DOCUMENT RESUME

ED 068 293 SE 014 557

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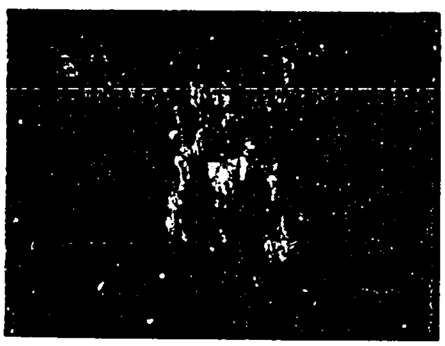
TITLE Theory of Aircraft Flight. Aerospace Education II.
INSTITUTION Air Univ., Maxwell AFB, Ala. Junior Reserve Office Training Corps.
SPONS AGENCY Department of Defense, Washington, D.C.
PUB DATE 69
NOTE 118p.

EDRS PRICE MF-$0.65 HC-$6.58
DESCRIPTORS *Aerospace Education; *Aerospace Technology; *Fundamental Concepts; Instruction; *Physical Sciences; *Resource Materials; Supplementary Textbooks; Textbooks

ABSTRACT

The textbook 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 atmosphere help make flight possible, how man can harness the air for flights, and several other questions related to balancing of forces in the air are discussed in this and the third chapter. The discussion centers, in the fourth and fifth chapters, on how aircraft move through the air. The next two chapters discuss the aircraft structure and various kinds of instruments used to control the flight. A brief description of navigation instruments is also included. The book is to be used only in the Air Force ROTC program. (PS)



Theory of AIRCRAFT FLIGHT

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

AEROSPACE EDUCATION II

Theory of Aircraft Flight

W. G. GLASCOFF, III
Academic Publications Division
3825th Support Group (Academic)

AIR FORCE JUNIOR ROTC
AIR UNIVERSITY
MAXWELL AIR FORCE BASE, ALABAMA

1969

This publication has been reviewed and approved by responsible personnel of the Air University in accordonce with current directives on doctrine, policy, essentiality, propriety and quolity.

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Preface

"YOU TAKE too much for granted!" The speaker might well be a parent, speaking tc a spoiled child. He might also be a letter writer, phrasing a letter to be sent in to a daily newspaper. Again, he might be about to launch into an explanation of why aircraft fly.

This notion that aircraft fly—of course we take it for granted. We see, hear, and ride in aircraft in flight. We read statistics on aircraft which do *not* fly, aircraft which have accidents, but how often do we read statistics or discussions of aircraft which *do* fly? How often does it occur to us that aircraft flight is a science and not a gift?

And how often do we wonder about the nature of this science of aircraft flight: What is it that makes an aircraft fly? 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 as complicated a piece of machinery as a 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. Today's high-speed aircraft use different propulsion systems, different building materials, and different designs from those of the early pioneers of aviation. Today's aircraft can fly much higher, longer, and faster than those early "iron birds." But certain principles are common to all aircraft, old and new, and newer aircraft still rely on many of these principles.

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 *why it is that men can fly*. To explain this phenomenon satisfactorily, it will be necessary to discuss some historical developments which have helped make aviation into a science, rather than a dream or a nightmare.

You will also learn about the air around you: what its properties are; why these characteristics help make flight possible; and how men can harness the air and predict results of flights.

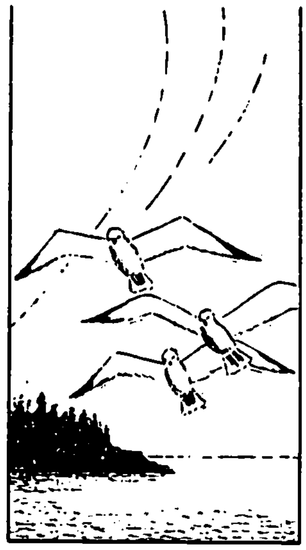
We'll then move on to examine the balance of forces which holds an aircraft in the air. Then, we'll see how an aircraft moves through the air. Next, we'll look at aircraft structure: what are the basic components of an aircraft; how and why an aircraft is designed; and what stresses occur on the airframe.

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 an actual fact; why, then, do we call it a theory? The only answer we can give is that the "theory" part of "theory of flight" comes from human attempts to explain what humans have accomplished. We know that an aircraft can fly; we know that the atmosphere has certain properties; etc., etc.—and the "theory" invloved is the tying-together of all these known facts into an explainable package.

Contents

Chapter 1



Aerodynamic Forces

THIS CHAPTER places man's attempts to fly in historical perspective. You will read about man's early attempts to fly. Then, you will trace through 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 keep it there. After you have studied this chapter, you should be able to do the following: (1) explain the importance of history in the development of "successful controlled, powered, heavier-than-air aircraft flight;" (2) show why the Wright brothers had to understand Newton's Laws of Motion and Bernoulli's Principle in order to make their aircraft fly; and (3) tell why four forces, in balance, are essential to flight.

WITH A ROAR and then a steady hum, your aircraft takes off. You, securely strapped into your seat, hear a blast and then a steady but subdued hum. 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, silently surging through the air. What makes them keep your aircraft in the air? Why don't you go plummeting down to the earth? How "on earth" did you get up where you are in the first place?

Sit back; relax; and don't worry. Something other than popular opinion 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, "Aerodynamic Forces," will take a quick 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 soar under his own power like the birds is an important aid to understanding why you are where you are right now. A rapid examination 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

It all began with the Greeks, like so many other things. You have probably heard or read about the legend of Daedalus and Icarus. In order to escape from the great 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. The Chinese, however, were separated from the Greeks, in space, in time, and in general cultural background, so it was not until much later that man directed his thoughts to solving the problem of flight.

The next 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 man-powered 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 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 anything da Vinci dared dream of. See Figure 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 balloons. Joseph and Etienne Montgolfier, eighteenth-century Frenchman, discovered that captive smoke, contained in a silk bag, rises, until, of course, the smoke cools off! Directing 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

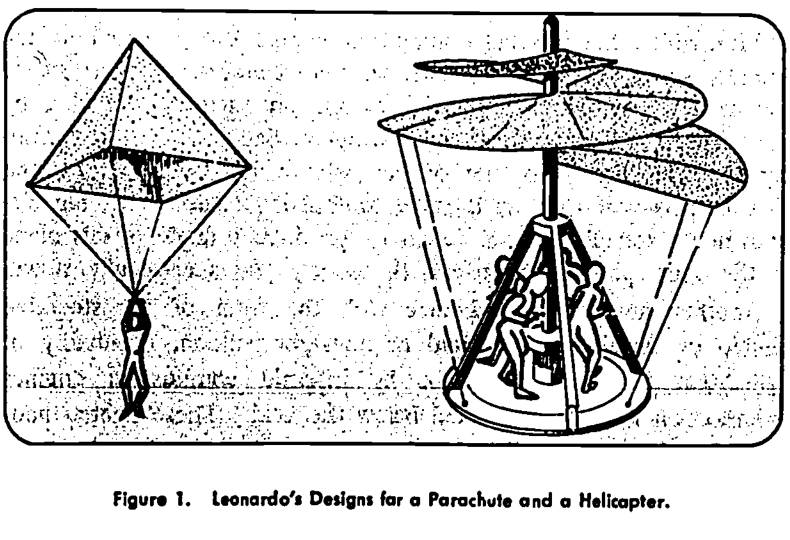


Figure 1. Leonardo's Designs for a Parachute and a Helicopter.

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 1600's. But this is not really flying, as we understand the term today—it is more like floating than flying.

In the early nineteenth century, the Englishman George Cayley constructed the first true model glider. Cayley's writings show 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, Lilienthal had built many successful gliders and had published a book titled *Bird Flight as the Basis of the Flying Art*. In 1896, he built a powered biplane with moveable 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 history of the development of the internal combustion engine is clouded by time, but it appears that Samuel Langley, Secretary of the Smithsonian Institution, was one of the first to build an aircraft and then to power it with an internal combustion engine. His big aircraft never actually flew, although a reproduction made of this plane 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 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 maneu-

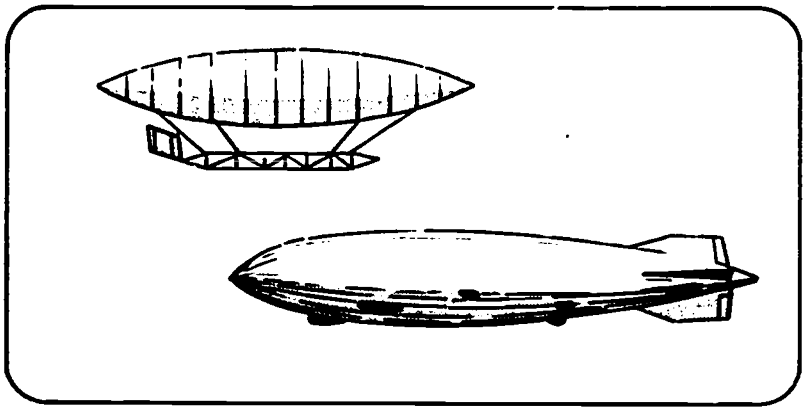


Figure 2. Dumont Dirigible and Zeppelin Rigid Airship.

verability and speed of the heavier airplanes greatly outweighed those of the dirigibles. See Figure 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.

Let's start here: "Heavier-than-air aircraft fly because, through the application of power to the resistance of the air, airfoils are made to lift and support a given weight in flight." That's the whole story in a nutshell. Now let's try to crack that nut and get at the meat. Aerodynamics includes physical laws which have a scientific basis in fact. Hence, we would do well to examine a few of these basic physical laws. An important formulater of three basic physical laws was Sir Isaac Newton (1642–1727). An understanding of his laws of motion is essential to an understanding of aircraft flight.

NEWTON'S LAWS OF MOTION

Newton based his laws on 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.

"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 suddently 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 demonstrating 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 hefty mouthful 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 that you hit it from.

Imagine, now, that the train you were taking (the one that came to the sudden stop) was taking you to the golf course. It's a beautiful spring day, and you place your tee into the ground and put your golf ball on it. 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 straight shot, right 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 also have 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*. Here's another way to state the same thing: "For every action there must be an equal and opposite reaction."

Let's go back to our golf game and see if we can find this law at work. 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 of 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 LAWS 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 0–50 miles per hour in X number of seconds; aircraft accelerate from one speed to another; etc., etc. A formal definition of acceleration states: "Acceleration is the change in velocity per unit of time." We're getting there, now: acceleration 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. We should be able to say, now, that 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 booklet.

Let's now take another look at Newton's Second Law of Motion. We've defined acceleration and velocity; how about force and mass? "Force" is defined in the *USAF Dictionary* as "Power or energy exerted against a material body in a given direction," and perhaps you had already learned that force has *both* magnitude and direction. "Mass," though, is a little trickier concept to get straight. Mass is the quantity of matter in a body, while weight, with which mass is often confused, is the pull of gravity on that quantity of matter. This really is not too confusing, to any of us who have seen the astronauts walk in space. When an astronaut steps outside his space capsule, he still has the same mass (the same quantity of matter), but since he is so far beyond the pull of the earth's gravity, he has no weight.

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 some critical understanding of what these words mean.

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

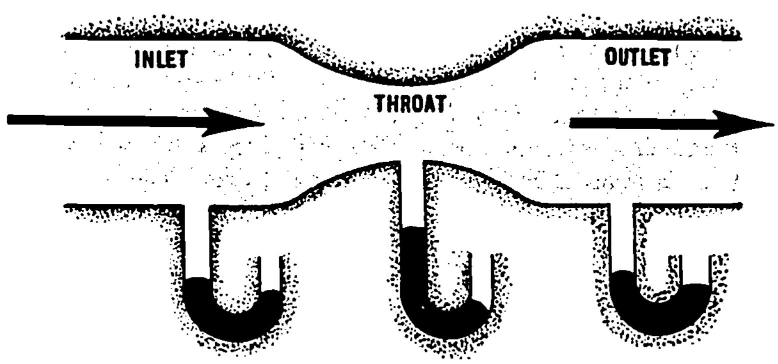


Figure 3. How a Venturi Tube Works.

Daneil 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?

One of the simplest ways to visualize this principle is to imagine what's called a Venturi tube. You'll run into a Venturi 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 constriction in the middle, it speeds up. According to Bernoulli's Principle, it then should exert less pressure. Let's see how this works.

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 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 produces 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 "friendly" to flight, and the other two—weight and drag—as being "unfriendly." 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

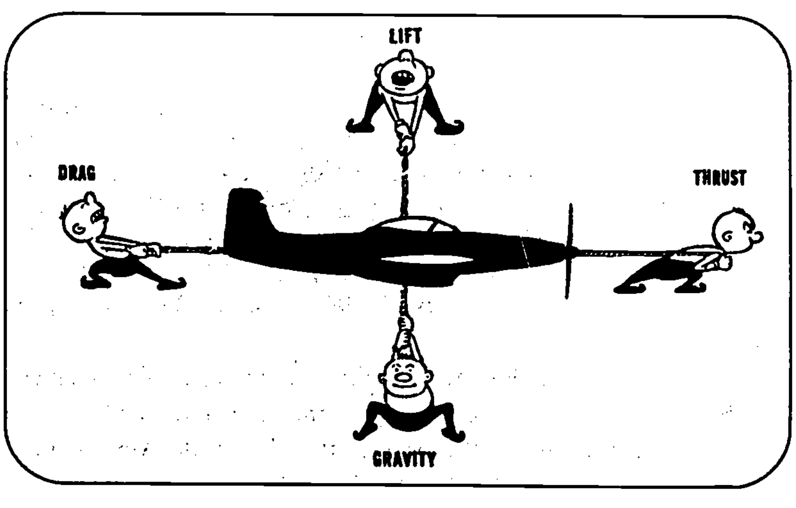


Figure 4. The Forces of Flight.

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." To allow a plane to fly straight and level, thrust must be equal and opposite to drag, and lift must be equal and opposite to weight.

Therefore, all four of these forces are both asset and liability—forces to use and forces to overcome. The thrust of the engines 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, contents), 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 "friendly" 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, in order that the plane can get off the ground!

We will be coming back to these basic four forces of flight in subsequent chapters of this unit. It is important here that you see that they are in balance with one another when an aircraft is in straight and level flight.

To sum up: Man's early attempts to fly were defeated primarily 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 increasingly confident. Man's success in the air can be explained by describing certain forces which hold his aircraft aloft, but the entire story is rather more complicated. The remaining chapters in this unit will cover other aspects of aircraft in flight.

REVIEW QUESTIONS

1. What major advances in man's knowledge and experience led up to the Wright brothers' first successful powered heavier-than-air aircraft flight?

2. What are Newton's Laws of Motion? Discuss their application to everyday life.

3. **What are acceleration, velocity, force, and mass? Give examples of these terms from everyday life.**
4. **State Bernoulli's Principle, and list several examples of the application of this principle.**
5. **What are the four "forces of flight"?**

THINGS TO DO

This chapter deals with basic principles of physics. You can prove for yourself that Newton's Laws of Motion, for example, are true by performing any of the experiments listed in standard physics books. You also can be aware of these principles in action around you every day.

SUGGESTIONS FOR FURTHER READING

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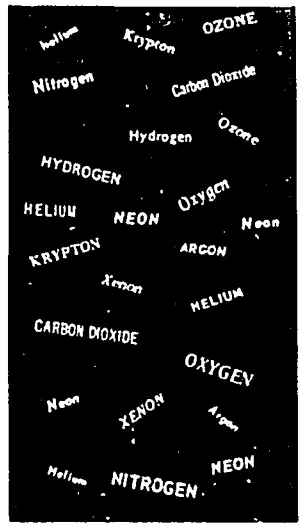


Chapter 2

Properties of the Atmosphere

THIS CHAPTER presents the atmosphere as an important factor in flight. You will read about definitions of the atmosphere. You will also read about the composition of the atmosphere. You will finally examine several physical properties of the atmosphere. After you have studied this chapter, you should be able to do the following: (1) define the meaning of atmosphere and identify some characteristics of its layers; and (2) explain certain physical properties of the atmosphere.

IT'S HARD to know where to begin a discussion of aeronautics. We began this unit by tracing the history of man's attempts to fly and then 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. 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 now look at the atmosphere as one of the "things."

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, a host of other questions. Another definition describes the atmosphere as "the layer of gases surrounding the earth." This definition is too general for our purposes.

The United States Air Force Dictionary gives this lengthy and comprehensive definition: the atmosphere is "the body of air which surrounds the earth . . . . The atmosphere is usually considered to consist of different layers, shells, or spheres. From one standpoint these are the troposphere, the stratosphere, and the ionosphere; from another, the lower atmosphere, the middle atmosphere, and the upper atmosphere. But these same spheres, or other spheres differently conceived, may have certain characteristics that result in other names being applied to them, as those of the chemosphere, the isothermal region, the ozonosphere, the exosphere, the esosphere, 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." *The USAF Dictionary* defines "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

The USAF Dictionary 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 equally 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. This layer is only about 5 or 10 miles thick. Even the top of Mount Everest is well within the upper limits of the troposphere. The main source of heat in this region of the atmosphere is the sun-warmed earth, which heats the troposphere from below. Most aircraft flight takes place in this zone of the atmosphere. Even though we said that it is only about 5 or 10 miles thick, you must remember that 5 or 10 miles represents a height of 26,000 feet to about 52,000 feet—and this is quite high for conventional and jet aircraft to fly.

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 a narrow border zone directly above the troposphere. This zone contains the jet stream, a high-speed, globe-circling wind. 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 increase 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 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 Figure 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. You certainly would be crushed. This does not happen with air, however. 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 weight and occupies space. Since this definition simply states two 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.

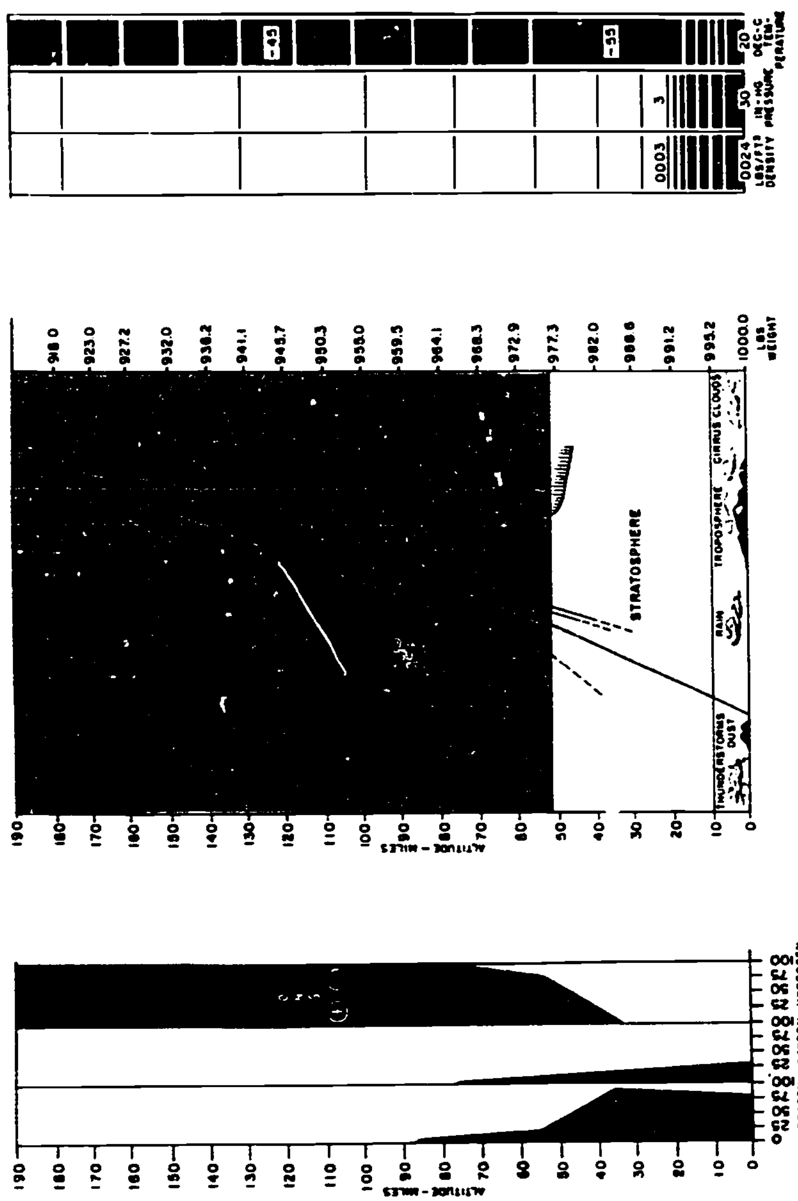


Figure 5. The Atmosphere: Composition and Characteristics.

Air occupies space. We all know that a vacuum is the absence of air; we all also know that 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 imcompressible. This brings us to our next characteristics.

Air is compressible. What does this mean? It means simply that a given quantity of air may be made to occupy practically any amount 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 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 are probably familiar with his experiment, but it does bear repeating here. See Figure 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

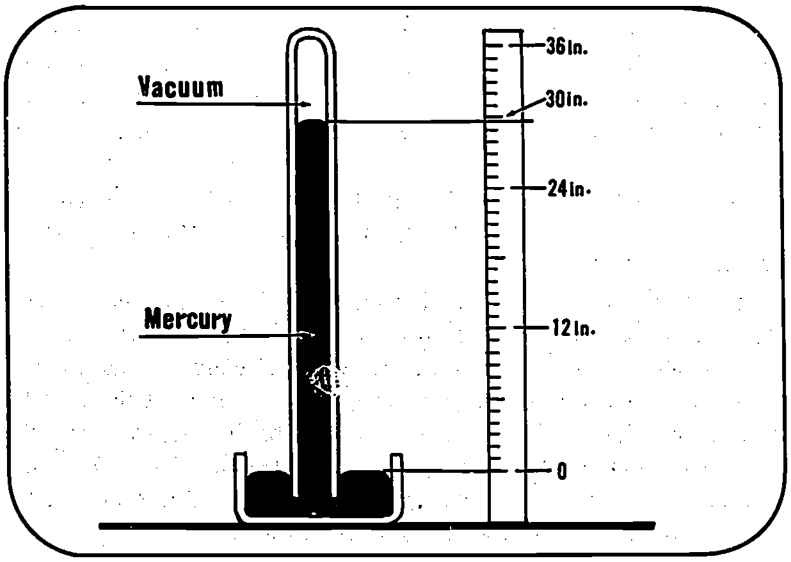


Figure 6. Torricelli's Barometer.

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. We don't have to go into this explanation here; 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. 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. So far, so good—the column of bricks is like the column of air in the atmosphere.

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. Figure 7 sums this up in chart form.

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.

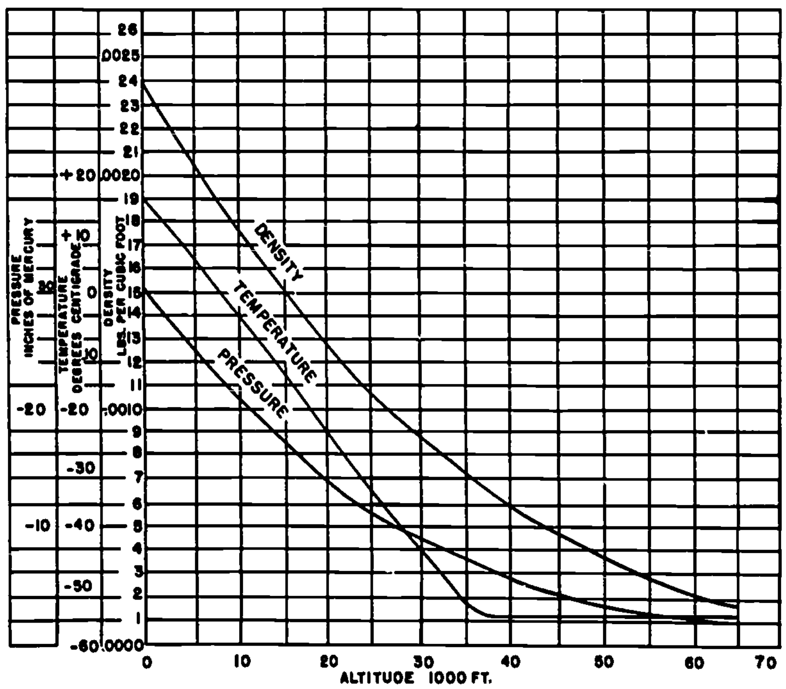


Figure 7. Pressure-Temperature-Density Variations with Increase in Altitude.

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, as you might expect. 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 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 troposphere 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.

REVIEW QUESTIONS

1. **What is the atmosphere?**
2. **What are the layers of the atmosphere?**
3. **What are some of the physical characteristics of the atmosphere?**
4. **Who was Torricelli? What did he discover? How is his discovery useful today?**
5. **How do we know that air exerts pressure?**
6. **How does a column of air 100 feet high differ from a column of bricks 100 feet high?**
7. **Which is denser, dry air or moist air? Which weighs more? Explain.**
8. **What happens to air when it is heated?**

THINGS TO DO

This chapter, like the first chapter, deals with basic physical laws. The first chapter discussed forces and laws of physics; this chapter discusses definitions and characteristics of the atmosphere. You can follow the progress of our national space program as we learn more and more about the higher levels of the atmosphere. You can also perform any number of experiments about air listed in your general science or physics book.

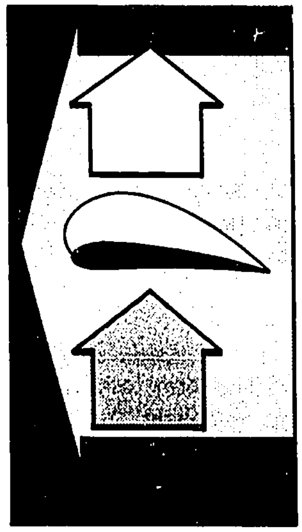
SUGGESTIONS FOR FURTHER READING

Aviation Education Research Group. *Science of Pre-Flight Aeronautics for High Schools.* New York: The Macmillan Company, 1942.

BERNARDO, JAMES V. *Aviation in the Modern World.* New York: E. P. Dutton & Co., Inc., 1960.

SUTTON, GRAHAM. *Mastery of the Air,* New York: Basic Books, Inc., 1966.

Chapter 3



Airfoils and Flight

THIS CHAPTER is perhaps the most critical section of the entire booklet. It explains exactly why aircraft can fly. First, you will examine the airfoil, in order to learn its parts and its role in generating lift. Next, you will see how wind and wing interact to produce lift. You will examine the Venturi tube and see how it, too, can explain the phenomenon of lift. Finally, you will examine several ways in which lift can be varied. After you have studied this chapter, you should be able to do the following: (1) discuss the elements of an airfoil, emphasizing the role of each part in generating lift; (2) tell how an airfoil generates lift; (3) show how lift can be varied and explain what happens when it is varied; and (4) relate what you learned about physical principles and the atmosphere in the first two chapters to the concept of lift in this chapter.

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 for you to begin to see the total impact of this statement. Now let's tie it all together.

AIRFOILS

The term "airfoil" will occur again and again in our discussion of aircraft flight. We would do well to define it here. 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, was extremely important for future aircraft design.

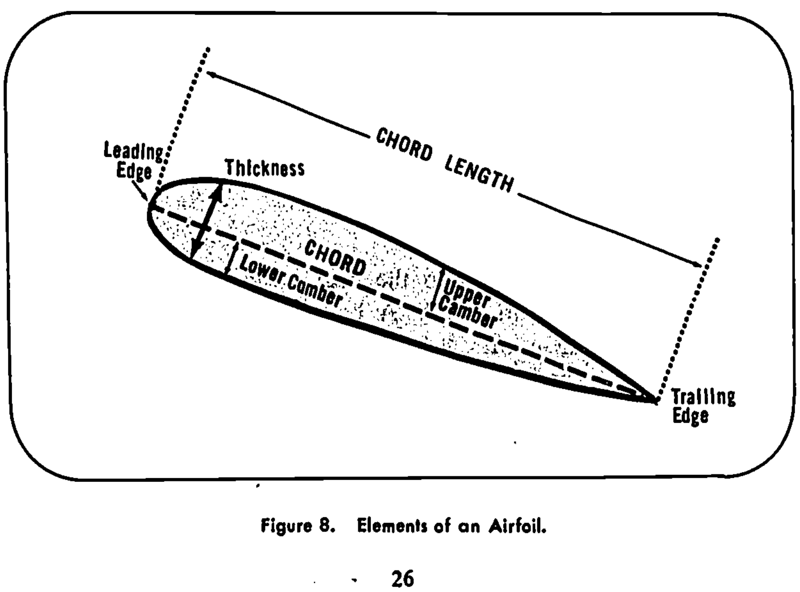


Figure 8. Elements of an Airfoil.

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

We'll take a moment out here to say that the air flowing past an airfoil suspended in a wind tunnel behaves in precisely the same way as the wind flowing over an airfoil in flight. Neither the wind nor the airfoil knows the difference. 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.

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 portion of the airfoil 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 almost razor-sharp, as on an F–104 fighter aircraft. If the airfoil is designed to produce a greater amount of lift at a relatively low rate of speed, as in a Piper Cub, the leading edge may be thick and fat. Actually, the F–104 and the Piper Cub are vitrually two ends of a spectrum. In between these two aircraft lie most other aircraft. The leading edges of their airfoils may have a compromise shape, designed to provide a moderate amount of lift at high subsonic speeds. The F–51 Mustang 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

This is the portion of the airfoil 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–104, has a very little camber. A low speed-high lift airfoil, like that on the Piper Cub, 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.

Think back a moment, now, to the first chapter, where we mentioned 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 a bit later on.

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.

RELATIVE WIND

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. The kite, like the airfoil suspended in the wind tunnel, doesn't know and doesn't care 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 April sky.

You know, however, much more about it than the kite does. You know that when the wind is light, you have to run your legs off at times to get the kite airborne.

Now imagine, if you will, a *kite chord.* (That's kite *chord,* not kite *cord!*) The kite chord is an imaginary straight line running through the kite from its leading edge to its trailing edge. The angle formed between this chord and the *relative wind* flowing past the kite is the *angle of attack.* The adjustment of the bridle on the kite will determine at what angle the relative wind meets the kite. You, therefore, control the direction of the relative wind.

The same is true of an aircraft in flight. The *relative wind* is the wind flowing past the airfoil. If the airfoil in question is the wing, then the *attitude* in which the pilot places the aircraft will determine two things: (1) it will determine the direction from which the *relative wind* is moving; and (2) it will determine the angle at which the relative wind meets the airfoil (the *angle of attack*). If the airfoil in question is the propeller blade, then the pilot can change the direction of the relative wind by adjusting the *angle* of the propeller blade.

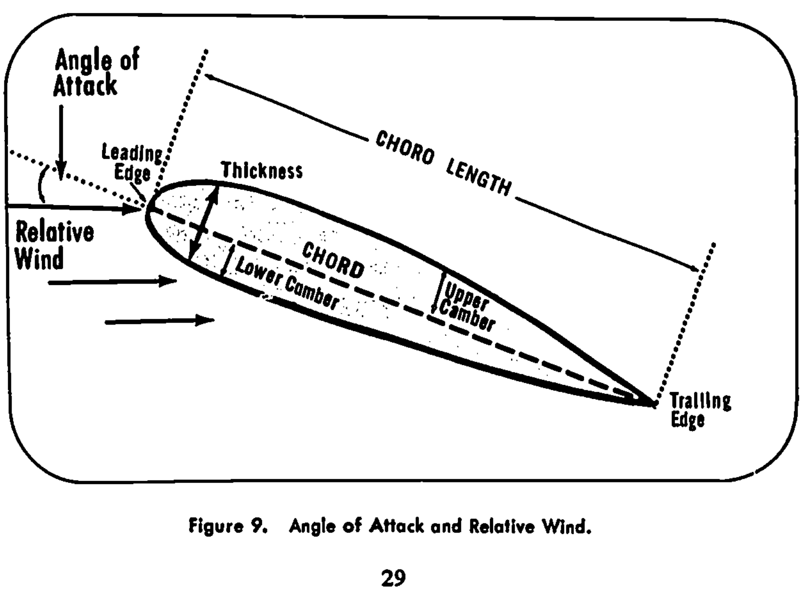


Figure 9. Angle of Attack and Relative Wind.

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 *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. See Figure 9.

ANGLE OF ATTACK

We mentioned the term *angle of attack* in our discussion of relative wind. We said it was the angle at which the relative wind meets the airfoil. The airfoil has an unusual shape, you may say; 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 of angle of attack, we may say that the angle of attack is the angle formed by the chord of the airfoil and the direction of the relative wind. The angle of attack is *not* a constant during a flight; rather, it changes as the pilot changes the attitude of the aircraft. The 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 the chord of the airfoil (our old friend) 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.

LIFT

We've sent you back to the first chapter mentally once in asking you to recall Bernoulli's Principle. Now we're going to bring the first chapter back to you, in our discussion of *lift*.

Let's begin with the diagram we showed you earlier of a Venturi tube, (Fig. 10) which illustrates Bernoulli's Principle: "As the velocity of a fluid increases, its pressure decreases."

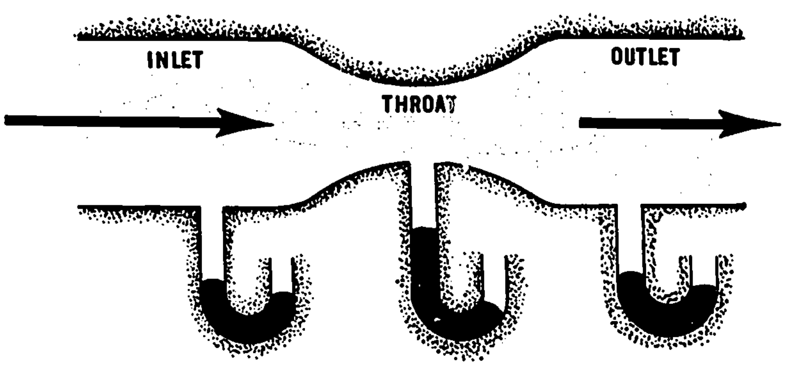


Figure 10

Imagine, now, that we remove the upper part of the Venturi tube. Fig. 11 is what we get:

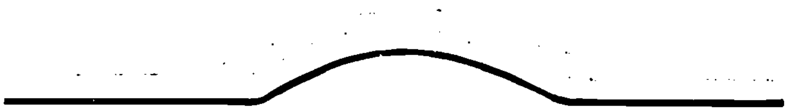


Figure 11

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, Fig. 12 shows what happens when we add a "bottom" to our surface:

Figure 12

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 13 is what we get:

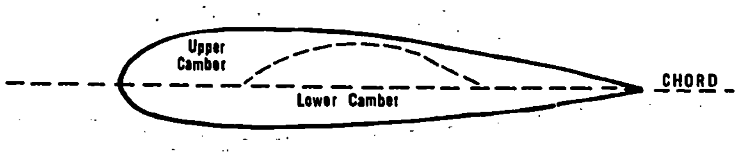


Figure 13

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 quite 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. Another 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 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, for the air to 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.* However, the amount of lift generated by this action-reaction process amounts to only about 15 percent of the total lifting force necessary to sustain aircraft flight.

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 the "airfoils create lift" section here. How do airfoils create 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. Lift also 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, climb, climb until it reached the top of the atmosphere! Here are some of the variables acting on the amount of lift generated: angle of attack, velocity of relative wind, 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

We're going to take a closer look, now, at angle of attack. Angle of attack, you remember, is "the angle formed by the chord of the airfoil and the direction of the relative wind." We also pointed out 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 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 14 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 15

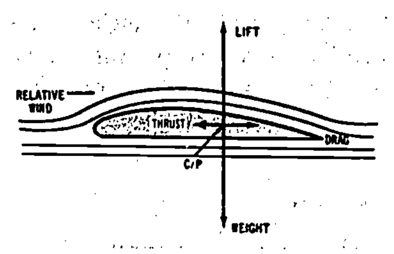


Figure 14. Straight and Level Unaccelerated.

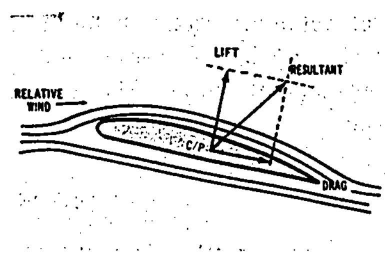


Figure 15. Low Angle of Attack.

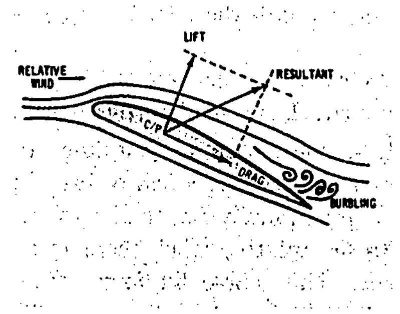


Figure 16. Approaching Stall.

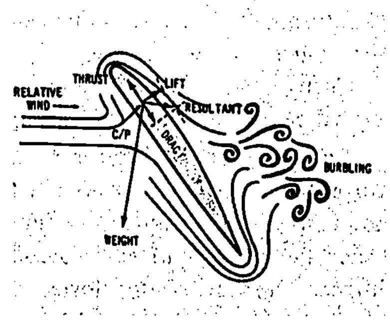


Figure 17. Full Stall.

shows the wing at a low angle of attack. The center of pressure (C/P) is in about the same place as in Figure 14. The resultant is upward and back from the vertical, and we can assume that the aircraft will climb. Notice Figure 16, 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; its angle back from the vertical becomes bigger; and the center of pressure either remains about the same or moves back slightly. See Figure 17.

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 vertical components, 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°, 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, then, 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 increases the angle of attack enough that 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 m.p.h. has four times as much lift as the same aircraft traveling at 50 m.p.h., 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 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 that water, the greater the weight they can support.

Air Density and Lift

Air density is another variable factor which can influence lift. We pointed out in Chapter 2 on the atmosphere what air density is and how it varies with altitude. We also said 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 weigh only half as much or 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 m.p.h. Then Vn must be 70.7 m.p.h. (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. 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), nonetheless this pressure differential will produce a lifting force of more than 20 pounds per square foot (144 square inches/square foot x 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. 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—but we'll have more on this area in a later chapter.

Although it is not a pilot-controlled variable, wing area certainly does vary from aircraft to aircraft, and more importantly, wing area variations provide great variations in 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 leads us to another way to measure the efficiency of the lifting force.

This means is called the *aspect ratio* of the wing. Aspect ratio is a statement of the relationship between the length and the width of a

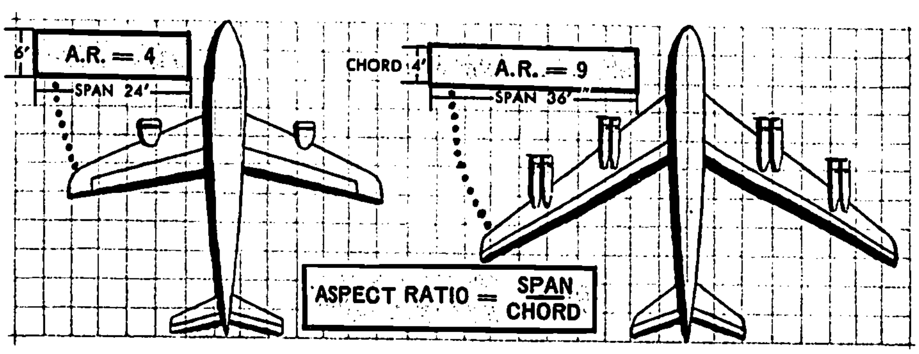


Figure 18. Planform of the Airfoil.

wing. It is computed by dividing the *span* (the distance from wing tip to wing tip) by the *average chord* of the wing. See Figure 18.

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. 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.

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.

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.

Slots, too, can affect lift by changing camber. Slots are either moveable 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, 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 al-

Figure 19. Slots.

lowing a smoother flow of air across the upper surface of the airfoil diminishes both burbling and the airfoil's stalling characteristics. See Figure 19.

Spoilers are small surfaces, recessed into the upper surface of the airfoil. The name 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. 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.

REVIEW QUESTIONS

1. **Define the term airfoil.**
2. **What is a wind tunnel? What is its purpose?**
3. **Draw an airfoil section, labelling the leading edge, and trailing edge, the chord, and the camber.**
4. **What is the relative wind? How can it be controlled?**
5. **Define angle of attack.**
6. **What are the two kinds of lift? How is each kind of lift generated?**
7. **What is an aircraft stall? What causes an aircraft to stall?**
8. **What happens to the lift generated by an aircraft in flight when its velocity is doubled?**
9. **When air density is decreased, is more lift or less lift generated? Explain.**
10. **What happens to the amount of lift generated when the size of a wing is increased?**
11. **Why is a long narrow wing more efficient than a short wide wing?**
12. **How do flaps, slots, and spoilers affect lift?**

THINGS TO DO

You can perform several interesting experiments in connection with this chapter. Here's a simple one: take a sheet of paper and hold it with both hands directly below your lower lip. Then, blow hard and watch what happens. Explain the results. Another experiment you can do is to examine a simple atomizer and compare it with the Venturi tube outlined in this chapter. Explain how the atomizer operates in terms of the Venturi tube. A final experiment you might try: go fly a kite! We don't mean to be totally frivolous here: a kite in the air is an airfoil without camber which is being sustained in flight by impact air against its lower surface. This also is a good example of science in our everyday lives.

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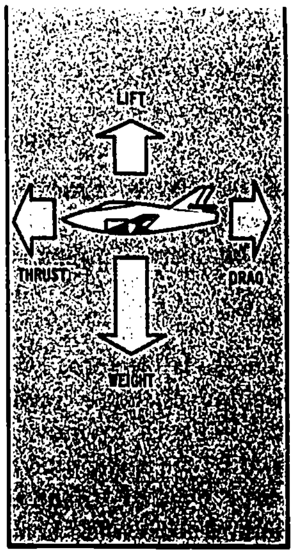

Chapter 4

Weight, Thrust, and Drag

THIS CHAPTER explains the other three forces acting on an aircraft in straight and level unaccelerated flight. The chapter is, in essence, three definitions: weight, thrust, and drag. You will read a definition of each of these terms in turn, and you will also read about how these factors influence aircraft design and performance. After you have studied this chapter, you should be able to do the following: (1) discuss the "balance of forces" which keeps an aircraft in the air; (2) explain how Newton's Third Law of Motion accounts for thrust; (3) differentiate between induced drag and parasite drag; and (4) explain how designers can reduce form drag.

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; we'll now 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. The point at which the total weight of the aircraft and contents may be considered to be concentrated is called the *center of gravity*. That's weight, and that's that. The next force, though, 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 of 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.

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 combusion 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. 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 high pressure area below the wings of the aircraft tends to move into the low pressure area above the wings. Because the aircraft is moving forward, the effect of this motion is trailing vortices. A vortex is simply a whirlpool, and the movement of the air imparts a whirling motion to the air at both the trailing edges and at the tips of the wings of the aircraft. At the center of these vortices are low pressure areas, and these low pressure areas behind the wing will tend to retard the forward movement of the aircraft. See Figure 20.

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

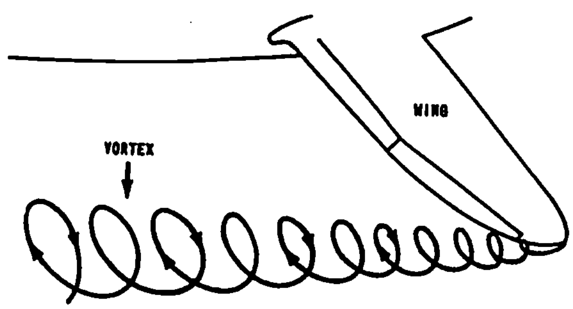

Figure 20. Induced Drag.

The designing of an airfoil can be measured by examining its *aspect ratio*. Remember aspect ratio? We talked about it in the last chapter on lift. Aspect ratio is a number which expresses the relationship between the span of an airfoil and its average chord. Lengthening a wing, then, will raise its aspect ratio. If its span remains constant. Varying the aspect ratio of a wing in either of these two ways will lower the amount of induced drag generated. This is how it works.

Air flowing over and under the wing creates different pressure differentials at different points on the wing. Let's look at all those "differents." 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 molecules at the tip of the wing. Air molecules between these two extremes have gradually decreasing amounts of kinetic energy. 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.

Similarly, pressure on the lower surface of the wing is greater than pressure on the upper surface of the wing. (This is basic Bernoulli, and it is the reason for lift.) Here, again, the equalizing tendency appears, and air tends to flow from the lower surface of the wing to the upper surface of the wing. The violent interaction of these two pressure movements, then, causes the trailing vortices that we mentioned earlier; these tip vortices tend to retard the forward motion of the aircraft.

What can the designer and the pilot do about this kind of drag? Well, the designer has to take into account the factors which will increase drag when he is designing the wing. The pilot, though, 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*. This type of drag is caused by the resistance of the air to non-lifting surfaces of the aircraft. Parasite drag includes all drag components except those causing induced drag. *Skin friction drag* and *eddy drag* (or *form drag*) are names applied to two of these components. Skin friction drag is caused by the friction between the outer surfaces of the aircraft and the air through which it moves. Eddy drag (form 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 eddy drag; we'll look at the *boundary layer air*.

Boundary layer air is a layer of air very close to the surface of a moving airfoil. In this very thin layer of air, separated from the actual surface of the airfoil by only a few thousandths of an inch, 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 form 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 form drag be reduced? Aeronautical engineers have discovered that the best way to reduce form drag 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 best adapted to flowing through

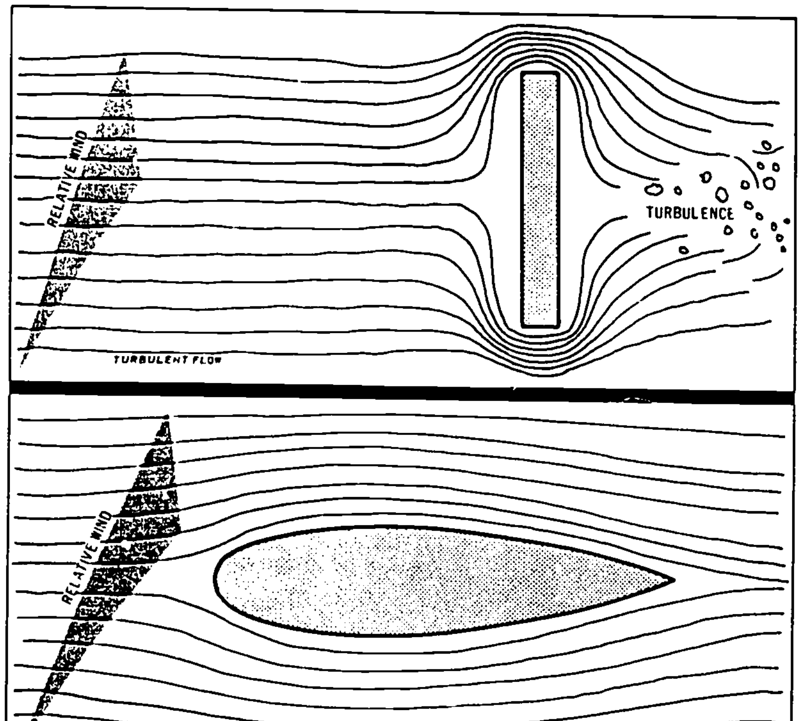

Figure 21. Turbulent Flow and Streamlined Flow.

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 21.

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 form 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 non-lifting 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.

In summary: lift, weight, thrust, and drag are the four forces which act upon an 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."

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

REVIEW QUESTIONS

1. **Define weight.**
2. **What causes thrust in an aircraft?**
3. **What are the two kinds of drag? How can the amount of drag generated by an aircraft in flight be controlled?**
4. **What is boundary layer air? How does it affect drag?**
5. **What is streamlining? How does streamlining affect the performance of an aircraft in flight?**

THINGS TO DO

Weight, thrust, and drag are all basic physical principles. You can read about experiments with these principles in your physics book or your general science book. We will list a few simple things you can do here. To demonstrate weight, simply drop something (non-breakable, preferably!). What happens? It falls, of course. More interesting, perhaps, is the state of weightlessness which our astronauts are experiencing in their space voyages. To demonstrate thrust, simply blow up a toy balloon and let it go. What happens? It flies around the room. This is thrust, and you can show how Newton's Third Law of Motion explains it. To demonstrate drag, we can ask you to repeat the experiment described in the text: stick your hand out the window of a car moving at medium speed—that's drag. Another way to look at drag is as friction, pure and simple. Your science book can tell you more about friction and ways to demonstrate it.

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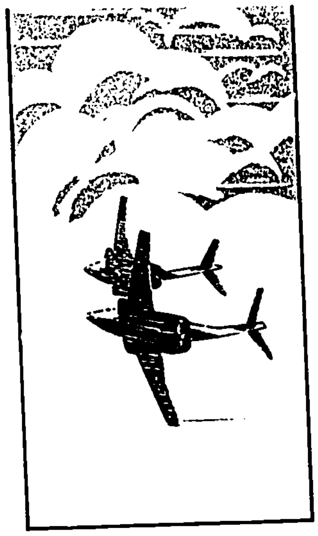
Chapter 5



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. You will find that these axes of rotation lead to the concept of stability, which is very important to an aircraft in flight. You will then read about the 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 relating the physical principles involved in stability to the ways in which the pilot controls the aircraft. After you have studied this chapter, you should be able to do the following: (1) differentiate among the various kinds of stability; (2) explain the effect of varying stability factors on an aircraft in flight; (3) discuss the concept of control of an aircraft and list several of the control surfaces; (4) explain what happens when an aircraft climbs; 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 had to get there somehow, you may say; what other types of aircraft motion are there, besides straight, level, unaccelerated flight?

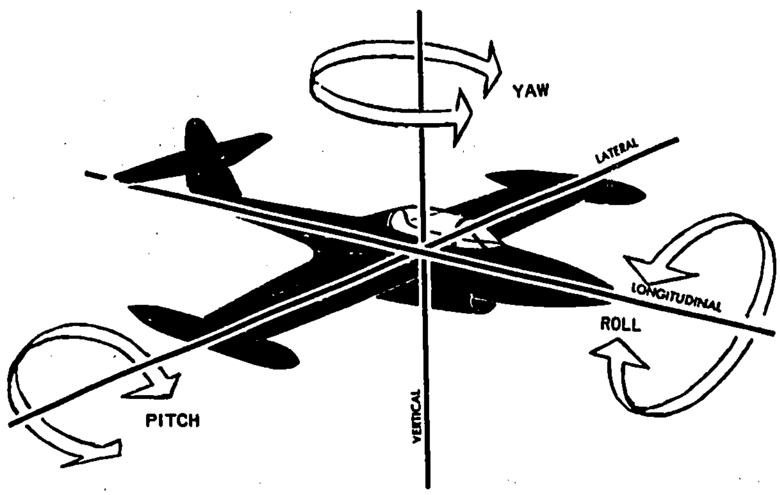


Figure 22. The Axes of Rotation.

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 22 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. Take hold of 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. Bring the nose back up, now, and 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 a bit later on.

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 stable equilibrium when all the forces acting on it balance one another. Stability, then, is a description of this state.

The three types of this mechanical stability are called *positive*, *neutral*, and *negative*. See Figure 23 for example of these. Ball A has positive stability. This simply means that when it is disturbed from its present state, it will tend to return to its original state. Ball B has neutral stability. This means that when it is disturbed from is present state, it will tend neither to return to nor to move further from its original state. Ball C has negative stability. This means that when it is disturbed from its present state, it will tend not to return to its original state. Sometimes we simply say that Ball A is *stable* and Ball C is *unstable*.

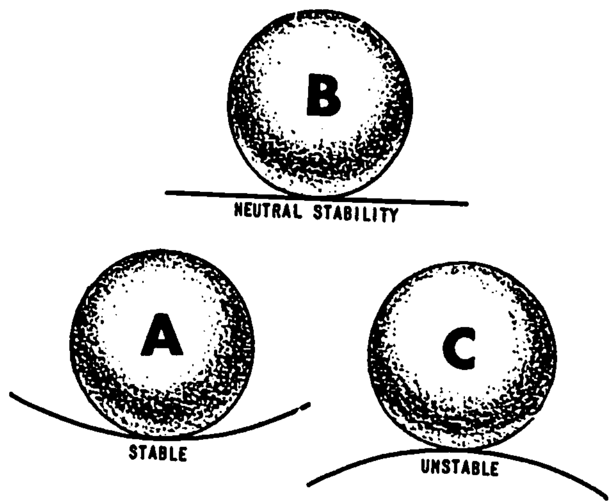


Figure 23. Types of Stability.

An unstable aircraft tends constantly to change from normal flight into abnormal flight, and it must just as constantly be restrained from doing so by proper use of the controls. Obviously, unstable aircraft are extremely dangerous, and so aircraft of this type are not used by either civilian or military units.

Another division of the concept of stability is into *static stability* and *dynamic stability*. 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; etc., etc., until the aircraft finally stalled. 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 oscillating restorative forces.

Another type of stability is called *catastrophic (inherent) instability*. This rather awesome term simply describes a state of stability in which the body is 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 take two pieces of 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 nose-heavy. 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, now. Remember what happens to the relative wind passing over the airfoil? It 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 24.

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 hap-

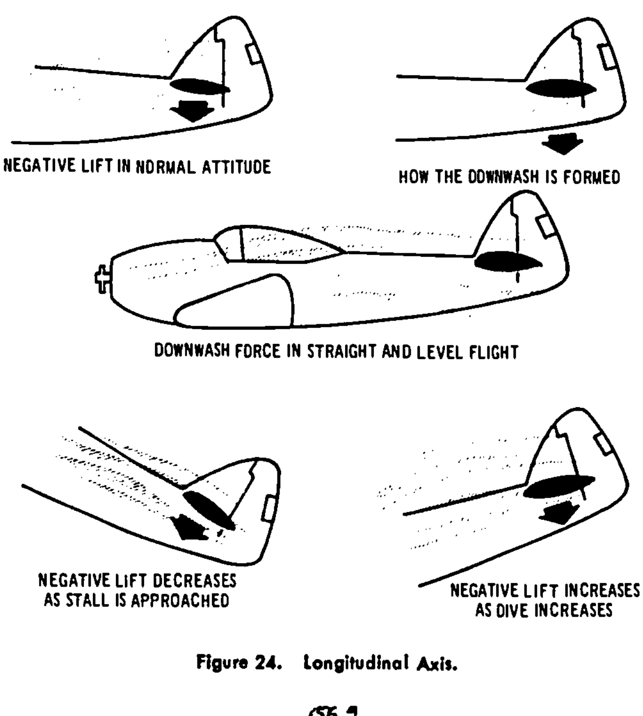


Figure 24. Longitudinal Axis.

pens 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 because of 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 talk about how to correct these tendencies in aircraft a bit later on; 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 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 25 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. 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 gravity than below it,

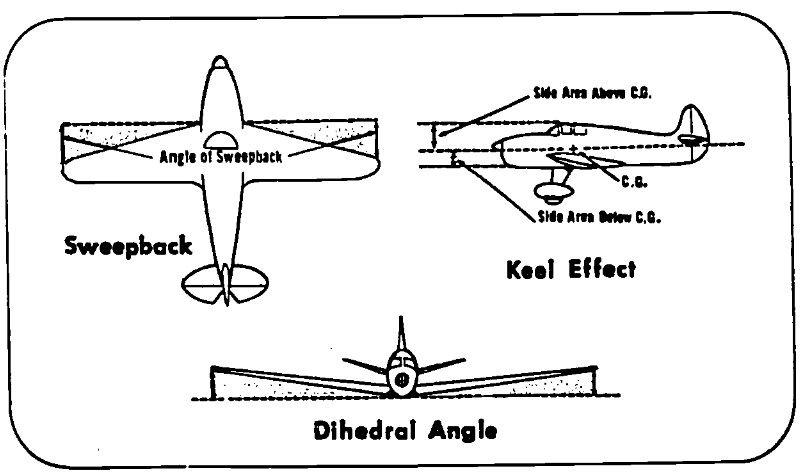


Figure 25. Dihedral, Keel Effect and Sweepback.

the resistance of the air to the downward movements of the aircraft tends to return the aircraft to a stable position.

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, the same 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 nose-heavy. 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 direction. 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 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 Figure 26.

Visualize a weathercock, and you'll see what we mean. 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 weathercock tends to face into the relative wind.

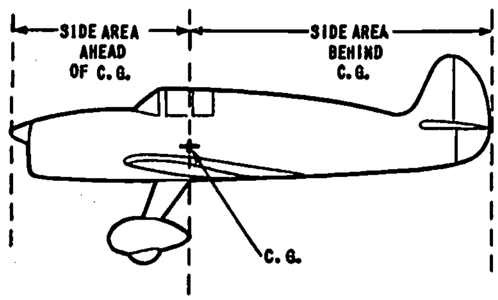


Figure 26. Directional Stability.

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. This, then, brings us to our next major topic area, control.

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 moveable 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 27.

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 the control of 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 raising and lowering of the wings 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 controlling the aircraft's tendency to roll. Ailerons are moveable

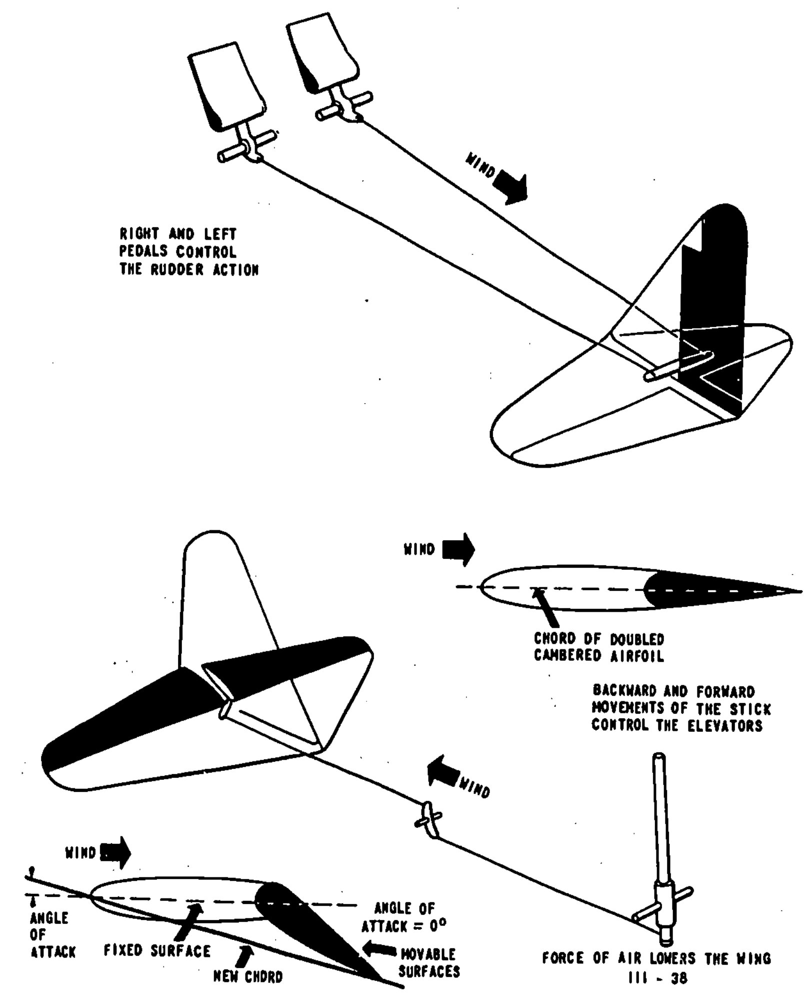


Figure 27. Operation of Tail Control Surfaces.

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 lowers the right aileron. 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. Remember? 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 aileron is decreased; and the rudder can be used to offset the tendency to yaw. The *Frise aileron* (Figure 28) 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.

The rudder is the primary device used to overcome the tendency of the aircraft to yaw. The rudder is a moveable 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

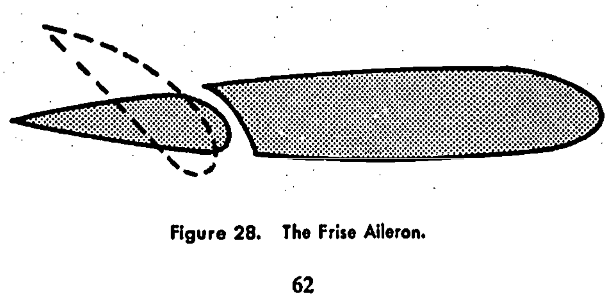


Figure 28. The Frise Aileron.

creates a force on the tail, causing it to move to the right and 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. O.K.? 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 tail-down 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 in 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. We might point out that all aircraft do not have all these surfaces—and we might point out further that it would be quite difficult to describe a specific aircraft which would be a "model" having all these control surfaces. We should point out, though, that virtually all aircraft are flown by the movement of stick 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 *tabs* (and sometimes *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, by, for example, 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, it is impossible to climb at the maximum speed of the aircraft, because then the power is all being used for forward motion, and 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 horsepower is equal to 33,000 foot-pounds per minute (see the unit on aircraft propulsion 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 "raise" 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

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

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 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 Figure 29.

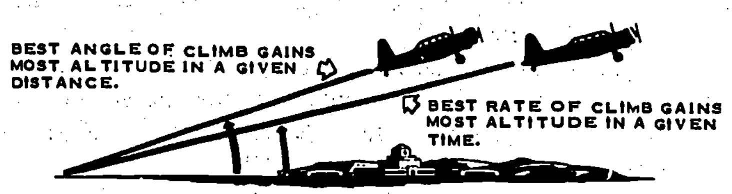


Figure 29. Angle of Climb and Rate of Climb.

Some other terms you may encounter which deal with climbing flight are important, too. *Service ceiling* is the altitude at which the 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

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 added together to form a resultant force. This force acts downward and outward. If the wing is not banked, the aircraft will skid. See Figures 30-33 for examples of the various types of forces in turns in this discussion.

The angle between the wing and the horizontal 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 (sum of the mass and the centrifugal force) makes with the vertical. The lift must equal this 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 little, the lift will not be acting in a direction exactly opposite to the resultant of the weight and centrifugal force. Then, regardless of the amount of lift, the aircraft will tend to move outward, or *skid*. See Figure 30.

Take a look, now, at Figure 31. Here, the angle of bank is too great. The lift force and the resultant obtained by combining the

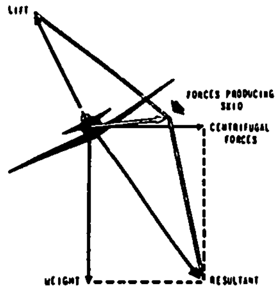


Figure 30. Skid.

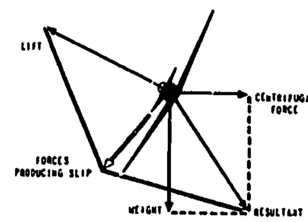


Figure 31. Slip.

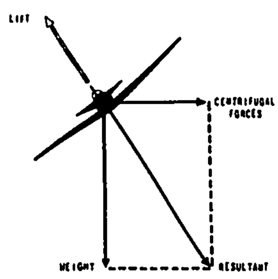


Figure 32. Lift Less than Resultant.

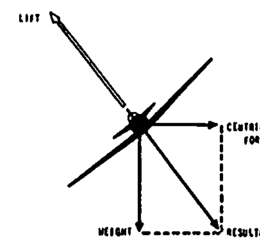


Figure 33. Lift Greater than Resultant.

weight and the centrifugal force combine to produce a force acting inward and downward, and the aircraft will *sideslip* (or *slip).*

In Figure 32, the bank is right, but the lift is too low. Since the resultant is greater than the lift, the aircraft will "squash" or settle.

The opposite holds true in Figure 33. 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.

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.

Let's take another look at turns, now, this time in a rather more simplified version. Take a look at Figure 34. 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 (C.F.) as well. Hence, we have to compute a resultant, and the resultant is greater than the lift. Now, take a look a 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.

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. Hence, remember that in any turn, it is the *elevators* that really do the work.

Take another look at Figure 34. What will the *rudder* do in turning flight? The rudder controls movement about the vertical axis, you will remember; hence, 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

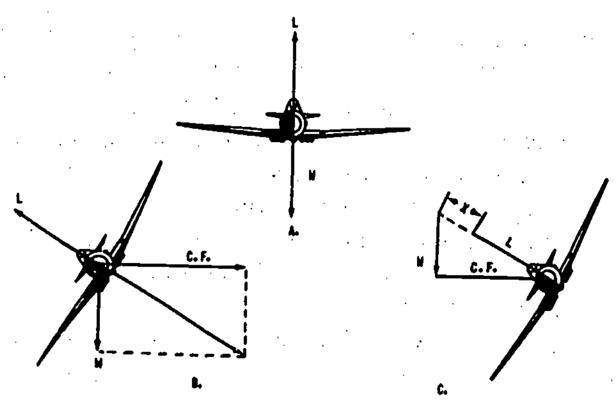


Figure 34. Additional Forces Acting on Turning Aircraft.

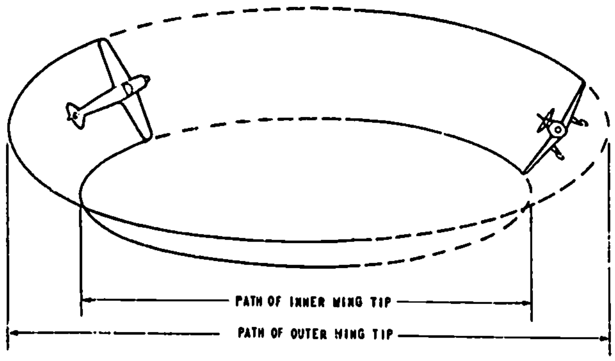


Figure 35. Ailerons and Turns.

discuss a bit later on, 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 Figure 35. 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. Further: 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. Are you with us so far? 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 the pilot did not do this, the aircraft would bank more and more steeply as 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 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 come to this a bit later on.

AIRCRAFT MOTION AND CONTROL

Do you *really* know how an aircraft flies? Most people do not know, even though they think they have it all straight. 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. The *wings* lift the aircraft around in a turn. 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 stabilizer so that the aircraft flies straight and level. We'll assume that this is a propeller-driven aircraft, for this explanation. 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 constant *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 close the throttle, 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 m.p.h. Now, we pull back on the stick, and the airspeed drops to 60 m.p.h. Now, we push the stick forward, and the airspeed increases until it reaches 100 m.p.h. 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. The aircraft can stall in level flight, all things being wrong, and the aircraft can stall 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 with 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 Figure 36. The aircraft, then, must oppose this pulling force, and this requires extra lift.

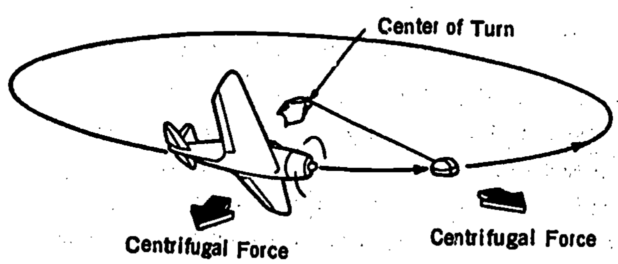


Figure 36. Centrifugal Force in Turns.

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 "adverse yaw." To correct for this adverse yaw, the pilot applies pressure to the right rudder. 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. Exprienced pilots often say that one rule will be of 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 aircraft 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, take-off, 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.

REVIEW QUESTIONS

1. **What are the axes of rotation of an aircraft in flight?**
2. **What is stability? How can the concept of stability be divided?**
3. **How does an aircraft maintain longitudinal stability?**
4. **How does an aircraft maintain lateral stability?**
5. **Using a weathercock as an example, explain how an aircraft maintains directional stability.**
6. **What is aircraft control? What are the principal aircraft control surfaces, and how do they work?**

7. What characteristics of his engine and his aircraft should a pilot remember when he executes a climb?

8. What is centrifugal force? How does it affect aircraft turns?

9. How are aircraft controls used in turns?

THINGS TO DO

This chapter deals for the most part with aircraft in motion. You can demonstrate for yourself many of the principles discussed here with simple paper or wooden aircraft models. At the beginning of this chapter, we discussed the axes of rotation of an aircraft. You can demonstrate which axis is which by holding a model at about the center of gravity and then moving it about each axis. Flying models can help you, too. You can demonstrate for yourself how varying the control surfaces affects flight, simply by maneuvering the control surfaces on simple flying models and then seeing what effect this has on actual flight. Your instructor has several books which include experiments which you can perform.

SUGGESTIONS FOR FURTHER READING

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STRICKLER, MERVIN K., JR., ed. *An Introduction to Aerospace Education.* Chicago: New Horizons Publishers, Inc., 1968.

SUTTON, GRAHAM. *Mastery of the Air.* New York: Basic Books Inc., 1966.

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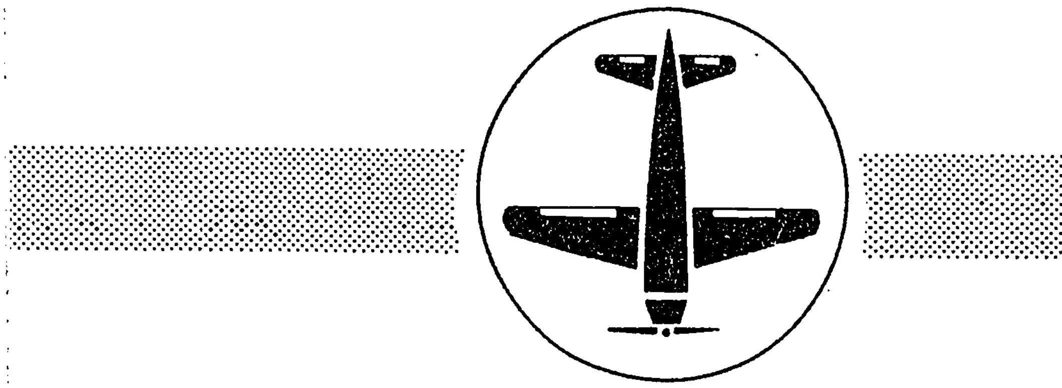
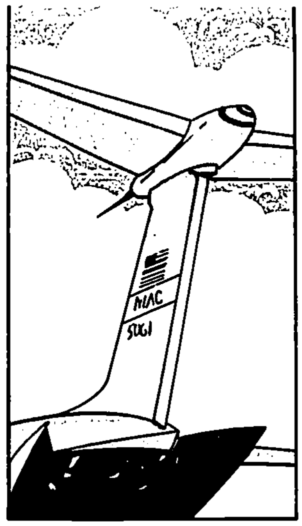


Chapter 6



Aircraft Structure

THIS CHAPTER examines the aircraft itself. You will look at the various parts of an aircraft, one at a time, and you will read about how the various parts are built and why they are built that way. First, you will read about the power plant of the aircraft. Then, you will examine the fuselage and the way in which it is built. Along the way, you'll encounter a brief discussion of stresses and how they affect aircraft construction. You'll then move on to examine wing and tail construction, including a close-up look at some control surfaces. The chapter concludes with a brief discussion of the hydraulic and electrical systems in an aircraft and examines one of these systems, the landing gear, in some detail. After you have studied this chapter, you should be able to do the following: (1) describe the function of the aircraft's power plant; (2) differentiate among the five types of stress which act on an aircraft in flight; (3) explain how aircraft construction counteracts these stresses; (4) discuss the essential differences between the various types of fuselage construction and point out some advantages of each; (5) explain why internal wing construction is an important part of aircraft design; (6) outline the principal parts of the empennage; (7) list several applications of hydraulic and electrical systems in an aircraft; and (8) explain how the landing gear on aircraft used today work.

WE'VE COME quite a long way, from man's first desire to fly to how he finally achieved controlled powered flight. We've discussed the theories underlying flight, and we've talked about how

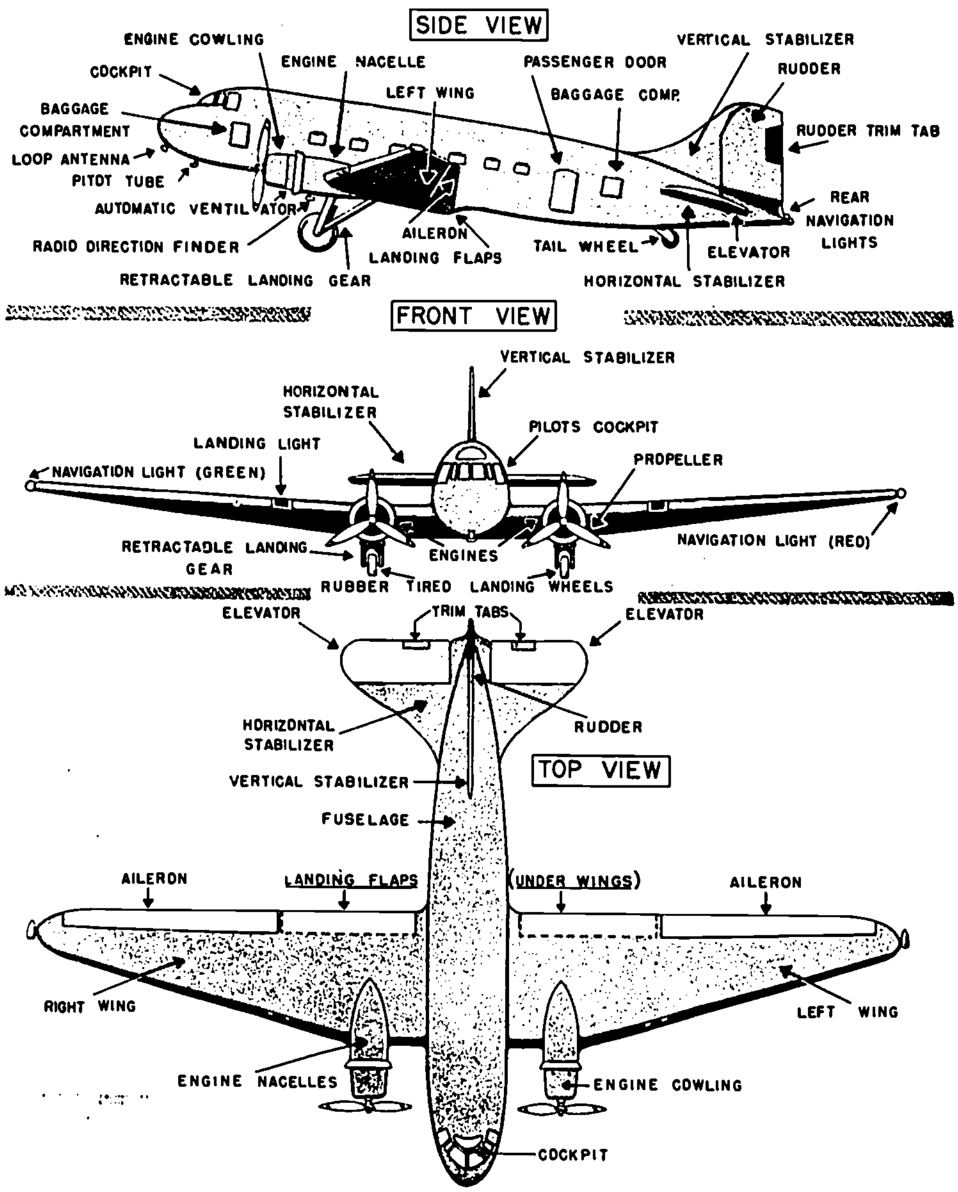


Figure 37. Structural Elements of an Aircraft.

an aircraft maneuvers in the air. Let's now take a closer look at the aircraft itself. You will perhaps 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 three-view diagram of a conventional aircraft (Figure 37). We will refer to this diagram often. This particular diagram allows you to see just where on the aircraft each of the parts we'll be discussing is located.

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 tell you that the power plant is as essential as anything else to making the aircraft fly. You'll soon be covering propulsion systems for aircraft in another unit, so we won't go into much detail on how the various systems in use today operate. Rather, we want to tell you what the power plant does, what it looks like, and where it is located.

In Figure 37, you can see the *propeller*, the *engine nacelles*, 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 seen at work earlier in this booklet). 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 from the elements, and it also directs cooling air onto the engine itself.

The engine nacelles are streamlined containers for auxiliary engine systems. You'll notice in the side view shown in Figure 37 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" of fuel, note the shape of the tanks: they, too, are nacelles. Certain aircraft may have passenger nacelles, such as the *C–119 "Flying Boxcar,"* which has, in effect, two greatly extended engine nacelles with a passenger nacelle in between. Single-engine aircraft do not have engine nacelles. Why? Simply because the engine is attached directly to the fuselage, our next major structural element.

FUSELAGE

The fuselage is the main part of the aircraft. It carries the crew, passengers, cargo, instruments, and 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 *semi-monocoque*. The truss type of construction is made of steel tubing, and the semi-monocoque type of construction is made from internally braced metal skin. In order to understand these two types of construction better, you need to know something about the *stresses* which act on an aircraft in flight. We'll look first

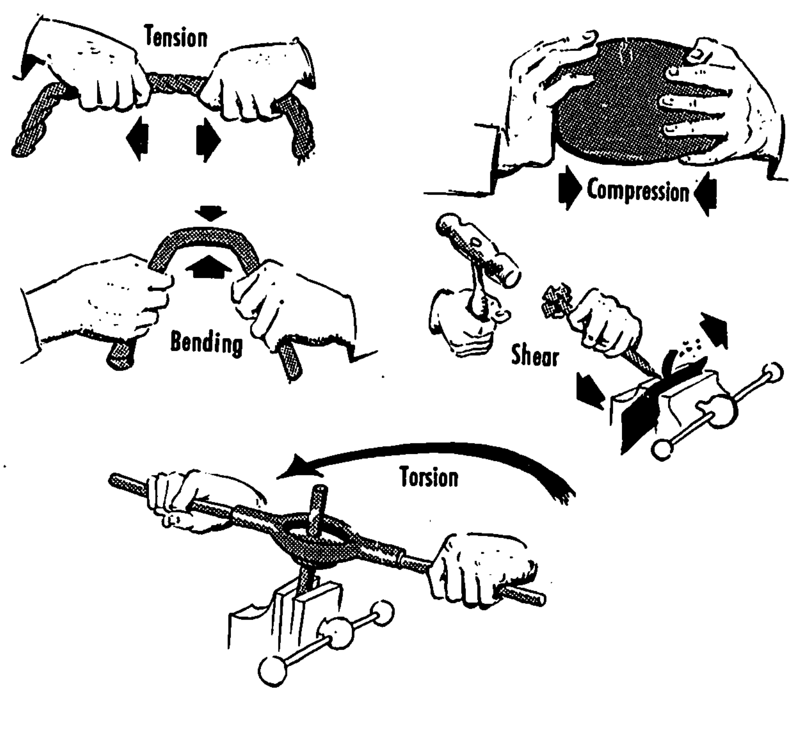


Figure 38. Types of Stress.

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 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 Figure 38.

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 prevents a member from being pulled apart. A member, incidentally, 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 resists a force of pushing 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. 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.

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. 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 resists being twisted apart. You produce a torsional force when you tighten down a clamp on something clasped in a vise. The aircraft engine exerts a torsional force on the crankshaft.

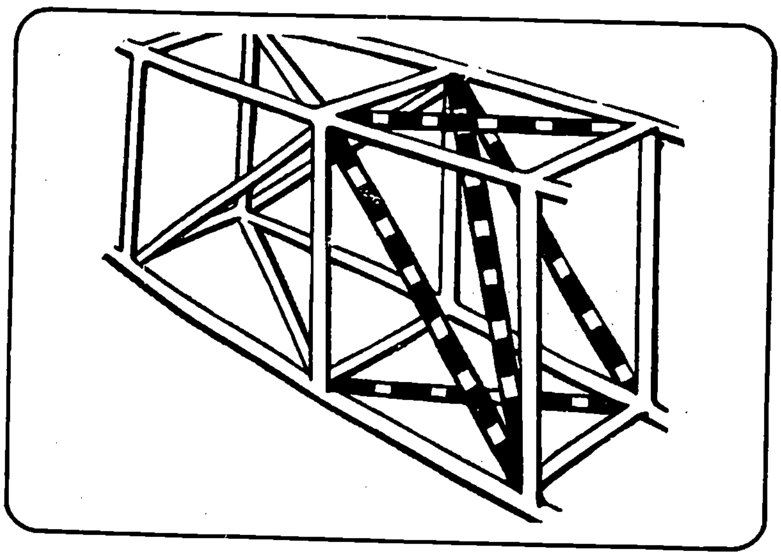


Figure 39. The Warren Truss.

All the members in 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, can 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. The Warren truss (Figure 39) is most often used in today's aircraft which have trussed fuselages. The members in this type of truss can carry either tension or compression. When the load is acting in one direction, tension loads are carried by every alternate member, 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 compression. 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 is then covered with a fabric cover. Were this fabric cover to be applied directly to the truss, it would fall into all sorts of valleys and ridges. The rough surface thus formed would not provide a smooth surface, and as we mentioned earlier, the smoother the external surface of the aircraft, the less drag will be generated. To produce a smooth surface, the fabric cover is put on *fairing strips,* which are like lath strips. 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 Figure 40.

The semi-monocoque 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.

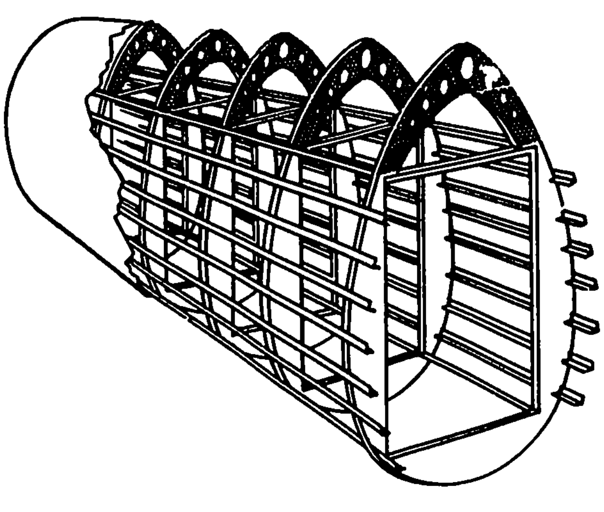


Figure 40. The Turtle-Back Fairing.

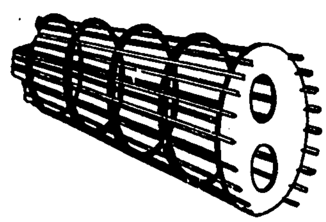


Figure 41. Semi-monoque Fuselage.

As its name implies, the semi-monocoque type of construction allows for both the skin of the aircraft and the internal bracing to carry the stress. The internal bracing is made up of longitudinal members, called *stringers* and *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 Figure 41.

The semi-monocoque type of fuselage is easy to build in streamlined 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 unaffected by climatic conditions if proper protective coatings are applied. For this reason, the semi-monocoque fuselage can take considerable gunfire and still hold together.

The skin itself is usually made of sheets of aluminum alloy, although plywood has also been used. Expanding technology may develop plastics and other synthetics in the future 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 air load is just equal to the weight of the aircraft. If the pilot pushes the controls forward or pulls the controls back, an additional force is exerted which increases 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 extremely thin of high quality material. Corrosion, rust, scratches or nicks may weaken them and cause a structural failure or a 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, which means that it is the break-off point between a part's holding together or its coming 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 *factor of safety.*

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 fuse-

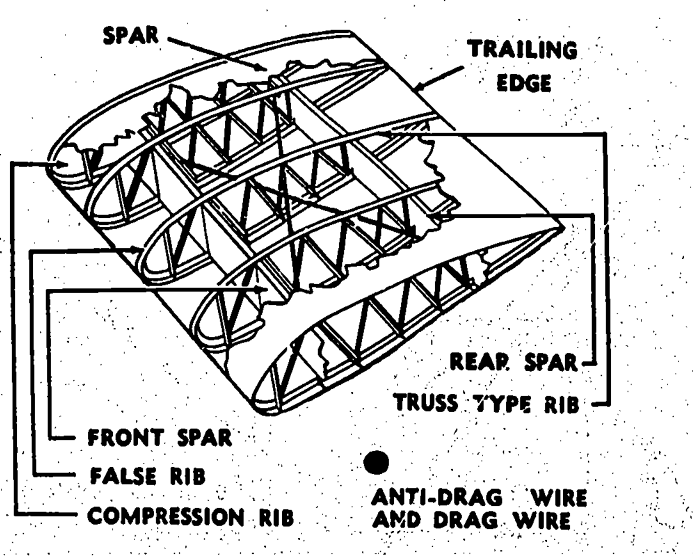


Figure 42. Details of Construction of Cloth Covered Wing.

lage. The semi-monocoque 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 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 end of the wing 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 Figure 42 for the details of construction of this kind of wing.

Metal wings are constructed along the same general lines, except that the ribs are generally made of light metal, and thin sheets of

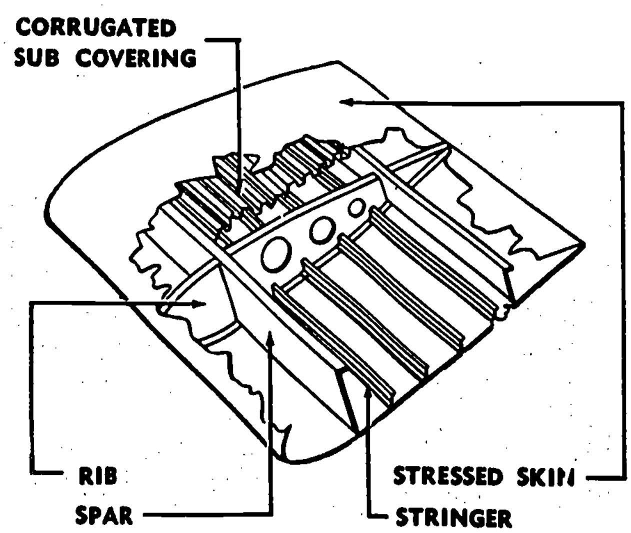


Figure 43. Construction Details of Stressed Skin Type of Wing.

metal replace the fabric. This type of wing is obviously very much stronger; hence, it is used most often on military aircraft and large commercial aircraft. However, its far greater weight and cost make it undesirable for the average light transport or sport aircraft. See Figure 43.

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

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 or 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 cloth, 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 strip of wood or metal called the wing tip bow maintains the shape of the outer 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 this type of 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. Now let's see how they're attached to the aircraft fuselage. Three systems are used to attach the wings to the fuselage: *full cantilever, semi-cantilever,* and *externally-braced*. The full cantilever type 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 semi-cantilever 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. More on landing gear a bit later on.

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 semi-cantilever 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.

EMPENNAGE

This five dollar word is simply a French term for *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 stability in the air, of course. This is exactly what the primary function of the tail assembly is, too. We've 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 non-control 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. It is quite difficult to single out any one aircraft's empennage as "typical." We'll discuss these assemblies in general, then, pointing out what's where and why it's there.

When you stand behind an aircraft and look at it, you'll 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 Figure 44. 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

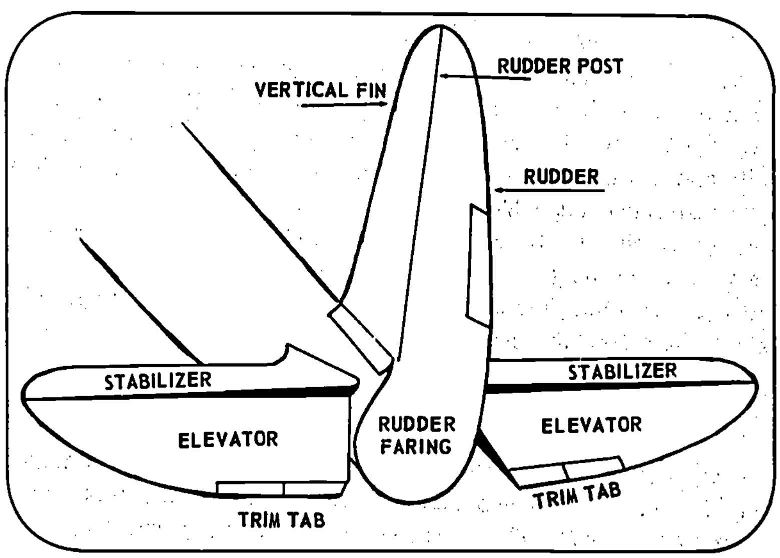


Figure 44. Parts of the Empennage.

provide longitudinal stability. We said it is a fixed section; in most aircraft, this is true. However, in 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, and hence, it controls its speed.

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 sort of aircraft, 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*, moveable 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.

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." Basically, these words explain how a hydraulic system works: pressure exerted anywhere on a confined fluid is transmitted undiminished to every portion of the interior of the vessel containing the fluid, wrote the French mathematician and philosopher Blaise Pascal more than three centuries ago. This pressure acts at right angles with an equal force on equal areas.

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. Assume that one of these has an area of 1 square inch and that the other has an area of 10 square inches. If 5 pounds of pressure is placed on the smaller piston, 50 pounds (10 x 5) of pressure will be created 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.

Aircraft have hydraulic pumps to generate the hydraulic pressure necessary to operate the various components of the aircraft.

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

As you might imagine, an aircraft's *landing gear* operates to help the pilot land his aircraft. You know, too, that the landing gear comes into play when the aircraft takes off. The Wright brothers 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 take-off and merely skidded along the ground on landing. This type of landing gear created a great deal of friction on take-offs and failed to absorb much of the shock of landing.

These are the two main functions of the landing gear: to assist take-off, and to absorb the shock of landing. Most light aircraft today are equipped with fixed type landing gear. Balloon type, low pressure tires are used extensively on this type of gear to absorb the landing shock.

Shock absorbers on many light aircraft with fixed type landing gear are of the *shock cord* type. These shock cords are simply large rubber bands. The shock of landing is absorbed by the shock cords and is distributed over a longer period of time than if the body of the aircraft were to take the shock immediately upon impact.

The more usual type of shock absorber is the *oleo strut*. "Oleo," in this context, refers to oil, rather than to spreads for bread! Oleo struts are shock absorbing devices using oil to cushion the blow of landing. This type of shock absorber is part of 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 Figure 45.

In order to eliminate the drag of the landing gear during flight, the wheels and struts are usually retracted into the aircraft. The landing gear may be retracted into various places in the aircraft itself, 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.

To aid in controlling most aircraft on the ground, the main wheels of the landing gear are fitted with brakes which operate independently. These brakes are used to slow up a fast rolling aircraft. They also are 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

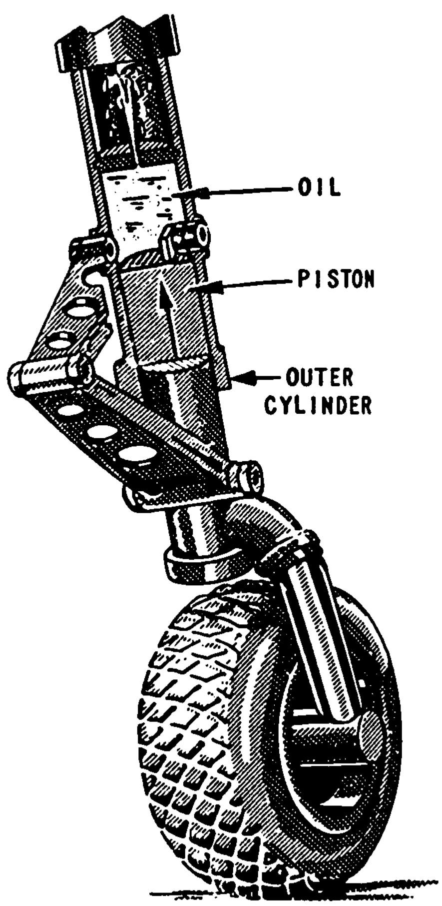


Figure 45. Principle of Oleo Strut Operation.

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.

How are the parts of the landing gear arranged on the aircraft? Three major systems 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, simply because any inclination 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 as many as four tires. Auxiliary wheels on the wingtips provide additional support on the ground. Large transport aircraft, equipped with bicycle landing gear, are extremely heavy; hence, the more wheels and the more widely the load can be distributed over the runway, the better off the landing field will be.

This, then, covers the external parts of the aircraft. Its 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.

But what about the pilot, you may ask. How does he fit in? 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.

REVIEW QUESTIONS

1. **Describe the function of an aircraft's power plant.**
2. **What are engine nacelles?**
3. **Describe the two main types of aircraft fuselage construction.**
4. **What are the five types of stress which act on an aircraft in flight?**
5. **Discuss longerons, fairings strips, stringers, frames, and formers, explaining where each is located and what each does.**
6. **Why do wings have spars and ribs?**
7. **Discuss the systems used to attach the wings to the fuselage.**
8. **What are the elements of the empennage? How does each operate?**
9. **What kinds of landing gear do aircraft of today employ? What are the reasons aircraft have landing gear?**

THINGS TO DO

The best thing to do for this chapter is to actually examine an aircraft. You should be able to arrange to do this at either a civilian airport or a nearby Air Force installation. If you can't examine a real aircraft, examine a detailed model. As we pointed out in the text, not all aircraft have all the parts we described. With some help from your instructor, you could compare various types of aircraft in order to examine details of construction.

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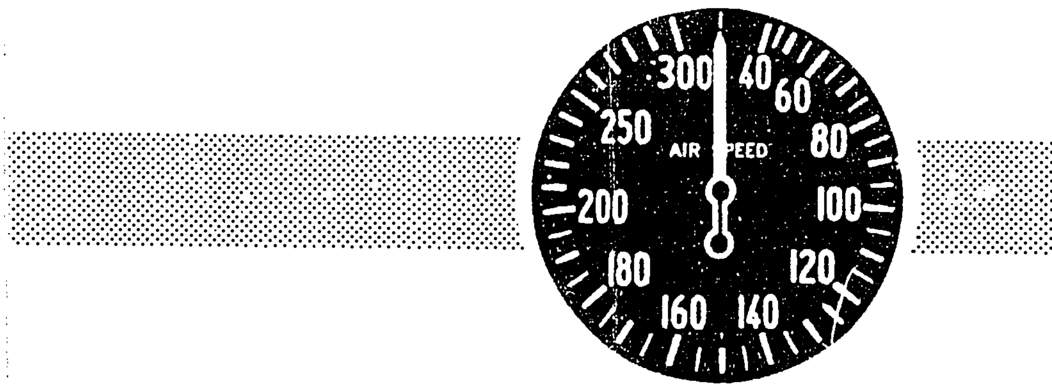
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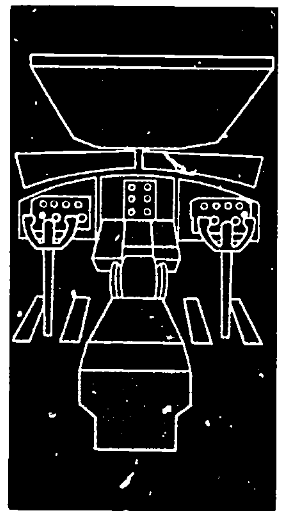

Chapter 7

Aircraft Instruments

THIS CHAPTER introduces you to aircraft instruments. You will read about how instruments may be classified. You will then examine engine instruments, navigation instruments, and flight instruments in turn. After you have studied this chapter, you should be able to do the following: (1) discuss the varicus ways in which instruments may be classified; and (2) tell what each class of instruments does and how it works.

"WHAT A LOT of dials and gauges! How can one man possibly keep track of all of them? I could never do anything like that. Why, just last Tuesday, my car ran out of gas . . . ." This might be your reaction the first time you took a long hard look at the instrument panel of a modern day aircraft. Today's automobile has several gauges with which you probably are 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 accustomed to seeing all of them and knowing what they do. (If 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 in today's car: 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 the various classes of instruments, their operation, and the information the pilot gets from them. You should agree with us that instruments in an aircraft are not as confusing as you might have thought!

INSTRUMENT CLASSIFICATION

Aircraft instruments are classified either in terms of their use or in terms of the principle underlying their 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 four major groups: *engine instruments, aircraft (safety) instruments, flight instruments,* and *navigation 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. *Aircraft (safety) instruments* let the pilot know the air temperature, the position of the landing gear and the flaps, the hydraulic pressure, and other information of this type. *Flight instruments* inform the pilot of his altitude, the airspeed, and the attitude of the aircraft. *Navigation instruments,* which help the pilot find his way from point of departure to destination, include the clock, the compass, the directional gyro, the driftmeters, the sextant, the radio, radar, and the radio direction finders. When you look at the instruments in this way, you can see that each one has a separate functional purpose and that the pilot draws information from all of the instruments. In other 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 classified by principle of operation fall into three major groups: *mechanical* (including gyroscopic) *instruments, pressure instruments,* and *electrical instruments.* We won't go into any of the finer details of how these principles operate the instruments, because 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 Figure 46. A gyroscope consists of a heavy wheel mounted so that it is free to rotate on its axis within a light frame. Two principles underlie the operation of the gyroscope:

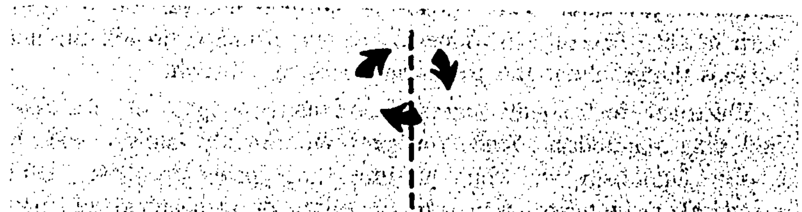

Figure 46. The Gyroscope.

rigidity in space and precession. Rigidity in space is the characteristic that makes a gyroscope point constantly to the same direction in space. 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.

Pressure instruments work on the principle of air exerting pressure, which we discussed at some length in the sections of this unit dealing with lift and the atmosphere. Air has weight, and hence, it can exert pressure. The amount of air pressure exerted decreases with height. Pressure instruments use this principle to tell the pilot various things about the performance of his aircraft.

Electrical instruments operate on the principles of electricity, including magnetism. Since you probably already know a good bit about magnetism, we won't go into those principles here. Other electrical instruments often take the place of mechanical and pressure instruments.

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 at comparatively low compression ratios. These engines required only tachometer, oil temperature gauge, and water temperature gauge. The modern engine requires all of these and, in addition, gauges which show pressure of oil, fuel, and manifold. It also requires indicators which show the temperature of the air, the carburetor, and the cylinder heads.

The *tachometer* tells the pilot the speed at which his engine is revolving. 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 a minimum operating speed 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 to mix properly, the carburetor may "ice up"; that is, the water vapor in the air may freeze on the carburetor, and the engine, in turn, may conk out.

The *pressure gauges* tell the pilot the pressure of the engine oil, the fuel, and the 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.

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.

Other aircraft engines may have other gauges. Modern technology is developing more and more complicated engines which require more and more gauges. 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 booklet on navigation 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.

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 navigating the aircraft. 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 informs the pilot of his aircraft's attitude with reference to the horizon. We just mentioned the fact that the line between flight and navigation instruments is sometimes a bit shaded, 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.

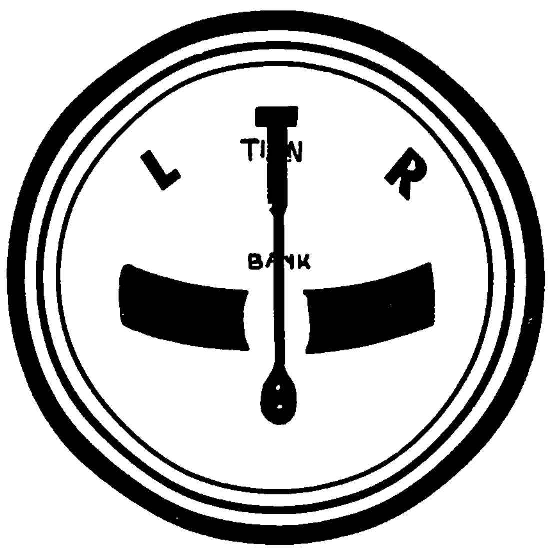

Figure 47. The Turn and Bank Indicator.

The *turn and bank indicator* is a true flight instrument. It is the pilot's chief tool in evaluating his execution of a turn. Figure 47 will show you why it's most 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 his turn is properly *coordinated*, which simply means if he has sufficient bank for the rate of turn. 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, he can be sure that the angle of bank is correct for the amount of turn his aircraft is making.

The *rate of climb indicator* tells the pilot at what rate (in feet per minute) he is gaining or losing altitude. 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

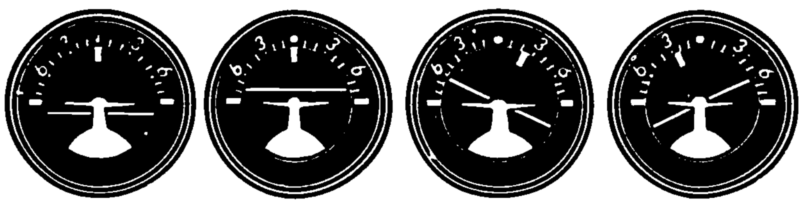

Figure 48. The Artificial Horizon in Flight.

distinction between rate of climb and angle of climb: this instrument registers rate of climb or descent, regardless of the attitude of the aircraft.

The *artificial horizon* is a gyroscopic instrument which shows the pilot of an aircraft his relationship to the true horizon. Take a look at Figure 48. The miniature aircraft fastened to the center of the instrument moves with the aircraft. The horizon line in the background 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 flying 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.

REVIEW QUESTIONS

1. How are aircraft instruments classified? Discuss both systems of classification.

2. What are the basic aircraft engine instruments? What do they tell the pilot about the operation of the aircraft's engine?

3. How can you distinguish between navigation instruments and flight instruments?

4. What do the primary flight instruments tell the pilot about his aircraft?

THINGS TO DO

The best thing to do for this chapter is to examine the instrument panel of an aircraft. A pilot can explain to you which instruments he uses for which purposes. He can also show you how the instruments are arranged and explain to you why they are arranged as they are. Your instructor may be able to get a mock-up of an instrument panel for you to look at in the classroom.

SUGGESTIONS FOR FURTHER READING

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Summary

WE HOPE that you now know more about this complicated business of aircraft and flight. We've discussed the principles behind the operation of aircraft, and we've presented the application of these principles in our discussions of the various sections and aspects of the aircraft and its flight. We don't expect you to be able to fly an aircraft, nor do we expect you to understand *all* that goes into successful and safe flight today. We do feel, though, that now you'll have a better understanding of how and why aircraft fly.

Glossary

A

acceleration—the change in velocity per unit of time

airfoil—generally, any part of an aircraft which is designed to produce lift

angle of attack—the angle between the chord of an airfoil and the relative wind

angle of incidence—the angle at which the wing is fixed to the aircraft's fuselage

aspect ratio—the ratio between the square of the span of an airfoil and its area

attitude—the position of an aircraft (or an airfoil) with respect to a horizon

axes of rotation—three fixed lines of references, each of which passes through the center of gravity of an aircraft and is perpendicular to the other two

B

Bernuulli's Principle—as the velocity of a fluid increases, its pressure decreases; also called Bernoulli's Law of Pressure Differential

burble point—the point at which lift begins to decrease; sometimes called angle of maximum lift

burbling—the forming of violent eddies by the stream of air moving over and under an airfoil

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 aircraft is assumed to be concentrated

centrifugal force—a force which tends to move an aircraft away from the center of the curve which 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

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

D

density—mass per unit volume

dihedral—the angle produced when the outer ends of the wings of an aircraft are higher than the inner ends

downwash—the slight downward movement given to the relative wind when it passes over an airfoil

drag—the force of an aircraft which tends to retard its progress through the air; the opposite of thrust

E

empennage—the tail assembly of an aircraft

F

fairing—an auxiliary structure added to an aircraft component in order to give it a streamlined shape

flap—a movable section of the trailing edge of an airfoil designed to control airflow

force—power or energy exerted against a material body in a given direction

L

Leading edge—that portion of an airfoil which meets the relative air first

lift—the force of an aircraft which acts perpendicular to the relative wind in an upward direction; the opposite of weight

M

mass—the quantity of matter in a body

N

nacelle—a streamlined container for sheltering or housing an aircraft component

P

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

planform—the shape of an aircraft wing as seen from directly above or directly below

pressure—the force exerted by a fluid, measured in force per unit area

R

relative wind—the wind moving past an airfoil, the direction of which is relative to the position of the airfoil

roll—rotation about the longitudianal axis of an aircraft

S

slipstream—the stream of air driven rearward by an aircraft's propulsion system

slot—a movable or fixed section of the leading edge of an airfoil designed to help control airflow

slug—the unit of mass

stability—a state of force in which all the forces acting on a body are in balance with one another

span—the distance from wing tip to wing tip of an aircraft

stall—the position of an aircraft or an airfoil in which it no longer generates lift

T

thrust—the force on an aircraft which gives it forward motion; the opposite of drag

trailing edge—that portion of an airfoil at which the airflow over the upper surface joins the airflow over the lower surface

velocity—rate of motion in a given direction

Venturi tube—a tube with a constricted central portion

W

weight—a measure of the pull of gravity on an object; the opposite of lift

Y

yaw—rotation about the vertical axis of an aircraft

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