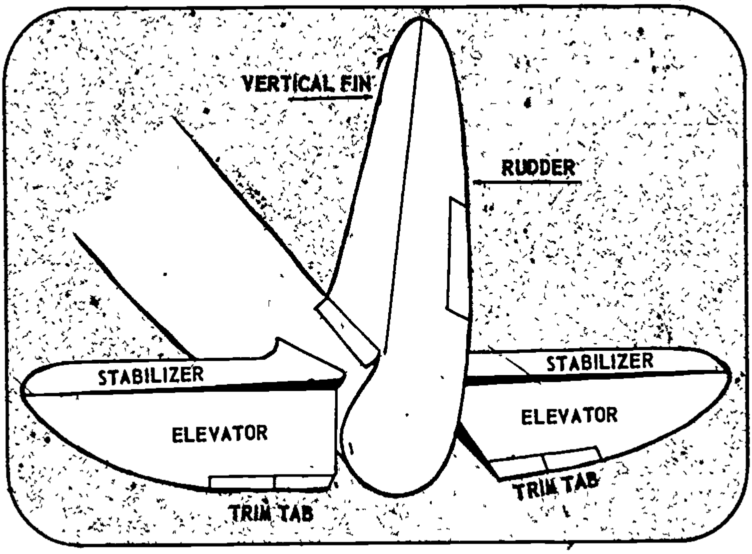


Figure 61. Parts of the Empennage.

The vertical structure is also divided in half. The front section is called the **vertical fin.** Its main purpose is to help the pilot maintain the desired direction of flight. The principle behind its operation is much like the principle of a deep keel on a sailboat. In some light, single-engine aircraft, the vertical fin serves to offset the tendency of the aircraft to swing toward the direction in which the propeller is rotating. In this case, the vertical fin is offset slightly to counteract the tendency of the aircraft not to fly in a straight line.

The rear section of the vertical structure is called the rudder. We've already talked about what the rudder does. it compensates for the adverse yaw an aircraft experiences in turning. We've also talked about the trim tabs, movable auxiliary control surfaces attached to the elevators.

What's in the empennage? How is it held together? The vertical fin and the horizontal stabilizer are built much the same way as wings. ribs provide the basic shape, spars hold the ribs in one unit, and stressed skin covers the surface. Elevators and rudders are constructed much the same way. The two stationary elements, the vertical fin and the horizontal stabilizer, are firmly attached to the fuselage in much the same way as the wings are attached to the fuselage. In some aircraft, external braces of one sort or another help to reinforce the connection.

HYDRAULIC AND ELECTRICAL SYSTEMS

These two auxiliary systems are actually among the most important of the aircraft's components. Your family car uses both types of systems, as well The whirring sound you hear when you turn the key (activate the starter) in the car is actually an electric motor. That safe and satisfying thump you sometimes hear when you hit the brake pedal is the hydraulic brake system, multiplying the force of your foot and stopping the car.

Hydraulics

The aircraft's hydraulic system operates the brakes, lowers the landing gear, and extends and lowers the flaps. In the case of a propeller-driven aircraft, the mechanism which controls the pitch of the propeller may be hydraulically operated. The word "hydraulics" comes from Greek words meaning "water tube."

More than three centuries ago the French mathematician and philospher Blaise Pascal stated what we know today as **Pascal's Law:** *pressure exerted anywhere on a liquid in a closed container is transmitted undiminished to all parts of the wall of the vessel containing the liquid. The pressure acts at right angles to all surfaces with an equal force on equal areas.*

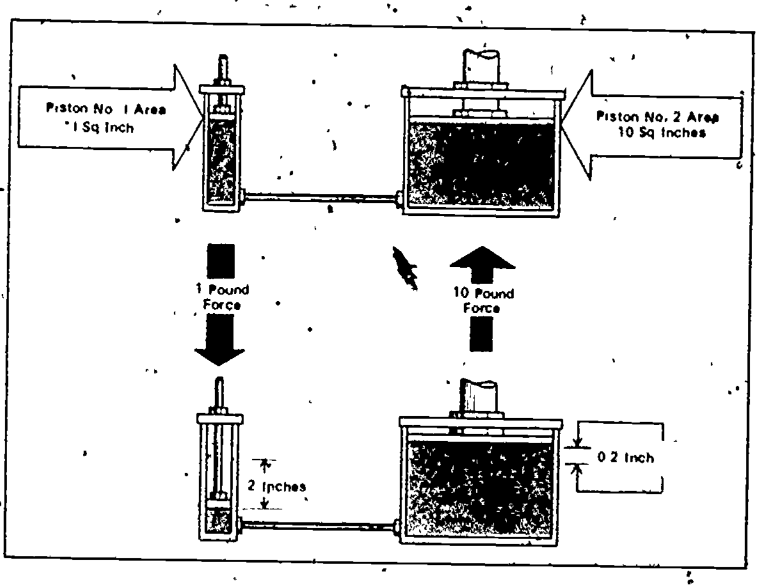


Figure 62 Basic Hydraulic System

What does this mean? It means this. when you confine a fluid, such as oil, in a container, the fluid does more than just transfer pressure put on it to something else. It multiplies the original pressure. Here's how. assume that attached to the container of hydraulic fluid are two pistons and their cylinders (see Fig 62). Assume that one of these has an area of 1 square inch and that the other has an area of 10 square inches. If one pound of pressure is placed on the smaller piston, 10 pounds (10×1) of pressure will be exerted by the larger piston. This is true because the pressure applied on the 1 square inch surface of the small piston will be transmitted undiminished to each of the 10 square inches of the surface of the larger piston. In addition, pressure applied to one piston in a hydraulic system is transmitted undiminished to all pistons throughout the system. This is how you apply pressure equally to each of the four brakes on a car. If you've ever used a lever to pry up a rock (See Fig 63), you know that you can exert more force than you could if you tried to lift the rock directly. This is called **mechanical advantage**, which is the same principle used in hydraulics.

Because energy cannot be created or destroyed, there must be a loss somewhere in the large piston. Like the lever under the rock, the loss comes in the distance and speed the large piston travels. Refer again to Figure 62. If the small piston travels downward 2 inches, the large piston will travel only one tenth that distance or .2 inches. This is because the area of the large piston is 10 times the area of the small

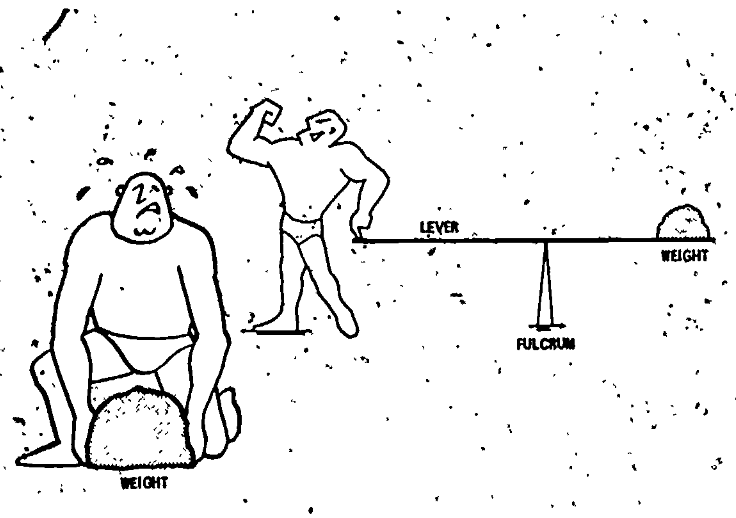


Figure 63. Mechanical Advantage of a Lever

piston ($2 \div 10 = .2$). You can readily see that if the large piston travels only 2 inches during the same time the small piston travels 2 inches, the large piston must be traveling more slowly.

By using the mechanical advantage gained in the hydraulic system, the pilot can exert great pressures on aircraft control systems or structures Aircraft have hydraulic pumps to generate the hydraulic pressure necessary to operate the various components of the aircraft.

Electrical Systems

An aircraft in flight also makes many uses of electricity. Radio communication depends on electricity. The propulsion system's generators charge storage batteries, magnetos provide current which spark plugs convert into sparks that in turn ignite the fuel mixture which keeps the propulsion system operating, solenoid switches use electric currents from batteries to supplement the pilot's muscles, making it possible to operate large switches, valves, and mechanical devices from the cockpit. Electric motors further increase the power at the disposal of the pilot. They help him start the engines, and they may help him operate the flaps or change the pitch of the propeller if these last two aren't hydraulically operated In fact, these electric motors can be adapted to serve almost anywhere that power is required.

LANDING GEAR

Without **landing gear,** the grinding and scraping of a battered airplane fuselage on the runway could be very hard on the ears. Obviously, the landing gear only comes into use during takeoff and landing The Wright brothers however were more concerned with getting their aircraft off the ground than with landing it safely. Their crude landing gear consisted of a ski, or runner, which slid down a greased track on the takeoff and merely skidded along the ground on landing. This type of landing gear created a great deal of friction on takeoffs and failed to absorb much of the shock of landing. For our purposes, the two main functions of the landing gear are. to assist takeoff and to absorb the shock of landing.

Landing gear may be classified as either fixed or retractable. As the name implies, fixed landing gear remain in the same position even while cruising at altitude. More thrust is required to overcome the additional drag Most light aircraft today are equipped with fixed type landing gear Balloon type, low pressure tires are used extensively on this type of landing gear to help absorb the landing shock.

In order to eliminate the drag of the landing gear during flight, on most larger aircraft the wheels and struts are usually retracted into the aircraft. The landing gear may be retracted into various places in the aircraft depending on where the landing gear is located. For example, in some aircraft, the landing gear retracts outwardly into the wings In others, the landing gear retracts inwardly into the wings, the fuselage, or the engine nacelles. Regardless of the type of gear, it must be designed to absorb shock.

The most common type of shock absorber in use today is the oleo strut, oleo refers to oil. **Oleo struts** are shock absorbing devices using oil to cushion the blow of landing. This type of shock absorber is part of

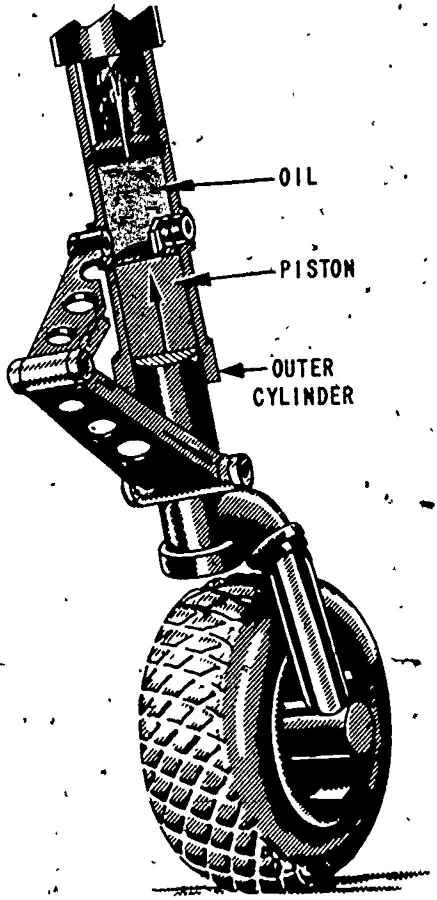


Figure 64. Principle of Oleo Strut Operation.

the main strut supporting the wheels and is composed of an outer cylinder fitting over a piston. The piston is on the end of a short strut attached to the wheel axle. Between the piston and a wall or bulkhead in the outer cylinder is a space filled with oil. The impact of the landing pushes the piston upward, forcing the oil through a small opening in the bulkhead into the chamber above it, cushioning the shock (see Fig 64).

To aid in controlling most aircraft on the ground, the main wheels of the landing gear are fitted with brakes. The left and right gear brakes operate independently. Brakes are used to slow up a fast rolling aircraft and as an aid to steering and parking an aircraft on the ground. For example, pressure on the left brake and slightly advanced throttle will cause the aircraft to turn to the left around the left wheel. Aircraft brakes aren't used as often as automobile brakes, however, because the weight and speed of the aircraft often can cause overheating, warping, or possible destruction of the brake mechanism.

Should a brake "lock" on landing, the tire could wear thru in a second or two and contribute to a loss of control. For this reason, large aircraft now employ a safety device called **antiskid** which prevents the wheels from locking. If a wheel starts to slip, the antiskid releases the brake until the wheel is no longer skidding and then brake pressure is again available for braking. Ideally the antiskid will hold the landing wheels at a point just before lockup so that maximum slowing is available without a locked wheel skid.

Antiskid also works where the surface is slippery such as on patches of ice. As with many things pioneered in the aviation industry, antiskid is now being adapted to automobile use. Let's look at landing gear wheel arrangements.

Three major systems of landing gear placement are in use today. the conventional, the tricycle, and the bicycle. The **conventional landing gear** consists of two main wheels and a tail wheel. The center of gravity of the aircraft is behind the main wheels, which are located toward the front of the aircraft. The **tricycle landing gear,** as you can guess from its name, has three wheels, two main wheels and a nose wheel. This type of landing gear makes the aircraft easier to handle on the ground and it also makes landings much safer. Visibility is improved. Additionally, any tendency of the aircraft to veer to one side or the other when it is rolling on the runway is compensated for by the natural tendency of the center of gravity to follow a straight line. The aircraft then tends to go straight ahead, rather than to one side or the other.

Bicycle landing gear is found on certain aircraft which have engine pods, rather than engine nacelles (Engine pods are engine nacelles slung beneath the wing). The two main units are set up in tandem, one behind the other, and on many heavy aircraft, each unit may have multiple tires. (The C-5A has 28 wheels.) Auxiliary wheels on the wingtips such as on the B-52 or U-2 provide additional support on the ground. Large transport aircraft, equipped with bicycle landing gear, are extremely heavy, requiring more wheels so the load can be distributed more widely over the runway. This protects the landing field

This chapter covers the external parts of the aircraft and their operation. These parts all work together to make the whole aircraft fly. Power plant, fuselage, wings, empennage, and landing gear are all equally necessary to the successful operation of the machine. The hydraulic and electrical systems provide the means to operate the aircraft systems. But the pilot is the most important "system" of all. The well-trained pilot's primary job in a well-designed and properly maintained aircraft is to manage all of these complicated systems and subsystems, and he does this primarily by means of his "know-how" and his aircraft instruments, our next major topic.

WORDS AND PHRASES TO REMEMBER

engine cowling
engine nacelles
fuselage
stresses
tension
member
compression
bending
shear
torsion
truss
Warren truss
longerons
fairing strips
turtle back
semimonocoque
stringers
bulkheads
rings
load factor
ultimate load
maximum applied load
safety factor
spars
false spar
ribs
drag wires
antidrag wires
stressed skin
full cantilever wing
semicantilever wing
externally braced wing
empennage
tail assembly
horizontal stabilizer
stabilizer control
vertical fin
Pascal's Law
mechanical advantage
landing gear
oleo struts
antiskid
conventional landing gear
tricycle landing gear
bicycle landing gear

THINGS TO DO

1. Go examine an aircraft Point out the various parts and explain what they do. If you are unable to see a real aircraft, use a detailed model
2. Visit an aircraft manufacturing plant.
3. Perform experiments demonstrating tension, compression, bending, shear, and torsion
4. Compare the electrical and hydraulic system of a car to those on an airplane. Do the same for an automobile shock absorber system and an aircraft landing gear.
5. Find out what hydroplaning is Does it also apply to cars?

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REVIEW QUESTIONS

1. **The propeller:**
   a. **provides thrust**
   b. **is essentially a curved airfoil**
   c. **works because of Newton's Third Law of Motion**
   d. **all of the above**

2. **Name two functions of the engine cowling.**

3. **Define engine nacelles.**

4. **The main or body part of the aircraft is called the ______.**

5. **Match the type of stress with the appropriate action:**

a. tension	1. folding
b. compression	2. shaving
c. bending	3. twisting
d. shear	4. pulling
e. torsion	5. squeezing

6. **True or False. Although some members of an aircraft are subjected to more than one type of stress, some can only carry one type of stress.**

7. **True or False. Members are stronger in bending than they are in tension or compression.**

8. **Name three good features of the Warren truss.**

9. The (welded steel truss/semimonocoque) type of fuselage is used in most military aircraft.

10. Define load factor.

11. The greatest load an aircraft will have to carry in flight is called the:
 a. maximum applied load
 b. ultimate load
 c. safety factor
 d. all of the above

12. Match the elements of construction with their proper location (locations may be used more than once).

a. longerons	1. wing
b. fairing strips	2. fuselage
c. spars	
d. stringers	
e. ribs	

13. Rather than carry stresses, the ____________ carries the aileron.

14. Match the type of wing construction to the proper description:

a. full cantilever	1. used on relatively inexpensive aircraft
b. semicantilever	2. uses streamlined wires or tie rods
c. externally-braced	3. extremely strong wing structure

15. What is the primary function of the tail assembly (or empennage)?

16. Match the appropriate fixed and movable airfoil sections:

a. wing	1. elevators
b. vertical fin	2. ailerons
c. horizontal stabilizer	3. rudder

17. A piston with a five square inch area is connected hydraulically to one with a fifteen square inch area. If the five inch piston is moved with two pounds of pressure, how much pressure will be exerted by the larger piston?

18. In the example above, if the smaller piston travels six inches, how far will the larger one travel?

19. Name three uses for electrical systems in aircraft.

20. An aircraft with retractable landing gear will require (more/less) thrust than a similar craft with fixed gear.

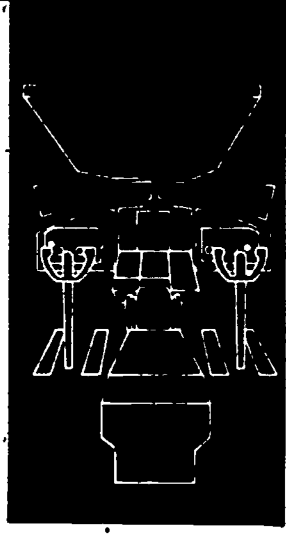
21. What is the most common type of landing gear shock absorber?

22. A device designed to keep aircraft wheels from locking on landing is called (antilock/antiskid).

23. Which of the following landing gear arrangements has a nose wheel?
   a. conventional
   b. tricycle
   c. bicycle

24. When the main units are set up one behind the other, the aircraft is said to have ________ landing gear.

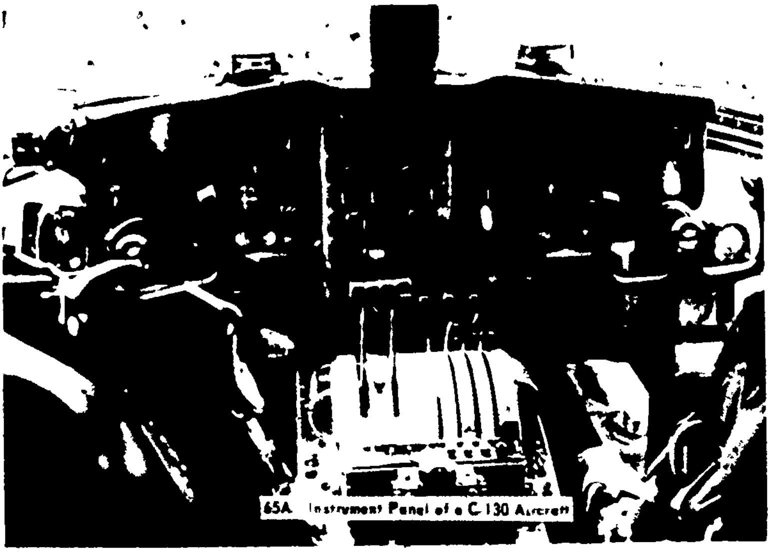
Chapter 7



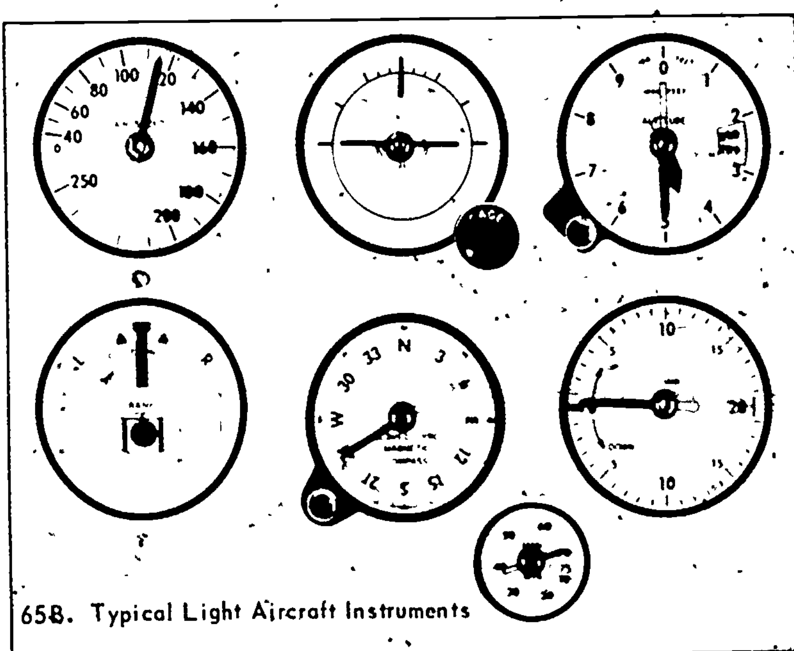
Aircraft Instruments

THIS CHAPTER introduces you to basic aircraft instruments. You will read about how instruments may be classified. You will then examine engine instruments, navigation instruments, and flight instruments. After you have studied this chapter, you should be able to: (1) discuss various ways in which instruments may be classified; (2) tell what each class of instruments does and how it works; and (3) explain how several flight control instruments are used.

"WHAT A LOT of dials and gauges! How can one man possibly keep track of all of them? I could never to do anything like that. I have a hard time reading the gauges on my car." This might be your reaction the first time you take a long hard look at the instrument panel of a modern-day aircraft (see Fig 65). Today's automobile has several gauges with which you are probably familiar. speedometer, odometer (mileage indicator), fuel gauge, temperature gauge (or warning light), oil pressure gauge (or warning light), and, possibly, a tachometer (engine speed gauge). You may also see some other switches and gauges as well. heater controls, ventilation controls, air conditioning controls, windshield wiper control, light switch, power antenna control, clock, radio, stereo tape deck, and the list could go further. You don't think that this is an excessive number of controls, primarily because you're used to seeing all of them and knowing what they do. (If



65A. Instrument Panel of a C-130 Aircraft



65B. Typical Light Aircraft Instruments

Figure 65 Instrument Panels

you're just learning to drive, relax, this will all become second nature to you.)

The pilot in today's aircraft is much like you when you're driving. he knows where his instruments are and what they do. He just has more instruments to watch, because an aircraft is a more complicated piece of machinery than an automobile. In this chapter, we will discuss various classes of instruments, their operation, and the information the pilot gets from them We're sure you will agree that instruments in an aircraft are not as confusing as most people think they are. Like early automobile instruments, the first aircraft instruments were very simple.

EARLY AIRCRAFT INSTRUMENTS

The earliest fliers had to rely on their senses as there were no flight instruments Although they were very primitive by today's standards, many early instruments proved to be adequate for "low and slow" aircraft.

Speed of the aircraft was first judged by the force of the wind on the pilot's face and the whine of the wind through the rigging. If the pitch of the wind whistling through the wires was right, his speed was correct. Early airspeed indicators were merely wind gauges and today's airspeed indicators still use the impact of the outside air in measuring airspeed.

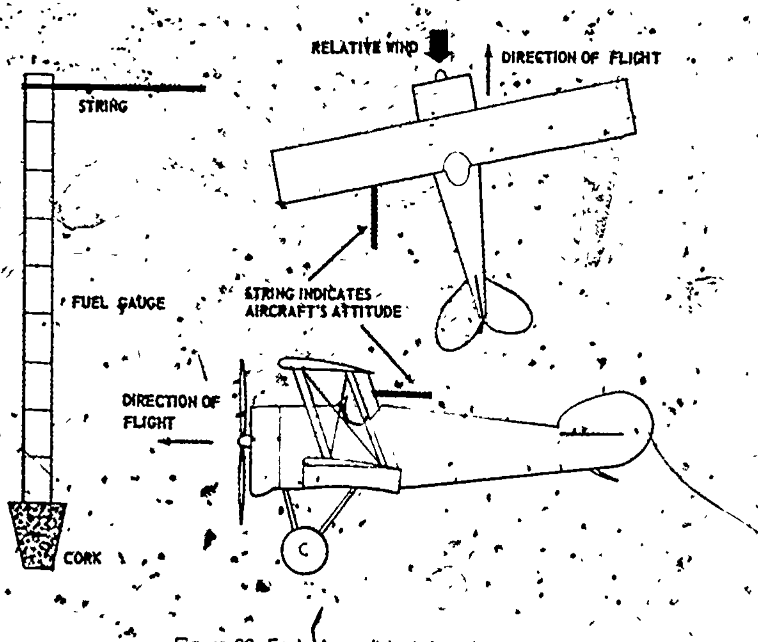


Figure 66 Early Aircraft Instruments

When you could see farther than you intended to fly, a heading indicator and navigation instruments were unnecessary luxuries. Similarly, altimeters weren't of much value when the aircraft could get only a few feet off the ground. Like the airspeed instruments, altimeters and heading indicators today use basically the same principles as those first developed.

Do you recognize the instruments in Figure 66? While it was possible to estimate how long your gas would last, it was also very easy to forget to check takeoff time and then have to guess when the gas would give out. The problem was solved by putting a stick with a cork on it in the gas tank. By tying a piece of colored string to the top of the stick, another safety feature was added. When the string disappeared, it was time to land.

The attitude of the aircraft was extremely critical in early aircraft. Some early pilots solved part of this problem by tying a piece of heavy string to the aircraft. If the string was flying straight back, the pilot was doing fine. However, if the free end of the string was off to one side, he was either in a skid or a slip.

These early instruments were designed to give the pilot specific information about the engine or the attitude of the aircraft. All aircraft instruments can be classified according to how they assist the pilot.

INSTRUMENT CLASSIFICATION

Aircraft instruments are classified either in terms of their use or in terms of the principle underlying their operation or construction. We plan to discuss these instruments in terms of their use, but we also will explain some general principles underlying their construction. However, what the instruments tell the pilot is far more important than how the instruments work.

Instruments classified by their use fall into three major groups: engine instruments, navigation instruments, and flight instruments. **Engine instruments** keep the pilot and flight engineer aware of engine speed (measured in revolutions per minute, or rpm), engine temperature, oil pressure, fuel supply, fuel flow, manifold pressure, carburetor pressure, and the like. **Navigation instruments**, which help the pilot find his way from point of departure to destination, include the clock, the compass, the directional gyro, the driftmeter, the sextant, the radio, radar, loran, doppler, radio direction finder, and so forth. **Flight instruments** inform the pilot of his altitude, the airspeed, and the attitude of the aircraft. When you look at the instruments in this way, you can see that each one has a separate functional purpose and that the pilot gains useful information from all of the instruments. In other

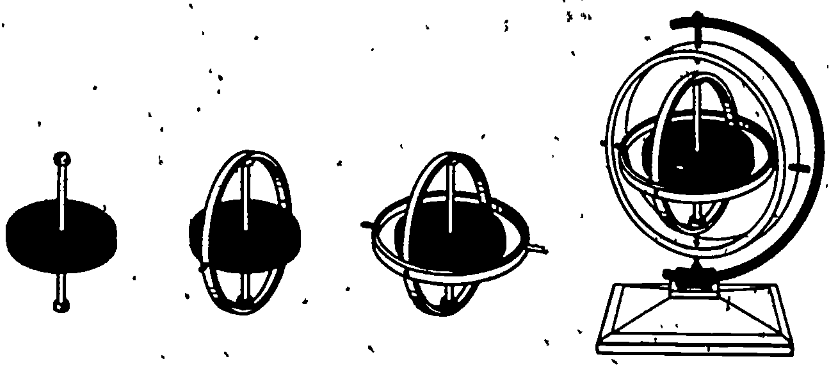


Figure 67. The Gyroscope.

words, even though the instrument panel of today's aircraft looks complicated and confusing, today's pilot needs to know all of the information which the instruments give him.

Instruments can also be classified by their principle of operation. The three major groups are mechanical (including gyroscopic) instruments, pressure instruments, and electrical instruments. We won't go into any lengthy explanation of the finer details of how these instruments are constructed or why they operate. The important thing for our purpose is to tell you what information the pilot gets from his instruments.

Some **mechanical instruments** work by means of a direct mechanical linkage. For example, a gear system may be attached directly to the engine of an aircraft in order to give a reading on a gauge of how fast the engine is operating Other mechanical instruments work on the principle of the gyroscope (see again Fig 65).

Because the gyroscope is used so extensively in flight instruments, we will review briefly how it operates. A **gyroscope** consists of a heavy wheel mounted so that it is free to rotate on its axis within a frame. This frame is designed so that the gyro can move in one or both of the axes perpendicular to the axis of rotation. Two principles underlie the operation of the gyroscope. rigidity in space and precession. **Rigidity in**

space is the characteristic that makes a gyroscope point constantly to the same direction in space. For example, if you held the gyroscope in Figure 67 by the base, you could move the base to any position, but the gyro would still point in the original direction. **Precession** is the characteristic that makes the spinning part of the gyroscope move at right angles to the force of the weight applied to it. This description is greatly oversimplified, of course, but these are the principles that make a gyroscope a useful tool to the pilot and the flight engineer Because it is not influenced by magnetic disturbances, it is extremely useful in heading indicator instruments.

Pressure instruments work on the principle of a fluid such as air exerting pressure. We discussed this at some length in the sections dealing with lift and the atmosphere. Air has weight, and hence, it can exert pressure. Pressure decreases with height, and pressure instruments use this principle to tell the pilot various things about the performance of his aircraft, e.g., altitude and airspeed.

Electrical instruments operate on the principles of electricity, including magnetism. You probably have studied electricity and magnetism in some of your other classes. Also, it is covered somewhat in other units, so we won't go into those principles here. Electrical instruments often take the place of mechanical and pressure instruments and are being used more and more in modern aircraft.

ENGINE INSTRUMENTS

As aircraft engines have developed and become more complex, the number of instruments the pilot needs to keep track of engine operations has increased. The purpose of the engine instruments is to keep the pilot informed of the operating conditions of his engine The engines used in the early days of aviation generated comparatively little horsepower. These engines required only a tachometer, an oil temperature gauge, and a water temperature gauge. The modern reciprocating engine requires all of these plus gauges which show oil, fuel, and manifold pressures. Indicators which show the temperature of the air, the carburetor, and the cylinder heads are also necessary.

The **tachometer** tells the pilot the speed at which his engine is revolving (see Fig 68). The instrument itself may be either mechanically or electrically operated, depending on the size of the aircraft and the number of engines involved. Because reciprocating engines run best at certain engine speeds, the pilot needs to be able to tell, at any given instant, how fast his engine is running. Another reason the pilot needs to know engine speed is that he has to keep his engine at the proper operating

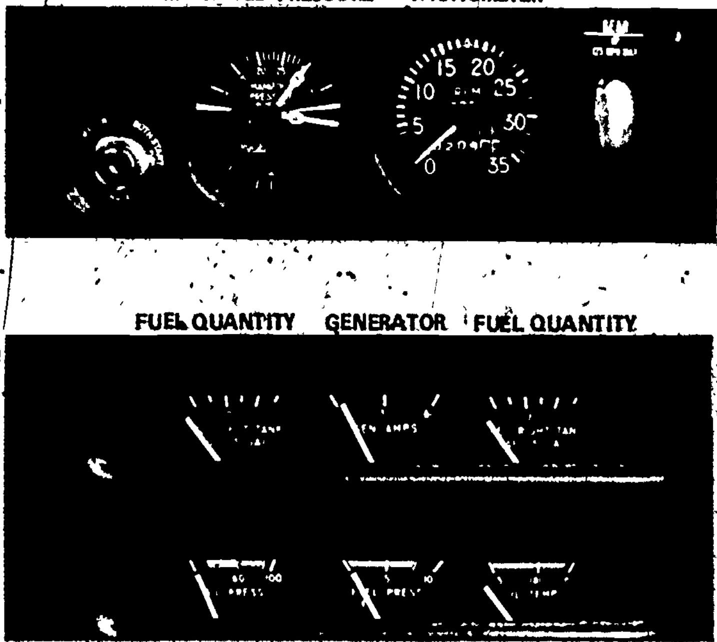


Figure 68 Typical Aircraft Engine Instruments

speeds so that it doesn't "conk out" and leave the aircraft without any source of thrust.

The **temperature gauges** tell the pilot the temperature of the engine oil, the engine cylinders, and the carburetor intake air. If the engine oil temperature exceeds certain limits, the engine will overheat and possibly be put out of commission. If the engine cylinder temperature is either too high or too low, the engine will not run efficiently. The pilot needs to know the temperature of the carburetor intake air in order to make sure that the air will mix properly with the fuel. If the intake air is too cold, the carburetor may "ice up", that is, the water vapor in the air may freeze in the carburetor, and the engine, in turn, may not get enough fuel.

The **pressure gauges** tell the pilot the pressure of the engine oil, the fuel, and tho manifold. The pilot has to know the pressure of the engine oil as well as its temperature. The oil pressure gauge tells him the pressure in pounds per square inch at which the lubricating oil is being supplied to the engine's moving parts. The gauge which shows fuel pressure is really telling the pilot the rate of flow of the fuel from the fuel tanks. Naturally, he needs to know this in order to figure out how long his fuel supply will last. The manifold pressure gauge provides the pilot with a good indication of the power being developed by the engine. The manifold pressure gauge serves to measure the density of the fuel-air mixture entering the engine, and this density can give the pilot a good indication of the power which the engine can develop.

Do you know why so many aircraft systems operate under pressure? Really, it's quite simple when you think about it. Unlike an automobile, an aircraft may operate on its side or even inverted for long periods of time. A gravity fuel system would soon result in fuel starvation leading to a very frightening silence. An engine that is properly lubricated only in an upright position would not last long. In aircraft, pressure systems offer the only means of insuring that all parts will continue to operate in any attitude.

Another important gauge for the pilot is the **fuel quantity gauge.** This gauge may be constructed in one of several ways, but no matter how it is built, it tells the pilot how much fuel he has on board his aircraft so that he doesn't run out.

There are many other aircraft engine gauges. As engines become more complicated, more gauges are required. The gauges we've just discussed, though, are basic to reciprocating engines.

NAVIGATION INSTRUMENTS

Because you will be covering an entire unit on navigation which contains a chapter dealing specifically with navigation instruments, we'll discuss this class of instruments only briefly here. Although modern aircraft have many navigation instruments, virtually all aircraft have four basic navigation instruments: a clock, an airspeed indicator, a compass, and an altimeter. The navigation book will discuss the construction and function of each of these instruments in some depth, and it will also point out why each of these instruments is essential to the safe piloting of the aircraft through the air, from take-off to landing. Some additional information on instruments can be found in *Civil Aviation and Facilities*.

We would do well to point out here that the line between navigation instruments and flight instruments is sometimes hard to draw. Certain instruments are clearly navigation instruments and nothing else. Other instruments, usually classed as flight instruments, are of great help in navigation Sometimes, these instruments are called navigational aids (navaids for short). However, it might help you to bear in mind this distinction between the two classes of instruments. navigation instruments give the pilot a picture of where his aircraft is in relation to the earth, flight instruments, on the other hand, tell the pilot where he is in relation to the horizon. Let's move on, then, and examine flight instruments.

FLIGHT INSTRUMENTS

This class of instruments helps inform the pilot of his aircraft's attitude with reference to the horizon. We just mentioned the fact that it is sometimes hard to decide which instruments are flight and which are navigation instruments since certain instruments serve two functions. The airspeed indicator and the altimeter are examples of this sort of instrument. The airspeed indicator is really measuring the speed of the impact air; hence, it is a flight instrument, because the pilot needs to know how much lift his aircraft is developing. Lift, you'll remember, is directly proportional to the velocity of the relative wind. the greater the relative wind, the greater the amount of lift that will be generated, within practical limitations, of course. The airspeed indicator, then, enables the pilot to keep the airspeed of his aircraft above the stalling speed (the speed at which the wings no longer generate enough lift to keep the aircraft aloft).

Similarly the altimeter can help the pilot judge the height of the aircraft above a given reference point. Since air density varies with altitude, the altimeter can provide the pilot with information about the density of the air through which his aircraft is flying. Lift varies directly with air density, you'll remember. the less dense the air, the less lift will be developed, all other factors remaining equal.

The **turn and bank indicator** is a true flight instrument. It is the pilot's chief tool in judging how well he makes a turn. Examine Figure 69 and you will see why it's often called a **needle and ball.** It is actually two instruments in one which work together with one purpose. to evaluate the amount and the quality of a turn. As you remember, a turn requires some degree of bank to prevent slipping or skidding. The needle and ball tell the pilot at a glance if he is making a **coordinated turn** which simply means he has the correct bank for the rate of turn. This requires the proper combination of ailerons and rudder. Here's how it works.

The needle measures the direction and the rate of turn. The ball tells the pilot whether the aircraft is slipping, skidding, or turning properly. As long as the pilot keeps the ball in the center of the glass, and assum-

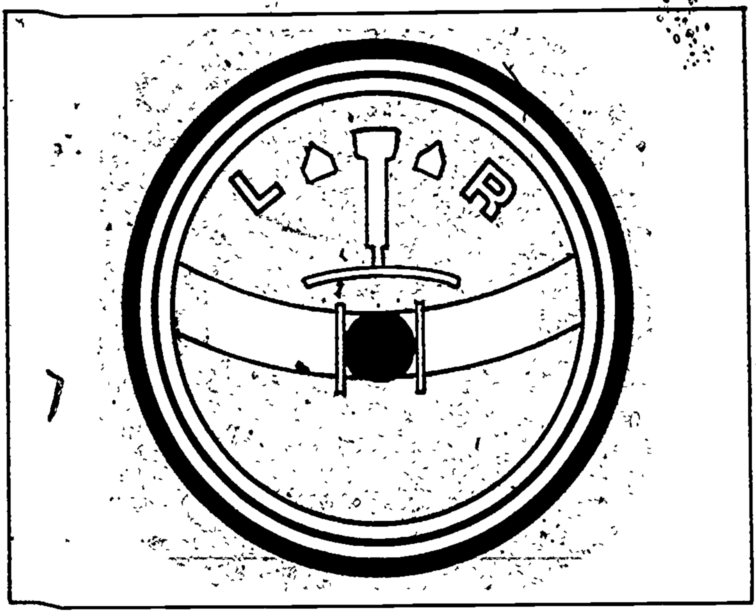


Figure 69. The Turn and Bank Indicator ("Needle and Ball").

ing that he is using the rudder properly, he can be sure that the angle of bank is correct for the amount of turn his aircraft is making (see Fig 70) If the needle and the ball are on the same side, he is slipping and needs to increase his angle of bank. If the needle and ball are on opposite sides, the aircraft is skidding and he must decrease his angle of bank

The **rate of climb indicator** tells the pilot the rate (in feet per min-

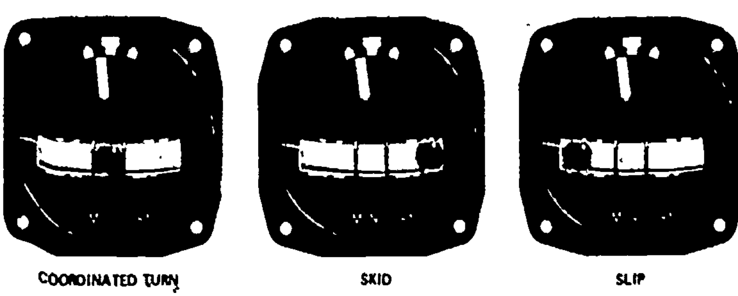


Figure 70. A pilot can use the Needle and Ball' Indicator to see how well he is making a turn.

Figure 71. Rate of Climb Indicator.

ute) at which he is gaining or losing altitude (see Fig 71). This instrument works on the pressure principle. it is actually measuring changes in barometric pressure and registering these changes as a rate of climb or a rate of descent We pointed out earlier that there is an important distinction between rate of climb and angle of climb. this instrument registers rate of climb or descent, regardless of the attitude of the aircraft.

Actually, several instruments work together to tell a pilot he's climbing or descending Let's suppose the pilot is sleepily flying along assuming everything is going smoothly. Then, without his realizing it, the aircraft starts to climb or descend. What instruments would serve to warn the pilot? As we just discussed, the rate of climb indicator would show the change. Similarly, the altimeter would show a change in altitude Another very important instrument in this case is the airspeed indicator Without a change in the power setting, airspeed will decrease during a climb and increase during a descent. An alert pilot, upon noting a change in any of these instrument readings, will automatically check the others Another instrument, the artificial horizon, not only supplies climb and descent information, it also gives detailed turn and bank information.

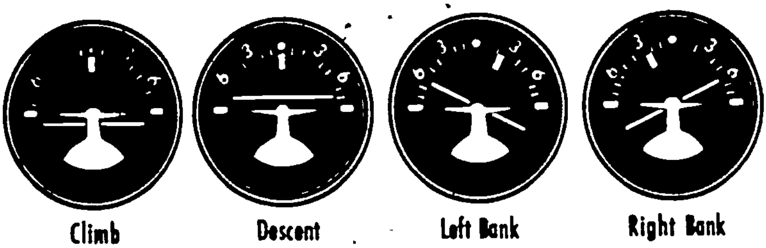


Figure 72. The Artificial Horizon.

The **artificial horizon** is a gyroscopic instrument which shows the pilot the relationship of his aircraft to the true horizon. Take a look at Figure 72. The miniature aircraft is fastened to the center of the instrument and moves with the aircraft. The horizon line in the background moves so that it remains parallel to the true horizon at all times By means of this instrument, the pilot can tell whether he is flying straight and level or whether he is climbing, descending, banking to the right, or banking to the left.

Many aircraft have many more instruments than those we've just discussed. Both civilian and military authorities require that aircraft have certain instruments to make sure that pilots will be able to fly safely We've simply hit the high spots of aircraft instruments, pointing out why several of the more basic instruments are virtually a necessity to today's pilot.

WORDS AND PHRASES TO REMEMBER

engine instruments
navigation instruments
flight instruments
mechanical instruments
gyroscope
rigidity in space
precession
pressure instruments
electrical instruments
tachometer
temperature gauges
pressure gauges
fuel quantity gauge
turn and bank indicator
needle and ball
coordinated turn
rate of climb indicator
artificial horizon

THINGS TO DO

1 Examine the instrument panel of an aircraft
2 The C-5 and C-141 have advanced instrument systems which combine many instruments See if you can find out how these work

3 Try to fly a flight simulator and see how the controls affect aircraft movement.
4. Find out what instruments Lindbergh had in "The Spirit of St Louis".
5 Have a class brainstorming session to predict what future aircraft instruments will be like
6 Many times during and immediately after takeoff, the ball in the turn and bank indicator will be off center even though the wings are level. Find out what causes this and how it is corrected.
7 Operate a gyroscope. Demonstrate precession and rigidity in space.

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REVIEW QUESTIONS

1. True or False. The earliest fliers relied more on their senses than they did on instruments.

2. One of the earliest attitude indicators was a:
a. turn and bank indicator
b. gyroscope
c. piece of string
d. jar of water

3. Three major groups of instruments classified according to their use are _______, _______, and _______.

4. Which of the following groups of instruments is not classified according to its principle of operation?
a. mechanical
b. gyroscopic
c. electrical
d. pressure

5. What two characteristics of a gyroscope make it a useful tool to an aviator?

6. True or False. Altitude is usually measured with an electrical instrument.

7. What kind of gauge (pressure and/or temperature) would you need to properly monitor the following engine parts?
a. carburetor intake air

b. fuel
c. engine oil
d. engine cylinders
e. manifold

8. Give two reasons why aircraft engine systems should be under pressure.

9. An instrument used to tell the aircraft location is called (a flight instrument/ a needle and ball/ a navigation instrument).

10. Name two instruments that are both flight and navigation instruments.

11. Define coordinated turn.

12. Match the following terms and definitions:

a. aircraft above horizon	1. needle left, ball centered
b. slip	2. descent
c. rate of climb indicator	3. quantity
d. fuel gauge	4. too much bank
e. coordinated turn	5. climb
f. skid	6. feet per minute
g. airspeed increase	7. too little bank

13. What instruments would warn a pilot if he's descending?

Now that you've finished reading this book, let's see how much ground you've covered. Put briefly, you've looked at the how, when, and why of aircraft flight from man's earliest known attempts to fly to the basic design and operation of today's heavier-than-air craft.

As a starting point, we discussed Newton's Laws of Motion and Bernoulli's Principle because these basic physical laws are the first clues to understanding what makes an aircraft fly. We also took our first look at lift, weight, thrust, and drag—the four forces which, when in balance with one another, keep aircraft in straight and level, unaccelerated flight.

The next logical step was to examine the earth's atmosphere since this is where most heavier-than-air craft operate. We defined atmosphere and discussed its composition and structure and the properties of the atmosphere as they affect aircraft flight.

In chapter 3, we got down to cases as to why a heavier than-air craft can get off the ground and travel through the air. Here, we discussed airfoils—what they are, how they are designed, where they are on a plane, and what their function is in relation to flight. We also showed the relation between the physical laws discussed earlier and the use of airfoils to produce lift.

After studying lift, we looked at the other three forces, weight, thrust, and drag, as they affect aircraft flight. We examined how an aircraft can be designed to control these forces and put them to use in a check-and balance relationship, and we discussed what the pilot can do to control or counter these forces. We also looked at the effect of lift, weight, thrust, and drag on the movements of helicopters.

Up to this point we were talking about aircraft in straight and level, unaccelerated flight. But aircraft can maneuver and change speed, so we turned to the subject of aircraft motions and how they are controlled First, we looked at the three axes of rotation, the way the aircraft moves around them, and the terms that describe aircraft rotation about each axis. From the discussion of axes, we moved to the concept of stability You learned what stability is and what controls are used by the pilot to maintain stability about all three of the axes of rotation while maneuvering his aircraft in various directions. You also saw how the physical principles involved in stability are related to the way the pilot controls the aircraft.

In the next chapter we concentrated on the aircraft itself—the how and why of its construction. First, we looked at the power plant and learned the names and functions of its components. Next, we examined the two main types of fuselage construction and, to better understand the reasons for these types of construction, we discussed the stresses which act on an aircraft in flight. Then we looked at the wings, the empennage, or tail assembly, the hydraulic and electrical systems, and the landing gear.

Finally, we introduced you to the basic aircraft instruments. Here, you learned how instruments are classified, what the function of each classification is, and how each class of instruments works.

Of course, we don't expect you to be able to go right out and fly an aircraft just from reading this book, but you should have a better understanding of how an aircraft gets into the air, what keeps it in flight, and how it gets back down to earth.

Glossary

A

absolute pressure-The pressure of air relative to zero pressure, measured by means of a column of mercury.

acceleration-The change in velocity per unit of time.

adverse yaw-Tendency of a turning aircraft to be pulled around in a direction opposite to the turn, caused by increased drag on the higher wing and corrected by use of the rudder.

ailerons-Hinged airfoil segments located on the trailing edges of wings, used to produce a bank or rolling movement about the longitudinal axis of the aircraft.

air-A gaseous fluid which has mass and occupies space, composed primarily of nitrogen, oxygen, water vapor, and rare gases.

airfoil-Generally, any part of an aircraft which is designed to produce lift.

airspeed-Speed of the aircraft through the air.

airspeed indicator-Pressure instrument which measures airspeed.

altimeter-Pressure instrument which measures altitude above a standard reference point (usually sea level for light aircraft).

angle of attack The angle between the chord of an airfoil and the relative wind.

angle of bank-Angle between the aircraft wings and the horizon, degree of roll around the longitudinal axis.

angle of incidence-The angle at which the aircraft wing is fastened to the aircraft's fuselage (when viewed from the side).

antidrag wires Internal bracing wires running from the inner front to the outer rear of the wing.

antiskid-Braking safety feature which prevents the wheels from locking.

artificial horizon-Gyroscopic instrument which shows the pilot the relationship of his aircraft to the true horizon.

aspect ratio-The ratio between the square of the span of an airfoil and its area or between the length and width of a wing, a measure of wing efficiency.

atmosphere The body of air which surrounds the earth, consisting of layers or zones.

attitude-Position of an aircraft (airfoil) with respect to the horizon.

axes of rotation-Three fixed lines of reference, each of which passes through the center of gravity of an aircraft and is perpendicular to the other two.

B

bending-Type of stress which combines torsion on one side and compression on the other side of the member.

Bernoulli's Principle-As the velocity of a fluid increases, its pressure decreases; also called Bernoulli's Law of Pressure Differential.

best angle of climb-Where the aircraft gains the most altitude in a given distance; used to clear obstacles.

best rate of climb-Where the aircraft gains the most altitude in a given time.

bicycle landing gear-Where the two main landing gear units have wheels set up one behind the other, used to distribute the load more evenly, generally on heavy transport aircraft.

boundary layer air-Very thin layer of air next to the surface of a moving airfoil.

bulkheads-Vertical members of the fuselage frame used for internal bracing.

burble point-The point at which lift begins to decrease, sometimes called angle of maximum lift.

burbling-Where the air no longer flows smoothly over an airfoil and it breaks away from the surface forming eddies.

C

camber-The characteristic curve of an airfoil's upper surface (upper camber) or its lower surface (lower camber).

center of gravity The point at which the total weight of an aircraft is assumed to be concentrated.

center of pressure-The point at which the total force acting on an in-flight aircraft is assumed to be concentrated.

centrifugal force A force which tends to move an aircraft away from the center of the curve it is following.

chord-An imaginary straight line drawn through an airfoil from its leading edge to its trailing edge.

compressibility That characteristic of a fluid which permits it to occupy varying amounts of space.

compression-The stress which tends to push materials together.

control-The central concept of guiding an aircraft.

controls-Devices by which a pilot regulates the speed, direction of flight, altitude, and power of an aircraft.

control surfaces Movable airfoils designed to be rotated or otherwise moved by the pilot of an aircraft in order to change the attitude of the aircraft.

conventional landing gear Landing gear consisting of two main wheels and a tail wheel.

coordinated turn A turn where the pilot uses the proper combination of aileron and rudder resulting in the proper bank so that the aircraft does not slip or skid.

D

density-Mass per unit volume.

dihedral-Where the outer ends of the wings or horizontal stabliziers of an aircraft are higher or lower than the inner ends.

dihedral angle-The angle at which the wing slants from an imaginary line parallel to the ground.

directional stability-Tendency to keep the aircraft flying in a given direction and prevent yaw (movement about the vertical axis).

downwash-The slight downward movement given to the relative wind when it passes over an airfoil.

drag-The force which tends to retard an aircraft's progress through the air; caused by the resistance of air; the opposite of thrust.

drag wires-Internal bracing wires running from the inner rear to the outer front of the wing.

dynamic stability-The tendency of an aircraft to return to its original position with a minimum of oscillations and without pilot assistance

E

effective lift-Vertical component of lift which acts to oppose and overcome weight.

electrical instruments-Instruments which use electrical sensing devices to determine the magnitude of change.

elevators-Hinged sections on the trailing edge of the horizontal stabilizer used to control movement about the lateral or pitch axis.

empennage-The tail assembly of an aircraft, includes fixed and movable sections.

engine cowling-A cover for the engine.

engine instruments-Instruments used by the pilot to keep track of engine operating conditions.

engine nacelles-The streamlined containers used to house the engine auxiliary systems.

equilibrium-A state in which all the forces acting on a body are in balance with one another.

externally braced wing-Wings braced by external struts or braces connected to the fuselage or landing gear.

F

fairing-An auxiliary structure added to an aircraft component in order to give it a streamlined shape.

fairing strips-Thin flat strips of wood or metal used in fuselage construction.

false spar-A spar designed to carry the aileron rather than to carry wing stresses.

flaps-A movable section on the trailing edge of the wing used to change the airfoil camber and control lift, used primarily for takeoff and landing for added lift at low airspeeds.

flight instruments Instruments used by the pilot to determine airspeed, altitude, and attitude of the aircraft and to detect any changes, used primarily in aircraft control.

fluid A substance which may be made to change shape or to flow by applying pressure to it.

force Power or energy exerted against a material body in a given direction; has both magnitude and direction.

Frise aileron An aileron designed so that when the aileron is raised, the leading edge protrudes below the lower surface of the wing, increases drag and acts to overcome the yawing tendency.

full cantilever wing Wing attached directly to the aircraft without external bracing.

G

gravity Weight; the "pull" of a body on a quantity of mass.

groundspeed The speed of an aircraft over the ground, it has no bearing on airspeed or stall speed.

gyroscope A heavy wheel free to rotate on its axis and mounted so that it can rotate in two or more axes perpendicular to the axis of rotation.

H

horizontal stabilizer The front section (usually fixed) of the horizontal portion of the empennage, these two small winglike structures help provide longitudinal stability.

hydraulics Systems designed to use the mechanical advantage obtained and transmitted using liquids in a system of pistons and cylinders.

I

impact lift Lift created by the impact of the relative wind striking the lower surface of an airfoil, an application of Newton's Third Law.

induced drag Drag caused as a result of creating (inducing) lift.

ionosphere Upper atmosphere extending from roughly 55 to 250 miles altitude; contains many ions (electrically charged particles).

J

jet stream High speed, globe circling wind located near the tropopause; usual speed is 100-300 miles per hour.

K

keel effect Lateral axis stabilizing factor caused when more of the aircraft's side surface is above the center of gravity than below it, often produced by a large vertical tail surface.

L

landing gear-The understructure which supports the weight of the airplane while on the ground, wheels, skids, pontoons, skis, etc., which assist in takeoff and absorb the shock of landing.

lateral axis-The pitch axis, it extends crosswise of the aircraft (wingtip to wingtip) through the center of gravity.

lateral axis stability-Tendency of an aircraft to resist roll and to return to straight and level flight if the force causing roll is removed.

leading edge-The front portion of an airfoil which meets the relative wind first.

lift-The supporting force induced by the reaction of air with the wing, it acts perpendicular to the relative wind in an upward direction, the force which acts to overcome weight.

load factor-The load placed upon the aircraft under various conditions of flight, expressed in "G" factors, it is greatest during acrobatics and high-stress maneuvers.

longerons-The principal longitudinal structural members in a fuselage.

longitudinal axis-Roll axis which extends through the center of gravity lengthwise of the aircraft (nose through tail).

longitudinal axis stability-Tendency of an aircraft to resist changes in pitch and to return to straight and level flight if the force causing pitch is removed.

M

mass-The quantity of matter in a body.

mechanical advantage-The use of a machine (e.g., a lever, pulley, gear, or inclined plane) to exert greater force than a man could through his direct efforts.

mechanical instruments-Aircraft instruments which work by means of a direct mechanical linkage or by means of a gyroscope.

member-Any part of an aircraft that carries a stress.

N

nacelle-A streamlined container for sheltering or housing an aircraft component.

navigation instruments Instruments which help the pilot determine his position and navigate to his destination.

needle and ball-Turn and bank indicator, flight instrument used to evaluate the amount and quality of a turn.

negative stability-The tendency of a body to accelerate away from its original state once its equilibrium is disturbed.

neutral stability-Tendency of a body to neither return to its original state nor to move further away once its equilibrium is disturbed.

Newton's Laws of Motion-Three laws devised by Isaac Newton to explain inertia, acceleration, and equal and opposite reaction (See page 7).

O

oleo struts-Shock-absorbing devices using oil to cushion the impact of landing.

P

parasite drag-All drag components except those caused by induced drag; composed primarily of skin friction drag and turbulent flow drag.

Pascal's Law-Pressure exerted anywhere on a liquid in a closed container is transmitted undiminished to all parts of the wall of the vessel containing the liquid.

payload-Generally, the contents of an aircraft exclusive of fuel, crew, and other items necessary to operate the aircraft.

pitch-Rotation about the lateral axis of an aircraft or displacement along the longitudinal axis, controlled by the elevators. (Also refers to the angle a propeller blade makes with its plane of rotation).

planform-The shape of a wing or an aircraft as seen from directly above or below.

positive stability-Tendency of a body to return to its original state when its equilibrium is disturbed.

power loading-The weight of the aircraft in pounds divided by the horsepower of the aircraft.

precession-The characteristic that makes the spinning part of the gyroscope move at right angles to a force applied to it.

pressure-The force exerted by a fluid, measured in force per unit area.

pressure-differential lift-Lift created by the application of Bernoulli's Principle; faster moving air over the upper surface of an airfoil causes a decrease in pressure on the upper surface, creating lift.

pressure gauges-Instruments which indicate the amount of pressure in some system, e.g., oil or fuel.

pressure instruments-Instruments which work on the principle of a fluid such as air exerting pressure, by sensing a change in atmospheric pressure; for example, altitude and airspeed can be measured.

R

rate of climb indicator-A pressure instrument which tells the pilot how fast he's climbing or descending in feet per minute.

relative pressure-A measurement of pressure relative to the existing outside pressure.

relative wind-Direction of airflow past an airfoil relative to the path of flight; it is always parallel and opposite in direction to the path of flight.

reserve horsepower-Horsepower available over and above that required for straight and level flight.

resultant The sum of two or more forces, taking into account both their magnitudes and their directions.

ribs-Parts that support the covering and maintain the shape of the wing.

rigidity in space-Property of a gyroscope which causes it to oppose any force that tends to change its plane of rotation and point constantly in the same direction in space.

rings - Members used in semimonocoque construction which run around the fuselage and serve chiefly to give the fuselage its shape.

roll-Rotation about the longitudinal axis of an aircraft or displacement along the lateral axis; controlled by the ailerons.

rudder-A movable control surface attached to the vertical fin of the tail assembly; it controls adverse yaw.

S

safety factor-The ratio between the maximum applied load and the ultimate load.

semicantilever wing-A wing of lighter internal structure than the full cantilever wing and one that uses light wires or tie rods either internally or externally for bracing.

semimonocoque type of construction-Fuselage construction using both the skin of the aircraft and internal bracing to carry the stress.

service ceiling-Altitude at which the maximum rate of climb is 100 feet per minute.

shear-Side stress, such as that exerted on a rivet holding two pieces of metal together when an effort is made to pull the metal apart by sliding.

skid-Sideward motion of an aircraft caused by insufficient bank to overcome centrifugal force.

skin friction drag-Caused by the friction between the outer surfaces of the aircraft and the air flowing over the surface.

slip-Sideward motion of an aircraft to the inside of a turn caused by too much bank. (Also the pilot can induce a controlled slip by applying rudder and aileron control pressures in opposite directions).

slipstream-The stream of air driven rearward by an aircraft's propulsion system.

slot-A movable or fixed section on the leading edge of an airfoil designed to help control airflow.

slug-The unit of mass used in the United States.

span-The distance from wing tip to wing tip of an aircraft.

spars-Main load carrying members running lengthwise of the wing.

spoilers-Small surfaces on an airfoil designed to spoil the smooth flow of air over the airfoil and reduce the amount of lift generated.

stability Property of a body (aircraft) which causes it to return to its original position when its equilibrium is disturbed, without assistance from the pilot; also called static stability.

stall-The position of an aircraft or an airfoil in which it no longer generates lift.

stalling point-Point where lift is no longer sufficient to support the aircraft in the air.

static stability-See stability.

stick-Aircraft control used to move elevators and ailerons, also can be a wheel.

straight and level Assumed to mean straight and level, unaccelerated flight, where the aircraft is maintaining a constant altitude and is not accelerating or decelerating, the forces of flight are in balance, *not* related to attitude or angle of attack of an aircraft/airfoil.

stratosphere-Zone of the atmosphere extending from approximately 10 to 55 miles in altitude; middle atmosphere.

stressed skin-A metal aircraft covering (skin) which bears some of the stress.

stringers Longitudinal internal bracing members used in semimonocoque type of fuselage construction.

supercritical wing-Wing designed to reduce boundary layer separation and shock wave in the transonic speed range.

sweepback-Wing design where wing leading edges are angled or swept back toward the tail assembly, allows the designer to improve both lateral and directional stability.

T

tachometer-Instrument which registers the speed of the engine in revolutions per minute.

tail assembly Empennage, the rudder, elevators, and horizontal and vertical stabilizers.

temperature gauges-Instruments which indicate the temperature of the oil, engine cylinders, carburetor intake air, and so forth.

tension-stress which tends to pull members apart.

thrust Force which gives an aircraft forward motion, the opposite of drag.

tricycle landing gear Landing gear consisting of two main wheel assemblies and a nose gear.

torsion-Stress which tends to distort by twisting.

trailing edge-The rear portion of an airfoil at which the upper surface airflow rejoins the lower surface airflow.

trim tabs Small secondary control surfaces used to make fine adjustments in aircraft control.

tropopause The border between the troposphere and the stratosphere.

troposphere Lowest layer of the atmosphere from the surface upward to approximately 5 - 10 miles; where most aircraft fly.

truss-A rigid framework.

turbulent flow drag Drag caused by anything that interferes with the streamline flow of air about the aircraft.

turn and bank indicator-A gyroscopic flight instrument used to evaluate the amount and quality of a turn, needle and ball.

turtle back-The curved upper portion of internal fuselage construction designed to cut down air resistance.

U

ultimate load-The load that, if exceeded, will cause structural failure.

V

velocity-Rate of motion in a given direction.

Venturi tube-A tube with a constriction or narrowed portion.

vertical axis-Yaw axis; it extends vertically thru the center of gravity.

vertical fin-Fixed front section of vertical tail structure.

vortices-Whirlpools of air which trail out behind each wing tip, created by the higher pressure under the wing trying to flow over the wing tip to the lower pressure area on top; they are frequently violent.

W

Warren truss-Welded steel fuselage truss designed so the members can carry either tension or compression.

weight-A measure of the pull of gravity on an object. the opposite of lift.

wing warping-Changing the shape of the wing to control angle of attack and lift.

Y

yaw-Rotation about the vertical axis of an aircraft or displacement along the longitudinal axis; controlled by the rudder.

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