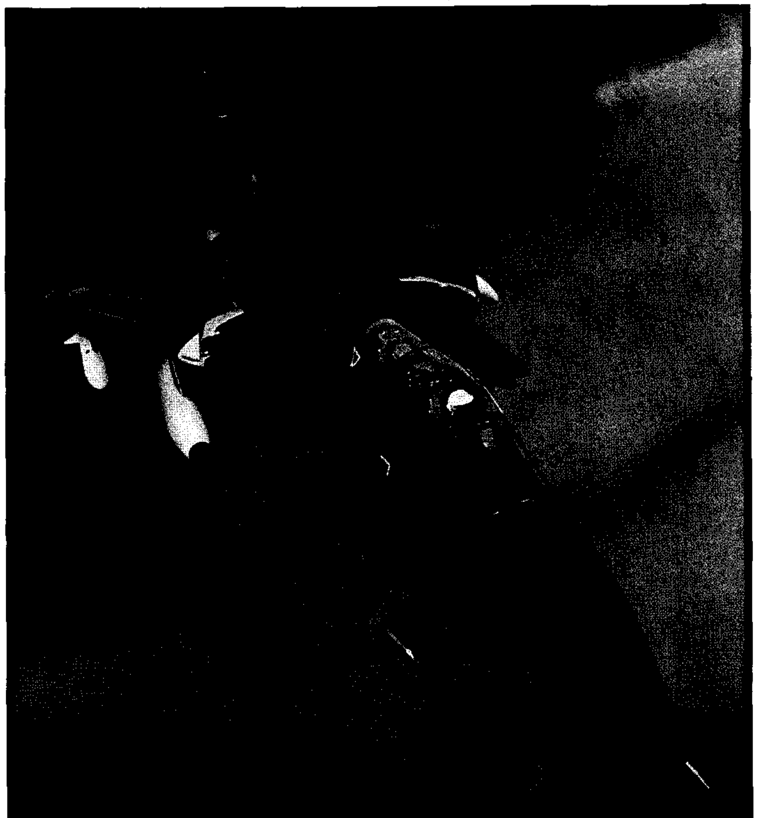
FLIGHT WITHOUT FORMULAE

A C KERMODE



FIFTH EDITION

UPDATED BY BILL GUNSTON

geosynchronous 24-hr orbit (actually at 22,300 miles) is 6,876 mph.

1988

Bill **Gunston**

CONTENTS

In order to preserve continuity of the argument, the usual method of dividing a book into chapters, each covering a different aspect of the subject, has been avoided. For reference purposes, however, the main sections have been given headings, and they are also numbered. A complete list of section headings is given below. In the index at the end of the book the references are to page numbers.

FLIGHT WITHOUT FORMULAE

1. The Argument

I am going to try to explain how an aeroplane flies, This does not mean that I am going to teach you how to fly an aeroplane-that is a very different matter. Many people who can explain how an aeroplane flies cannot fly one. Still more can fly an aeroplane, but do not know how it flies. A few people can do both.

Now, if you ask brainy people to explain to you how an aeroplane flies, they will tell you that it is all very complicated. If you persist in your search for knowledge they will instruct you by means of formulae, Greek letters, and various kinds of mathematics. When you are thoroughly fogged, they will shake their heads sadly and tell you that your knowledge of mathematics is insufficient to tackle the rather advanced problems involved in the flight of an aeroplane.

Mind you, there is some truth in what they say. If you wish to be an aeronautical professor, or a designer of aeroplanes, you must, sooner or later, acquire a fair knowledge of mathematics. But I take it that you have not got any such ambitions, at any rate for the present, and that you will be content with a simple explanation of the main principles on which the flight of an aeroplane depends.

That is all I am going to give you; and that is why I have called this book *Flight Without Formulae.*

2. What is an Aeroplane?

If you look up the definition of an aeroplane in a glossary, you will find that it is described in some such terms as these:

"A heavier-than-air flying machine, supported by aerofoils, designed to obtain, when driven through the air at an angle inclined to the direction of motion, a reaction from the air approximately at right angles to their surfaces."

There's a mouthful for you! When you have finished reading this book, you may care to look at this definition again. If you do so, you will find that it is perfectly sound and is a rather clever attempt to put a large amount of information into a few words. That is the object of a definition, and that is why a glossary makes rather dull reading in spite of the care which has often been exercised to ensure that conciseness should not lead to misunderstanding.

Many aeronautical books either begin or end with a glossary; but I prefer to explain any terms which may be necessary as and when we come across them. Even when explanation is necessary, the use of a hackneyed definition will be avoided because I want you to understand the term rather than learn to repeat, like a parrot, a string of technical words.

What, then, is an aeroplane ?

All man-made contrivances which fly, that is to say which are kept in the air by forces produced by the air, are called ***aircraft.***

There are two main kinds of aircraft: those which are ***lighter than air*** and those which are ***heavier than air.*** The former include ***airships, balloons,*** and ***captive*** or ***kite balloons;*** these are supported in the air not, as is commonly supposed, by the gas inside them, but rather by the air which this gas displaces. It is not the purpose of this book to deal with this type of aircraft, but a brief summary of the principles of their flight will be given. The latter, or heavier-than-air type, consists of many different forms which can conveniently be grouped under two headings, ***power-driven*** and ***non-power-driven-to*** which we should perhaps add a third, the very interesting ***man-power-driven*** (one of the problems of flight

that is still only on the threshold of being solved). The non-power-driven forms are ***gliders, sail planes*** and ***kites.***

The distinction between a glider and a sailplane is a subtle one, the latter being a lighter type which is able to "soar" in up-currents of wind. Every boy knows what a kite is, so I will not trouble to explain it. It might be imagined that, in these days, every boy knows what an aeroplane is, but unfortunately there has been much confusion over the terms used for heavier-than-air power-driven aircraft.

In an attempt to minimize the confusion, the British Standard Glossary of Aeronautical Terms divides them into three types—***aeroplanes, rotorcraft*** and ***ornithopters.*** The term ***aeroplane*** includes aircraft which fly off the land and those which fly off the water, and, of course, ***amphibians,*** which can fly off either. This means that a ***seaplane*** is merely a particular type of aeroplane so designed as to be able to fly off and on to water, and therefore, to distinguish them, aeroplanes which can only fly from land are classified as ***land planes.*** Seaplanes themselves may be divided into two types, ***float planes*** and ***flying boats.***

It will be noticed that ***helicopters,*** and other types of rotary-wing aircraft-the distinction between the three types will be explained later—are, strictly speaking, not aeroplanes at all; nor is the flapping-wing ornithopter, though that won't worry us very much. Whether ***hovercraft*** are a form of aircraft is still disputable.

Fig. 1 and the photographs at the end of the book should help to make the various terms clear. Fig. 2 shows the names of some of the main parts of a land plane; if you are not already familiar with them have a look at them now, they will help you to understand the rest of the text.

3. Lighter than Air

In the last section I promised to say a little more about aircraft which are lighter than air.

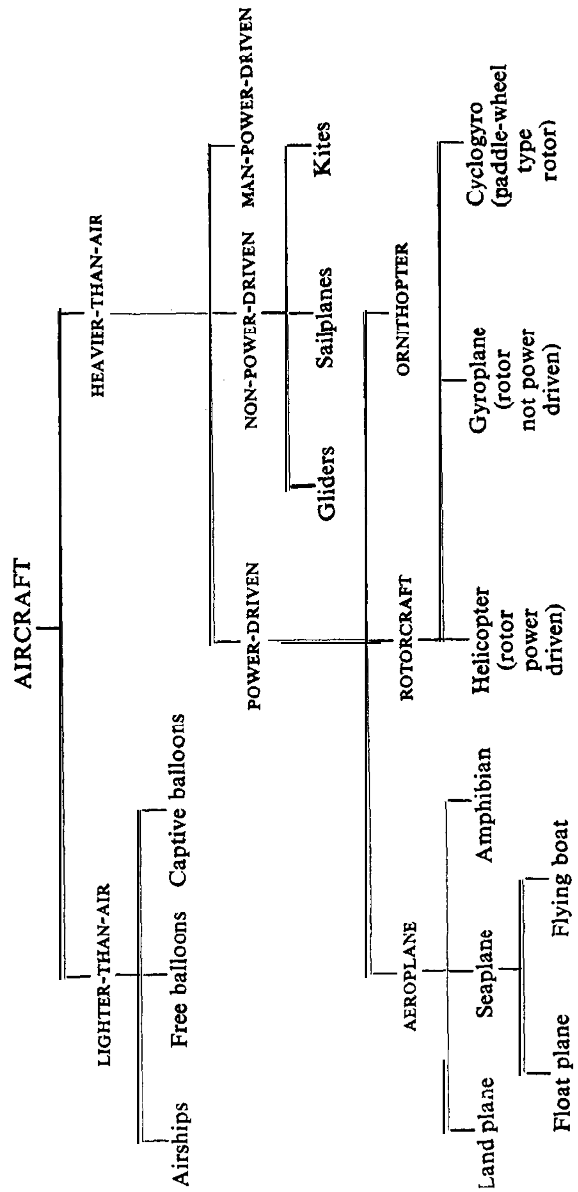


Fig. 1. **Types of aircraft**

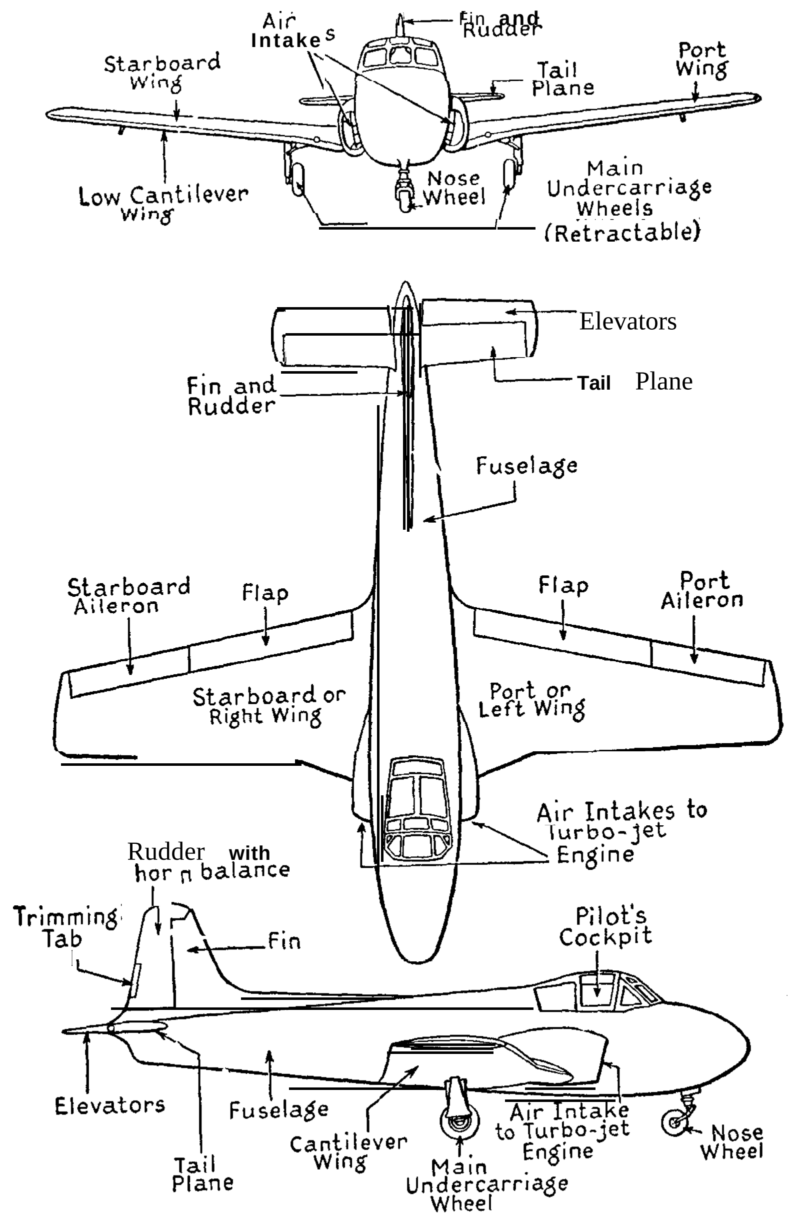


Fig. 2. **Parts of an aeroplane**

These depend for their lift on a well-known scientific fact usually called ***Archimedes' principle.*** When a body is immersed in a fluid, a force acts upwards upon it, helping to support its weight, and this upward force is equal to the weight of the fluid which is displaced by the body (Fig. 3). A fluid, of course, may be either a liquid, such as water, or a gas, like air. Thus a ship (or a flying boat when on the water) floats because

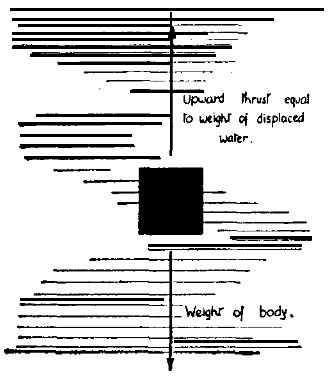


***Fig.* 3. Principle of Archimedes**

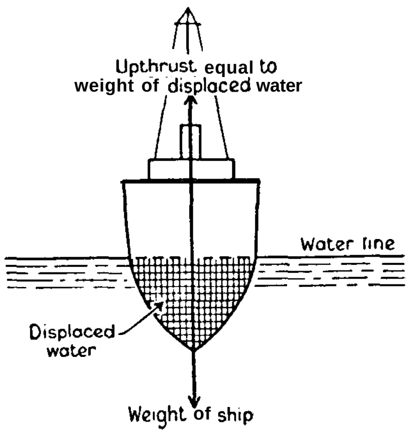


***Fig.* 4. Archimedes' principle applied to a ship**

the water which it displaces is equal to the weight of the ship itself (Fig. 4). The same ship will float higher out of the water when in sea water than in fresh water. This is because sea water is heavier, and therefore a smaller quantity needs to be displaced in order to support the weight of the ship. Only a small portion of a ship is immersed in the water, yet the same principle is true of bodies which are totally immersed and which may even be incapable of floating at all. For instance, if a lump of lead or other metal is weighed in water, it is found to weigh less than when weighed in air, and this apparent difference in weight is exactly equal to the weight of water which is

displaced by the metal, thus proving that there is an upward thrust equal to the weight of displaced water.

An airship (or blimp), balloon, or kite balloon obtains its lift in precisely the same way. The envelope of the airship displaces the air, and therefore there is an upward force on the airship which is equal to the weight of the displaced air (Fig. 5). If this upward force is equal to the weight of the airship, it will

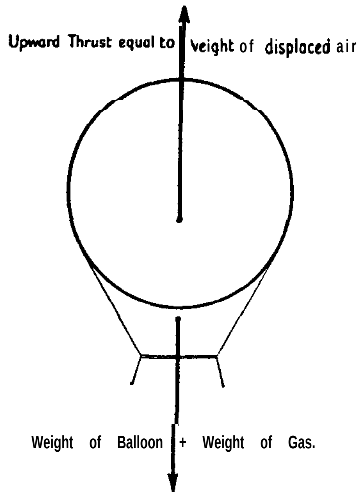


***Fig.* 5. Archimedes' principle applied to a balloon**

float; if the upward force is greater than the weight, the airship will rise; if it is less, it will fall. A cubic foot of air weighs only about 0·08 lb (roughly $1\frac{1}{3}$ oz), and therefore that is the greatest weight which one cubic foot can support. So you will soon see why it is necessary for the envelope of an airship to be so large and why the weight must be kept as small as possible. The R 100 and R 101, the last two airships to be built in Great Britain, had each a capacity of over five million cubic feet.

In order to keep the weight of the airship itself as small as possible it must in the first place be made of the lightest materials available, provided of course they are of **sufficient** strength. Secondly, a very light gas must be used in the envelope. Theoretically, the best thing which could be used in the envelope would be nothing, i.e. a vacuum; but in practice this cannot be done, because the pressure of the air outside

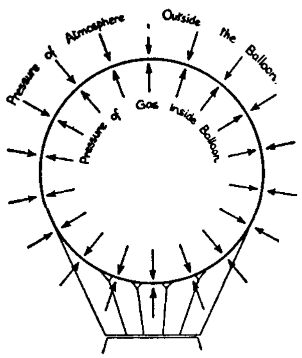


Fig. **6. Pressure inside and outside a balloon or airship**

the envelope would be so great that the sides would cave in unless the skin of the envelope could be made tremendously strong, in which case it would weigh so much that no advantage would be gained. However, even the lightest gases can exert a pressure from the inside which will balance the pressure of the atmosphere from the outside (Fig. 6), and this means that the skin of the envelope need have very little strength, and therefore very little weight, provided it is gas-proof to prevent leakage in or out. The lightest gas in commercial use is hydrogen, and, for many years, this gas was always used in airships and balloons. Unfortunately, however, hydrogen is very inflammable, and its use added considerably to the dangers of lighter-than-air flying. So the gas helium came to be used, in spite of the fact that it is much more expensive and twice as heavy as hydrogen.

Hydrogen weighs about 0·0055 lb/cu ft and helium about 0.011 lb/cu ft, and in each case, of course, the weight of the

gas tends to subtract from the lifting power of the displaced air. Thus, if an airship is filled with hydrogen, each cubic foot of envelope will support 0.0800 lb less 0·0055 lb, i.e. 0·0745 lb; but if filled with helium a cubic foot will only support 0·0800 lb less 0.0110 lb, or 0·0690 lb. If we multiply each of these by 5,000,000, they represent about 166 tons and 154 tons respectively. Thus the use of helium instead of hydrogen in an airship of this capacity will mean a loss of net lift of as much as 12 tons, and when it is remembered that the structure and engines of the airship itself will weigh over 100 tons, it will soon be realized that this loss of 12 tons is a very considerable proportion of the ***useful*** lift of the airship. However, so great was the fear of fire in airships, that the extra safety provided was held to justify the use of helium in spite of this consequent loss of lift.

We have said that a cubic foot of air weighs about 0·08 lb. Now, this is only true of the air near the earth's surface. As we ascend, the air becomes very much thinner and therefore a cubic foot will weigh less, and each cubic foot will consequently support less. So, if an airship is just able to float near the earth's surface, it will be unable to do so at a greater altitude, because the weight of displaced air will not be sufficient to support it. It is for this reason that ballast is carried; this can be thrown overboard to lighten the ship when it is required to climb. This is all very well while the climb is in progress, but what is to happen when we wish to descend? There is no means of taking on board extra weight, and therefore the only thing to do is to release some of the gas and allow air to take its place, thus decreasing the weight of air displaced, reducing the lift and allowing the ship to sink. It will be obvious that these processes cannot go on indefinitely, as neither the ballast nor the gas can be replaced until the airship returns to its base.

Another problem is that, owing to changes in the pressure of the air outside the balloon or airship, it is not easy to equalize the pressures inside and outside the envelope at all heights unless the volume of the envelope can change. Thus it is that a toy balloon, filled with hydrogen at a reasonable pressure at ground level, expands as it rises and eventually

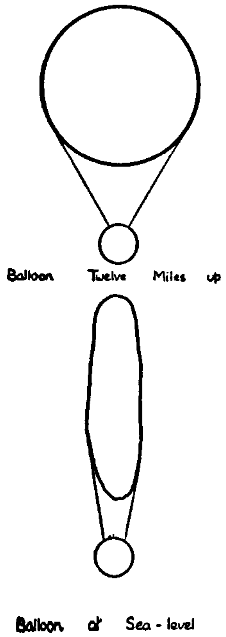


Fig. 7. **Stratosphere balloon**

bursts. To prevent such an occurrence with a real balloon it is only partially filled at ground level and presents the appearance shown in Fig. 7.

4. Lighter than Air-More Problems

These are some of the problems of lighter-than-air flight, but they are by no means **the only ones. In order that an airship may carry a reasonable proportion of useful load it must be**

very large; the large ship means expense, difficulties of housing and manipulation on the ground, large head resistance, and very considerable structural design problems. All these difficulties, together with that of the fire risk, were courageously **tackled** in various countries, but repeated failure caused such losses in men and material in the period between the wars that in Great Britain, at any rate, we felt compelled to stop any further experiments on this type of aircraft. The wisdom of this policy was much disputed, but the fact remains.

Until the outbreak of the Second World War, experimental work on airships was still being carried out in Germany and the United States; in the latter country the metal-clad airship had been proved to be a practical proposition.

The war itself retarded rather than advanced experimental work on the subject, and the steady improvement which has taken place in aircraft of the heavier-than-air type is certainly likely to decrease the chances of a revival of interest in airships. But one can never be sure-as recently as 1958 a new non-rigid airship of about one and a half million cubic feet capacity was launched in the United States, and the Germans have never completely lost their faith in this means of transport.

Of the other lighter-than-air types the free balloon may now be considered as obsolete except for scientific purposes such as the exploration of the highest regions of the atmosphere. There are also a few enthusiasts who still take part in ballooning as a sport.

The captive or kite balloon was extensively used during the 1914-18 war as a means of observation for gunfire. After that war its chief use seemed to be to provide spectators at the Royal Air Force Displays with the never-failing attraction of seeing it brought down in flames. In the Second World War the captive balloon again played its part; this time as a means of protecting important towns and ships at sea from attacks by enemy aircraft; or, rather, to force raiding aircraft up to such a height that accurate bombing was rendered diffkult. And although such balloons can have only a very limited use, either now or in the future, they still exist in reasonable numbers — which is more than can be said for the free balloon or airship.

5. The Atmosphere

But we cannot get much farther in understanding the problems of flight without considering in more detail the properties of the atmosphere on which it depends. The atmosphere is that very small portion of the universe which surrounds the surface of tbe earth with a belt of air-and it is only in this atmosphere that flying, as we have defined it in Section 2, is possible. The internal-combustion engine, whether piston or turbine, needs air in order to obtain its power; the lift of the aircraft, whether

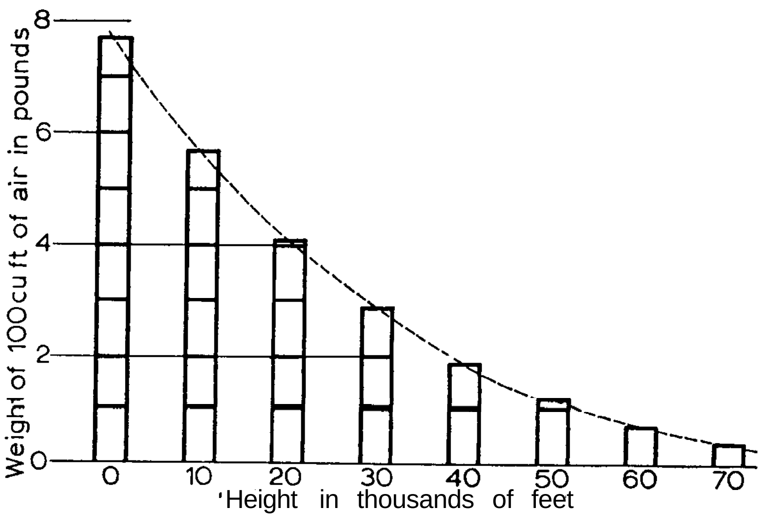


Fig. 8. **How density falls with height**

lighter or heavier than air, the controls, the stability, all depend on the air and the forces which it produces.

The most important property of the atmosphere, so far as flying is concerned, is its density. The way in which this falls off with height (Fig. 8) has already been mentioned in connection with lighter-than-air flight, but it is just as important

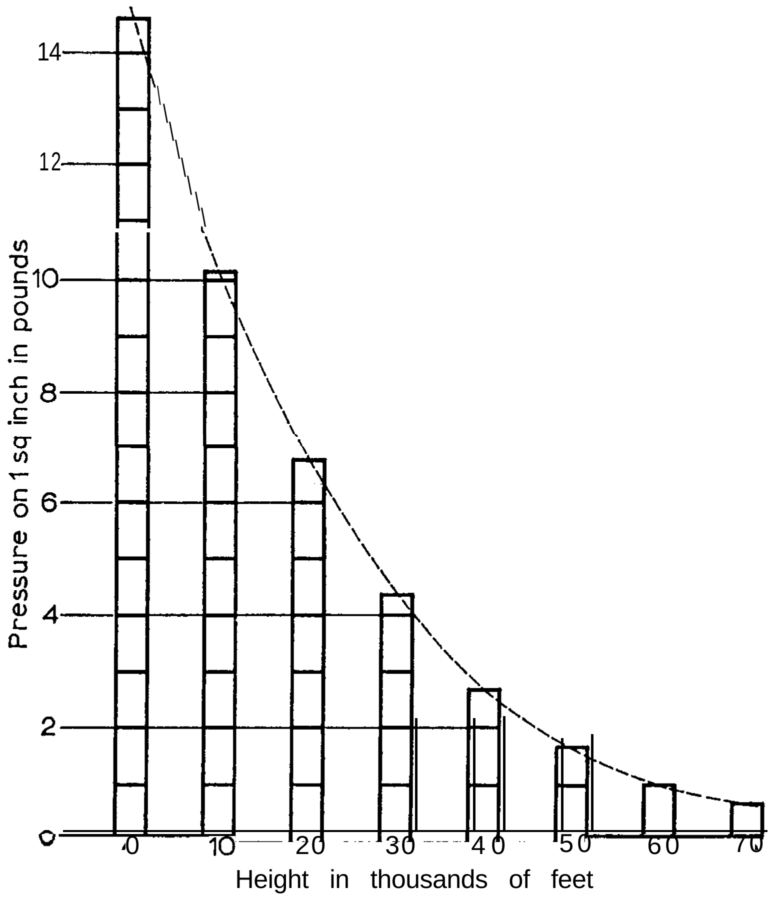


Fig. 9. **How pressure falls with height**

Although the curves of Figs. 8 and 9 look similar, they are not exactly the same: pressure falls off more rapidly than density

for heavier-than-air flight, and is clearly shown in the diagram; notice that whereas 100 cu ft of air weigh 8 lb at sea level, they weigh only 4 lb at 20,000 ft and less than ¾ lb at 60,000 ft.

Notice how the ***pressure*** also decreases with height (Fig. 9) —in fact, this is really the cause of the decrease in density,

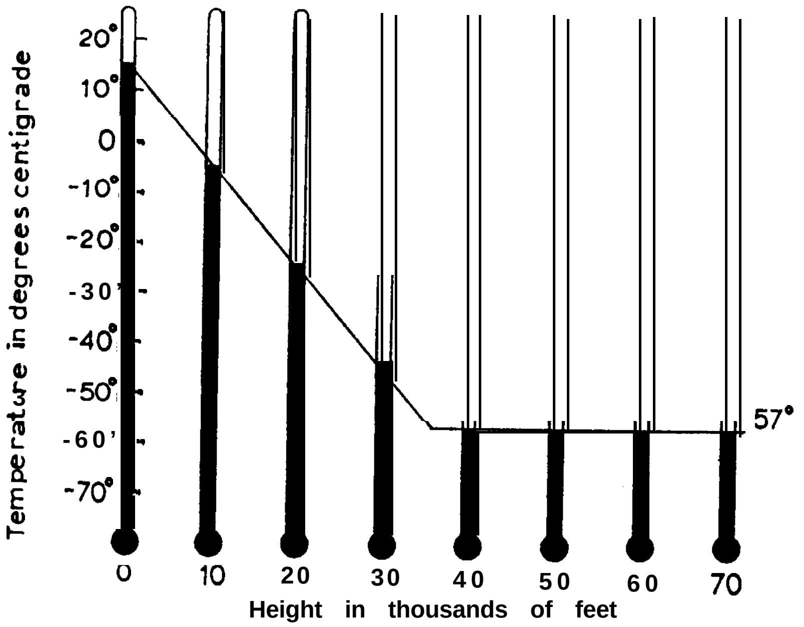


Fig. 10. **Change of temperature with height**

the air near the earth's surface being compressed by the weight of all the air above it, nearly 15 lb on every square inch at sea-level. As the pressure is released to 7 lb on each square inch at 20,000 ft and only 1 lb on a square inch at 60,000 ft, the air is able to expand and the density decreases.

The ***temperature*** also falls off, but in a rather curious way (Fig. 10). Up to about 36,000 ft above the earth's surface the

fall is quite regular (about 2°C, or 3°F, per thousand feet), then the fall suddenly ceases, and for greater heights the temperature remains fairly constant at about -57°C. At that temperature, however, there is not much consolation in knowing that it will not get any colder. This sudden check in the fall of temperature has resulted in the lower part of the atmosphere (that part with which we are most concerned in this book) being divided into two layers (Fig. 11), the one nearer the earth, in which the temperature is falling, being called the ***troposphere,*** the higher one, in which the temperature is constant, the ***stratosphere.*** The surface dividing the two is called the ***tropopause.***

But perhaps the most aggravating feature of the atmosphere is its changeability-it is never the same from day to day, from hour to hour. For this reason we have been forced to adopt an average set of conditions (as shown in Fig. 11) called the ***International Standard Atmosphere.*** Although there may never be a day when the conditions of the atmosphere all the way up are exactly the same as those average conditions, they do serve as a standard for comparing the performances of aircraft. For instance, when a height record is attempted, the height allowed is not the height actually achieved but the height which, according to calculation, ***would have been achieved if the conditions had been those of the International Standard Atmosphere.*** So it is no good choosing a lucky day!

It is not easy to say how far the atmosphere actually extends, for the simple reason that the change from atmosphere to space is so gradual that it is impossible to decide on a definite dividing line; for this reason it is hardly surprising to find that estimates of the maximum height vary from 50 to 250 miles or more-rather a wide range. So far as aircraft are concerned, the higher we get, the more difficult does it become to go any higher. At record-breaking heights we already have to pump air into the engine, enclose the pilot in an air-tight suit, supply

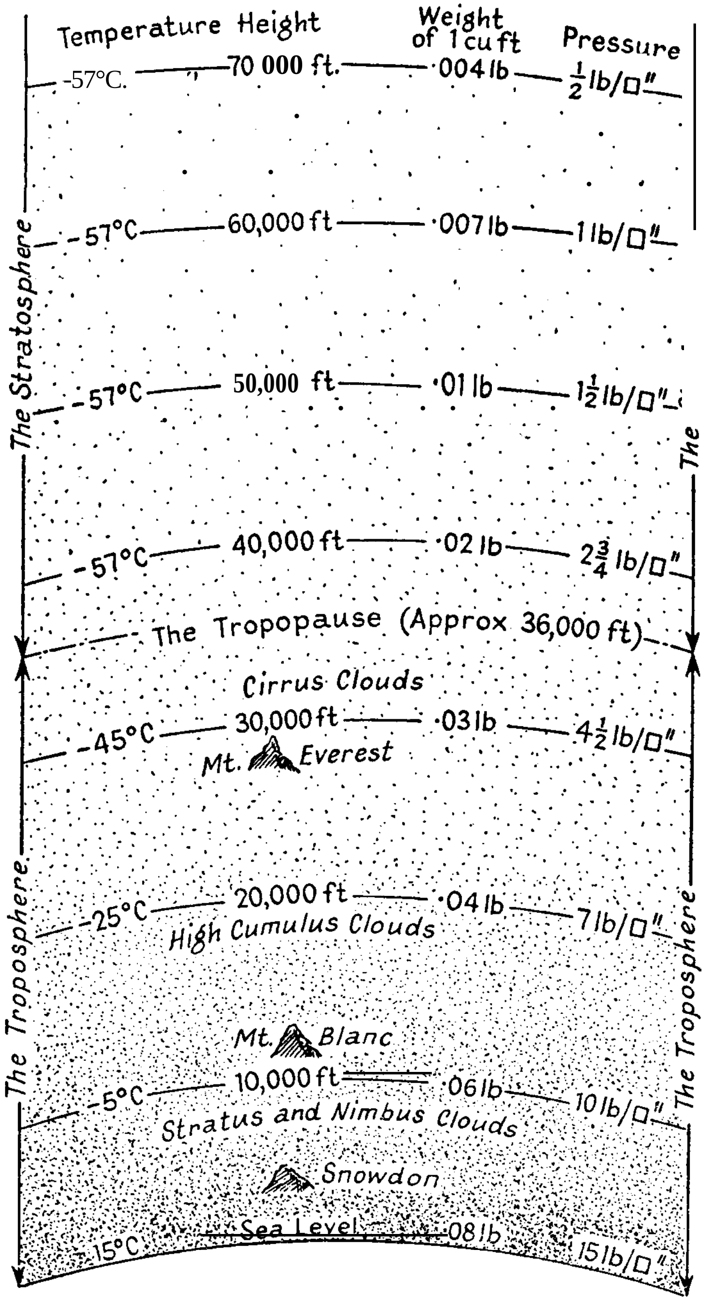


Fig. **II. The International Standard Atmosphere**

(See footnote opposite)

him with oxygen, and heat his clothing artificially, while the aircraft itself can hardly get sufficient support in air that has not got one-quarter the thickness of the air near the ground.

Nor is it surprising that estimates of temperatures in even higher regions of the atmosphere vary very considerably—between temperatures both above and below anything known on earth-when the air is so thin it isn't the temperature of the air that matters so much as the temperatures of the outer surfaces of the aircraft.

But in these days of ***missiles, satellites,*** and ***spaceships, we*** have become very interested, not only in the upper reaches of the atmosphere, but in the space beyond it. These may not be aircraft (as we have defined the term), and although they may not even fly (according to our definition), no book on flight, with or without formulae, can any longer leave them out of consideration; we shall have more to say about them towards the end of the book.

6. Lift and Drag

But, for the present, let us return to earth and turn our attention to real aircraft, and more particularly to the aeroplane in its various forms.

In order that an aeroplane may fly, we must provide it with a lifting force at least equal to its weight. In that respect there is no difference between the aeroplane and the airship; it is in the method by which the lift is provided that the difference lies.

Take a piece of stiff cardboard (Fig. 12) and push it through the air in such a way that it is inclined at a small angle to the direction in which you push it, the front (or ***leading edge)*** being slightly above the rear (or ***trailing edge).*** You will find that

The figures given in Fig. 11 are only approximate, but they are sufficiently accurate to give a good idea of the changes in the atmosphere with height.

the result of pushing the cardboard through the air is to produce on it a force which tries to push it upwards and backwards. The upward part of this force we call ***lift***, the backward part we call ***drag*** (Fig. 13).

It is quite likely that the upward force will be sufficient to lift the cardboard, which will thus be supported in the air. That

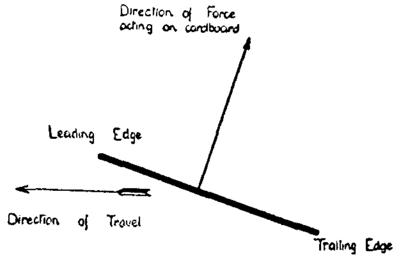


Fig. **12. Principles of heavier-than-air flight**

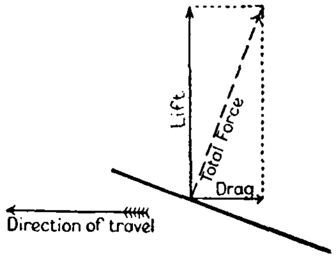


Fig. **13. Meaning of lift and drag**

is how an aeroplane flies. So simple, isn't it? Yes-the cardboard is, in fact, acting just like the wings of an aeroplane.

What will happen if we release the cardboard? Try it for yourself, and you will soon see. It may continue its flight for a short distance-in fact, it may actually rise as it leaves your hand-but very soon it will cease to move forward, it will probably turn over, its leading edge going over the top, and then flutter to the ground. This shows that in order to obtain lift we must constantly push the cardboard forward, and in

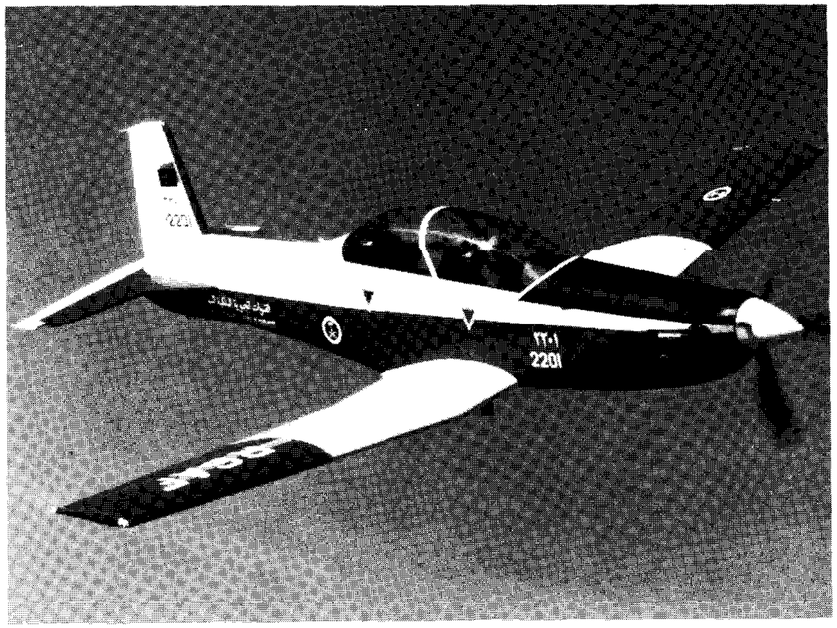


Plate 1. The Pilatus PC-9 typifies the new breed of fuel-efficient turboprop trainers being used to replace expensive jets in the world's air forces. The staggered cockpits give the instructor in the rear a good view. Modern ejection seats and fighter-type instruments are fitted.

Plate 2. The Swedish Saab 340 is one of the most popular of the 30/40-seat twin-turboprop regional airliners. Thanks to highly efficient engines and Dowty Rotol composite-blade propellers such aircraft are quieter than 1950s turboprops or jets and burn much less fuel per passenger seat. Note the black pulsating-rubber deicers on the leading edges.

the real aeroplane this is provided for by the thrust. How thrust is obtained is explained in a companion book in this series, ***Thrust for Flight.***

7. Air Speed and Ground Speed

In the last section we suggested that you should push the cardboard through the air. If you happen to try this simple experiment out of doors and if a wind is blowing, it will only be necessary to hold the cardboard ***still*** in a similar position, i.e. with its higher edge facing the wind. You will again feel the upward force, or lift, and the backward force, or drag, and if you release the cardboard it will behave very much as before. This is because it really amounts to the same thing whether the cardboard is pushed through the still air, or whether a stream of moving air moves past the cardboard. ***The speed at which a body moves through the air, or at which the air moves past a body, is called the air speed. The speed at which a body moves over the ground is called the ground speed.*** In our first experiment there was both a ground speed and an air speed, but in the second experiment there was an air speed but no ground speed, because the cardboard was held still relative to the ground.

We are so accustomed to thinking of speed and directions of movement ***in relation to the ground*** that it is very easy to forget that flying takes place in the air, and it is only movement ***relative to the air*** which matters when we are studying the flight of an aeroplane. I say "when we are studying the flight of an aeroplane," and you must understand clearly that this means when we are studying the principles and methods of flight; it is fairly obvious that if we wish to fly from London to Moscow it will make a considerable difference to the time taken whether the wind is with us or against us. In other words, the ground speed will matter very much when reckoning the time taken to fly between the two capitals, but the air speed, and therefore the lift and the drag, will be the same in both instances. An aeroplane is always travelling ***against*** a head wind. Thinking of it from a position on the ground, we may say that there is a following wind or a side wind, we may say that an aeroplane is flying "up wind" or "down wind"; but to the airman there is only a head wind. Anyone who has had experience of flying just above the clouds will have had convincing proof of this; he will have noticed how the clouds always seem to come to the aeroplane from the front, even though there may be a side wind or a following wind.

Once you understand it, all this will sound very simple and obvious, but I have emphasized it because I have found that many do not see daylight until the point has been pressed home.

Now ask yourself the following questions:

(a) The normal air speed of a certain aeraplane is 80 m.p.h. If it is travelling from west to east with a 100 m.p.h. westerly gale blowing behind it, in what direction will a flag on the aeroplane fly?

(*b*) In what direction will the flag fly if the gale is from the north and the aeroplane is still heading towards the east? (It will, or course, travel crabwise over the earth's surface.)

(c) In what direction will a flag fly in a free balloon which is flying in a steady wind of 30 m.p.h. from the north?

(*d*) An aeroplane has enough fuel to fly for 4 hours at 100 m.p.h. If there is no wind, how far can it fly out from base and get home again; that is to say what is its radius of action?

(e) Will the aeroplane of question (*d*) have the same radius of action if there is a steady wind of 20 m.p.h.?

(*f*) You are asked to handicap aeroplanes of different speeds for a race in which they will be required to fly from A to B and back from B to A. Will the speed of the wind at the time make any difference to your handicapping ?

If the answers to the questions are: (a) Directly backwards; (b) Directly backwards ; (c) Downwards (will not fly at all) ; (*d*) 200 miles; (e) No; (*f*) Yes-then all is well, and I apologize for all the fuss. But if, as I suspect, they may be somewhat

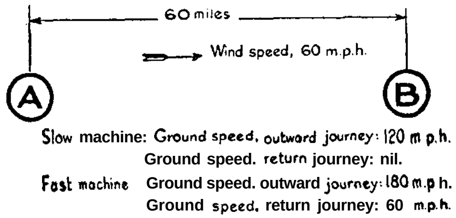


Fig. 14 **Air speed and ground speed**

different, then think again and you will soon begin to see through it all. If (e) and (*f*) puzzle you, and you reckon that what you lose when the wind is against you, you gain when it is behind you, then take some figures for (*f*). Imagine two aeroplanes of ***air speeds*** 120 m.p.h. and 60 m.p.h. Suppose the distance from A to B is 60 miles (Fig. 14) and the wind is blowing at 60 m.p.h. in the direction AB. Start off your slower machine first-it will fly from A to B at a ground speed of 120 m.p.h., reaching B in half an hour, then it will turn round and . . .? Start your faster machine an hour later, a week later-it does not matter, it will still win. But if there had been no wind and you had given your slow machine anything over an hour's start, it would have won. The conditions quoted may be ***unlikely,*** but they are not impossible, and in any case they serve to show the principle that handicapping of air races depends on the wind. Another simple fact, but one that has often been forgotten-even by handicappers!

Much the same kind of argument applies to question (e), even though the wind speed is only 20 m.p.h. Work it out for yourself assuming that the wind comes from, say, the north and that you decide to fly against the wind first, and have the advantage of it coming back. You will find that you only have enough fuel to fly 192 miles and get back. The answer will be just the same if you start by flying south. If you decide to fly east or west the calculation is rather more difficult, but the point is that in whatever direction you fly the radius of of action will be less than 200 miles.

8. Direction Relative to the Air and Relative to the Ground

The examples show that we must be careful to distinguish, not only between air speed and ground speed, but between the *direction* of travel of an aeroplane relative to the air and relative

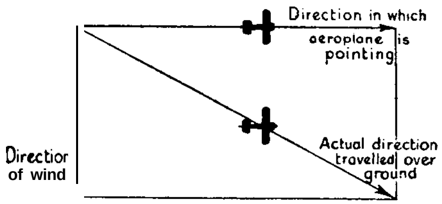


***Fig. 15.* Effect of wind**

to the ground. In the example (b) given above, the aeroplane, although *pointing* towards the east, will actually *travel* in a south-easterly direction (Fig. 15); this is the main difficulty of aerial navigation, a subject which all pilots must learn. But there is yet another aspect of this air direction and ground direction when we consider the climbing or gliding of an aeroplane; an aeroplane which climbs or glides against a head will *appear* to climb or glide more steeply when viewed from the earth, although *relative to the air* the path of climb or glide

will be the same as in a calm or a following wind. This fact is of tremendous practical importance in flying, as the illustration will clearly indicate (Fig. 16). The difference between air direction and ground direction is even more noticable when the wind is ascending, as on the slope of a hill or beneath a cloud; thus it is that a sailplane may "climb" (relative to the earth) and even move "backwards" (relative to the earth),

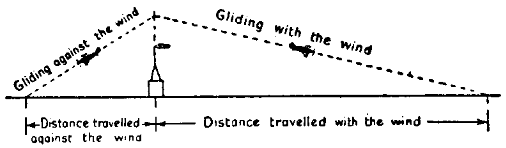


***Fig. 16.* Effect of wind on angle of glide relative to the earth**

whereas it is really all the time gliding downwards and forwards (relative to the air).

Now, after all that, you must always try to think *relative to the air* when you are studying the theory of flight; but if you are a pilot, or ever become one, you will be well advised not to forget the importance of your movement *relative to the ground*, especially when you wish to make contact with it after a flight!

9. Wind Tunnels

We began our study of how an aeroplane flies by means of a practical experiment, even if it was only with a piece of cardboard. We need not feel ashamed of ourselves for beginning in this way, for we are only following in the footsteps of great men. The Wright brothers, the pioneers of power-driven flight, were compelled, rather reluctantly, to resort to such experiments before they were able to build an aeroplane that would fly. Even at the present day, when our knowledge of

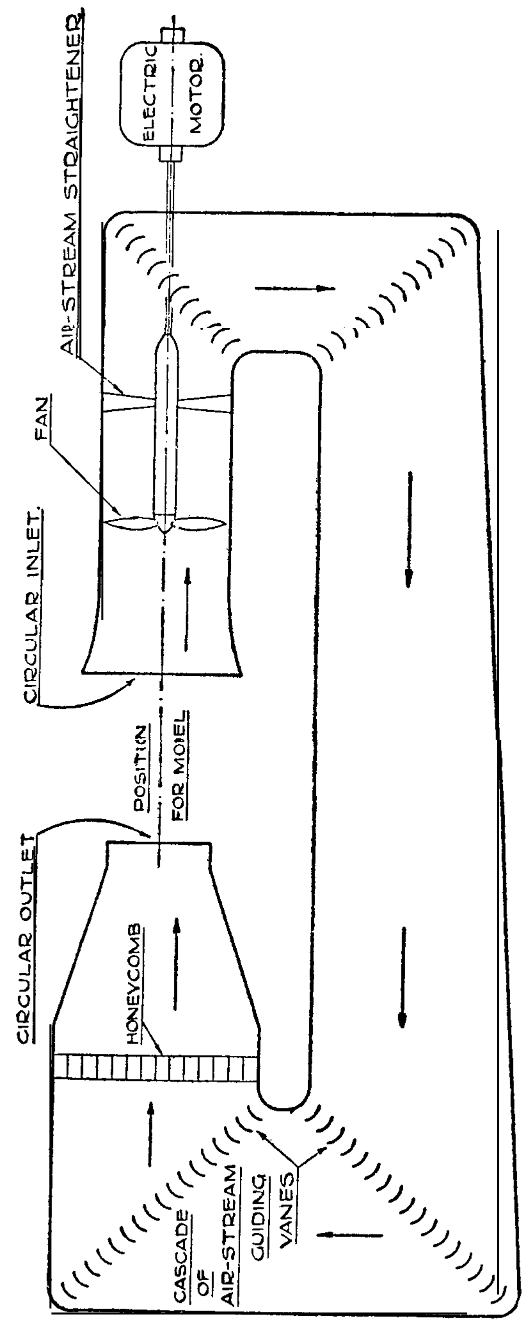


Fig. 17. **A wind tunnel**

the theory of flight has advanced so much, the greatest designers hesitate to use any new device until it has been tried out on a model.

The most common method of experiment is to use a wind tunnel (Fig. 17), in which the model is supported while the air flows past it, the air being sucked through the tunnel by a fan driven by an electric motor. As we have already noticed,

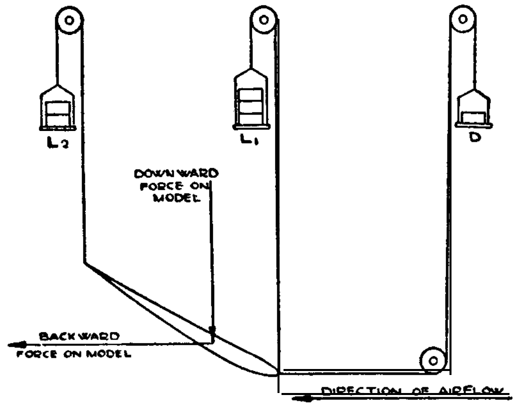


***Fig.* 18. Principle of a wind-tunnel balance**

The weights L_1 and L_2 together measure the total downward force or lift; the weight D measures the backward force, or drag.

it is the relative air velocity which matters, so that for most purposes the air flowing past the stationary model will produce the same results as the model moving through the air. The forces on the model are measured by means of a balance, similar to an ordinary weighing machine, to which the model is attached by fine wires or thin rods (Fig. 18).

The results of wind-tunnel experiments are apt to be misleading for various reasons, the chief one being what is known as ***scale effect***. The object of making experiments on models is to forecast the forces on the full-scale aeroplane when in the air. In order to do this we must know the laws which connect the forces on the model with those experienced in flight. It is fairly easy to form theoretical laws, and these, which will be mentioned in later paragraphs, are confirmed by experiment so long as there is not much difference between the size of the model and the full-scale aeroplane, or between the velocity of the wind-tunnel test and the velocity of actual flight. When the differences are great, and they often are, the laws seem to break down and our forecasts are found to be untrue. This is what is meant by scale *effect*, and it becomes more serious as the size and velocity of aeroplanes tend to increase. Fortunately we have learned to make corrections to allow for this error, and we are also building larger and larger wind tunnels—so large in fact that real full-size aeroplanes will go in them- but even so we cannot achieve the same air velocity in a tunnel as that of modern flight.

The reader may wonder why the wing is upside-down in Fig. 18. The explanation is quite simple; in this position the downward force caused by the air flow merely adds to the downward force due to the weight so that we only have to measure downward forces. If the wing were the right way up the lift due to the air flow would be upwards and the weight downwards and so we might have to measure forces in both directions.

In connection with scale effect you will hear highbrow people talking about ***Reynolds numbers.*** This is one of the instances where they try to pretend that they are talking about something which is far beyond your understanding. Don't believe it! A high value of the Reynolds number of a certain test is only a fancy way of saying that either the speed or scale of the test approaches full-scale value; the greater the speed, the greater the scale, the higher is the Reynolds number. Owing to the units used in calculating this number the numerical values are high, ranging from 100,000 or so in a test at low speed in a small wind tunnel to 20,000,000 or more for a large

machine in high-speed flight. The term is an old one, dating back to Professor Osborne Reynolds, the famous British physicist of the nineteenth century, who discovered that the flow in water pipes always changed in character when the velocity multiplied by the diameter of the pipe reached a certain value-which came to be called the Reynolds number after him. The highbrows will say that I haven't told you the whole story. Nor have I-but I have told you enough to give you a good idea of what it is all about.

Another difficulty with wind-tunnel experiments is that all the details of a full-scale aircraft cannot be reproduced accurately on the model. Any reader who has made models will understand this difficulty. On an aeroplane there are many small parts, not to mention the roughness of the surfaces, and it is often these very details which are so important. There can be no way out of this difficulty except to make the models as large and as accurate as possible.

This leads us to yet another error. Both the difficulties already mentioned seem to suggest that we should make our models large, but, unfortunately, if the model is large, the tunnel must be much ***larger still,*** since otherwise the air is forced by the walls of the tunnel to flow quite differently from its flow in the free atmosphere. So once again we need large tunnels, and we are only limited by the expense involved and the power necessary to get high air velocity.

Some of our troubles can be overcome by working in compressed air, and there are compressed-air tunnels which can be pumped up to pressures of as much as 25 times that of the atmosphere. This is really an artificial means of increasing the Reynolds number while still keeping speed and scale within reasonable limits. In short, it helps to complete the story which we left unfinished earlier in this section, the truth being that the density (and viscosity) of the fluid also affects the Reynolds number of the test.

One would naturally expect the most valuable experiments to be those made on full-scale aeroplanes in flight. While it is clear that this must be the eventual test, there is much to be said against it-when compared with the wind tunnel-for experimental purposes. Flying with new and untried devices may be dangerous, and it will certainly be expensive. The air is never steady, nor are conditions the same from day to day, and one cannot test separate parts, such as a wing, a strut or a wheel. So, with all its faults, there is something to be said for the wind tunnel after all.

10. Smoke Tunnels

One of our difficulties in experimental work is that we cannot see *the air*, and it is the way in which the air flows that is so important (Fig. 19). If the air were visible, there is no doubt

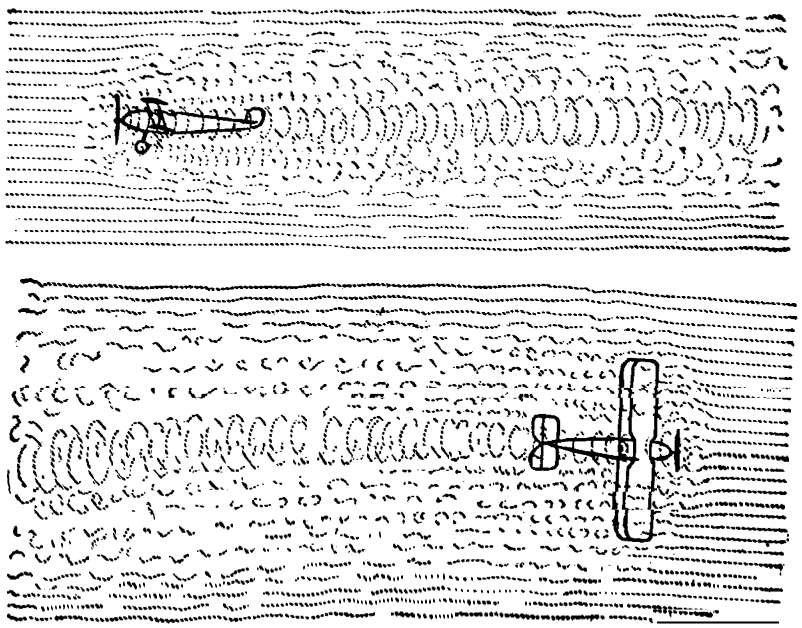


Fig. 19. **Seeing the air**

that many so-called aeronautical discoveries would have been obvious to everyone. For this reason attempts have been made to show the flow of air by introducing jets of smoke, and this is best done by using a small *smoke tunnel* and projecting the results by means of a lantern on to a screen. Very effective demonstrations can be made in this way, but the difficulty is to find a suitable smoke. Most smoke that can be produced in large quantities, and is about the same density as air, is objectionable in some other way. After experiments with complicated and difficult chemicals, the most satisfactory results were eventually obtained with smoke produced by heating paraffin or burning cardboard or rotten wood.

Although the reader may have no chance of seeing experiments in a smoke tunnel, he should always watch dust or leaves being blown about, or tobacco smoke; a lot can be learnt in this way. Very often short streamers, or tufts of wool, are attached to models or aeroplanes, as all these are useful aids towards "seeing the air."

11. Air and Water

Sometimes experiments are done by moving models through water, because, strange as it may seem, water behaves very much like air except that the velocity need not be so high, and this is an advantage from the experimental point of view. To get similar results a body need only move through water at about one-thirteenth of the speed at which it moves through air.

Quite apart from the scientific use of water as a means of aeronautical experiment, it is much more suitable than air for amateur observation. Move your hand through air and nothing *appears* to happen-in fact, *quite* a *lot* does-but move your hand through water and you can not only see the effect but you can feel the resistance to motion. There is no need to give to Archimedes all the credit for making discoveries in his bath; you can do the same yourself and not only can you discover, or rediscover, his principle (on which, as we have said, lighter-than-air flight depends), but you can discover, too, many of the principles of heavier-than-air flight as outlined in this book.

The reader may wonder at the idea of water behaving like air; if he does so, he certainly deserves a word of explanation. Both water and air are fluids; but water is a liquid and air is a gas, and one of the differences between a liquid and a gas is that the former is, for all practical purposes, incompressible, whereas the latter is easily compressed. Is not this question of compressibility important in flight? The answer is, at low speeds, no; at highspeeds, yes. That is all very well, but high speed and low speed are relative terms; where is the dividing line? You may be surprised at the answer. ***Low-speed flight***—that is to say, flight in which the compressibility of the air is not of practical importance—***is flight at speeds less than that at which sound travels in air. High-speed flight***—that is to say, flight in which the compressibility of the air is of importance—***is flight at speeds greater than that at which sound travels in air.*** What is this speed? And why is it so significant? The first of these questions is easy to answer-about 760 m.p.h. or 1,100 ft/set-not exactly dawdling! The second question needs and deserves a longer answer, and it will be given in some of the later sections. Suffice it now to say that sound, which is in effect a compression of the air, travels or is transmitted through the air on a kind of wave which compresses first one part of the air, then the next, and so on. When a body moves through the air at speeds lower than the speed of sound these sound or pressure waves go out in front and warn the air that the body is coming; the air then simply gets out of the way, passing on one side of the body or the other, just as water divides when a ship passes through it. The air is not compressed, and behaves

just as if it were incompressible-like water. But when a body travels at speeds above that of sound, the warning wave does not travel fast enough to get ahead of the body, so the air, instead of dividing and passing smoothly past the body, comes up against it with a shock and is compressed.

Now, most aeroplanes even in these days cannot fly at the speed of sound, and even those that can must start and end their flight below that speed-let us hope that they always will!-and so the subject that we are still most concerned with is that of low-speed flight, that is flight in which the air behaves as if it were incompressible and in which we can therefore learn from experiments in water. Most of this book is devoted to this kind of flight, but the time is past when an author can avoid the obligation of saying something about the other kind, and this obligation will be fulfilled to the best of my ability in later sections.

While discussing the subject of air and water it may be appropriate to mention a type of vehicle which is actually supported by wings under water-the ***hydrofoil craft.*** We can hardly call this an aircraft, but if we substitute "driven through the water" for "driven through the air", it fulfils the definition of an aeroplane as given on page 2. The similarities-and differences-between hydrofoil craft and aircraft are so interesting that a book on ***Hydrofoils*** has been included in this series.

12. Centre of Pressure

After this long but important diversion, let us return to our cardboard. If, as we push it through the air at a small angle—this angle, by the way, is called the ***angle of attack*** or ***angle of incidence*** (Fig. 20)-we hold it at the centre of each end, then not only shall we feel an upwards and backwards force exerted upon it, but it will tend to ***rotate,*** its leading edge going over the top. Similarly, if we try to make it glide of its own accord, it will turn over and over. This is because the effective or resultant force acting upon it is ***in front of the centre-line,*** whereas we are holding it on its centre-line, or, when it is left free to fly by itself, its weight is acting downwards at the centre. If we hold it farther forward, or if we add weights to it so that its centre of gravity is farther forward, we shall eventually

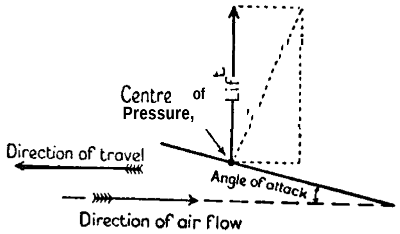


Fig. 20. **Angle of attack and centre of pressure**

find that it tends to turn the other way, the nose dipping downwards. With a little practice we can find a position such that it does not tend to turn either way, and then we have found what is called the ***centre ofpressure*** (Fig. 20).

13. Stability and Instability

When the centre of pressure and the centre of gravity coincide, the plane is balanced, or is ***in equilibrium*** (Fig. 21*a*). If the centre of pressure is in front of the centre of gravity, it is said to be ***tail-heavy*** (Fig. ***21b)*** ; whereas if the centre of pressure is behind the centre of gravity, it is ***nose-heavy.*** At present we are talking about a piece of cardboard; we are doing things in a simple way at first, but we are all the time learning big principles, and what is true of the cardboard is equally true of an aeroplane weighing many tons.

Now, all would be very simple if the centre of pressure always stayed in the same place, but unfortunately it does not.

As we alter the angle of attack, i.e. the angle at which the plane strikes the air, ***the centre ofpressure tends to move.*** We shall investigate the reason for this later; at present, let us be content with the fact that it ***does.*** If, as we increase the angle, the centre of pressure moves forward, then it will be in front of the centre of gravity and will tend to push the nose farther

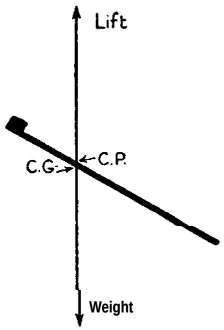


Fig. 21a. **Balance**

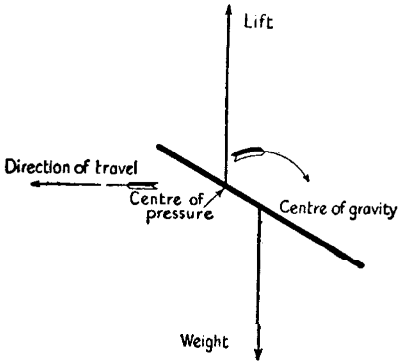


Fig. 21b. **Tail-heavy**

upwards, thus increasing the angle still more. This in turn will cause the centre of pressure to move ***farther*** forward, and this -well, you can guess the rest. This is called an ***unstable*** state of affairs-the mere fact that things become bad makes them tend to become worse. If, on the other hand, as we increase the angle, the centre of pressure moves backwards, it will then be behind the centre of gravity and will tend to push the nose down again and restore the original angle. This is called a ***stable*** state-when things become bad, influences are set up which tend to make them become better again. As before, what is true of the cardboard is true of the aeroplane-if we want the aeroplane to be stable, and you can probably guess that we do, then we must arrange for the latter conditions to apply. How? That is a long story; but it will all come out in due time.

14. The Wing Section

Everyone nowadays knows that, although we still call an aeroplane wing a "plane," it is not, in the geometrical sense a "plane" at all. It is a curved or cambered surface-in fact, it is really made up of two surfaces, each with a different curve or camber. The technical name for such a wing is an ***aerofoil,*** and the cross-section through an aerofoil is called an ***aerofoil section*** (Fig. 22).

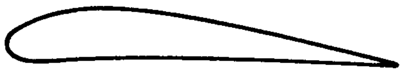


Fig. 22. **An Aerofoil Section**

There are two reasons for curving the surface : first, ***a curved surface gives much better lift,*** and secondly, we must have ***thickness*** to give strength to the structure. Some old books on the subject devoted a lot of space to the study of the flat plate; and in the last edition of this book we were rash enough to say that no flat surface had ever been used or was ever likely to be used for real aeroplanes. What a wonderful example of how careful one has to be in this subject-instead of ***real*** aeroplanes we ought to have said ***low-speed*** aeroplanes, because in fact many supersonic aerofoil sections have some flat surface, though of course they must still have thickness to give them strength..

It is true that we began our study with a flat piece of cardboard, but it did serve to explain terms like angle of attack, lift, and drag. Besides, there was another reason: bend it into a curved wing section and try it for yourself. It won't fly so well as it did when it was flat-in fact, the chances are that it will turn over on its back. You then may try to readjust the weight because the centre of pressure is in a new position. If you do, it will probably turn over in the other direction. It

has become ***unstable*** (Fig. 23), whereas, as a flat plate, it was slightly ***stable.*** We have discovered the only disadvantage of the curved surface for aircraft that fly below the speed of

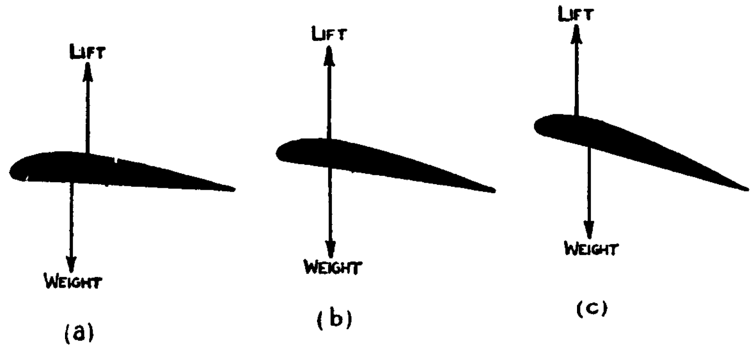


Fig. 23. **Movement of centre of pressure**

(a) Small angle-nose-heavy.
(b) Medium angle-balanced.
(c) Large angle-tail-heavy.

sound ; but before we enlarge on that, let us turn to a further investigation of its ***advantages.***

15. Air Flow over a Wing Section

If ***we*** wish to ***go upwards*** we must push something, or try to push something, ***downwards.*** In climbing a rope one gets a hold of it and pulls oneself upwards by trying to pull the rope downwards. In going up a flight of stairs one puts one's foot on to the next stair and attempts to push it downwards, and the stair exerts an upward reaction by which one is lifted. It is true that in these instances neither the rope nor the stairs actually move downwards and it is better that they should not do so; but there are instances, such as in ascending a sandy slope, where for each step upwards sand is pushed downwards. A drowning man will clutch at a straw-it is his last dying effort to get hold of something and pull it downwards so that he can keep himself up.

An aeroplane is no exception to these rules; the wing is so designed, and so inclined, that (in passing through the air) it will first attract the air upwards and then push it downwards and by so doing experience an upward reaction from the air.

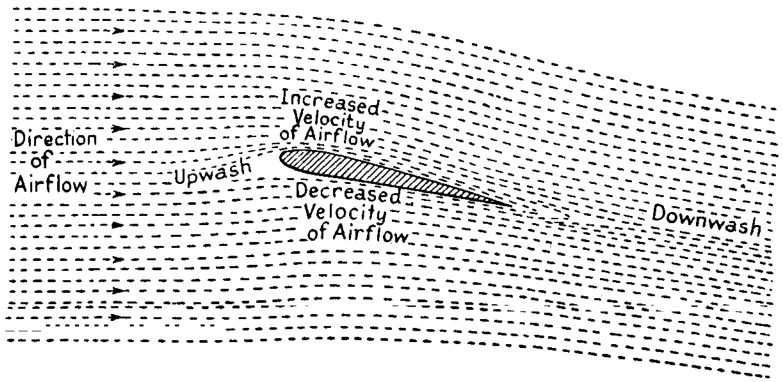


Fig. 24. *Air flow over* an aerofoil inclined at a small angle

Fig. 25. Air flow over a flat plate

It is a simple example of one of Newton's laws-"To every action, there is an equal and opposite reaction." The downward flow of air which leaves an aeroplane wing is called *downwash.*

Now, the greater the amount of air which is deflected downwards by a wing in a given time, the greater will be the upward

reaction, or lift; on the other hand, the greater the disturbance caused by the motion of the wing through the air, the greater will be the resistance to motion, or drag. Therefore the aim in the design of a wing, and in choosing the angle, is to secure as much downwash as possible *without at the same time causing eddies or disturbance.* This is where the curved aerofoil is superior to the flat surface (Figs. 24 and 25), and this also explains why the angle of attack used in flight is so small. The gradual curvature of the wing section entices the air in a downward direction and prevents it from suddenly breaking away from the surface and forming eddies, and although a larger angle would give more lift, it would create more disturbance and cause more drag.

16. Pressure Distribution round a Wing Section

Notice how effective the *top* surface of the wing is in curving the air flow downwards; the bottom surface acts in much the same way on both the aerofoil shape and on the flat plate, but it is the top surface of the aerofoil which scores.

We have, so far, considered the reaction on the wing as if it were a single force acting at a place called the centre of pressure,

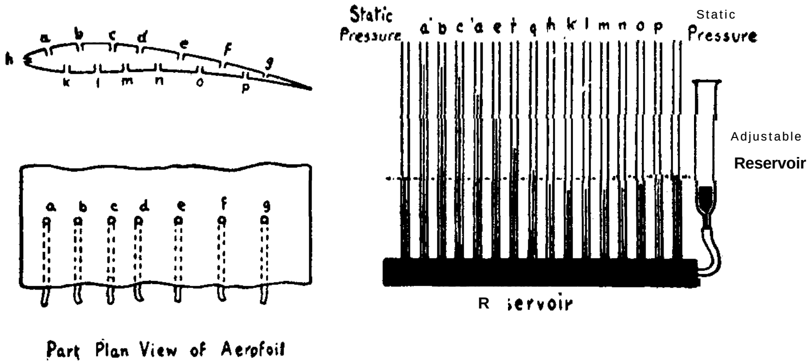


Fig. 26. Pressure plotting

but it is in reality the sum total of all the pressure acting upon the surface of the aerofoil, this pressure being distributed all over the surface. Distributed-yes; but not, by any means, *equally* distributed. This can easily be shown by what is known as *pressure plotting.* Small holes round the wing are

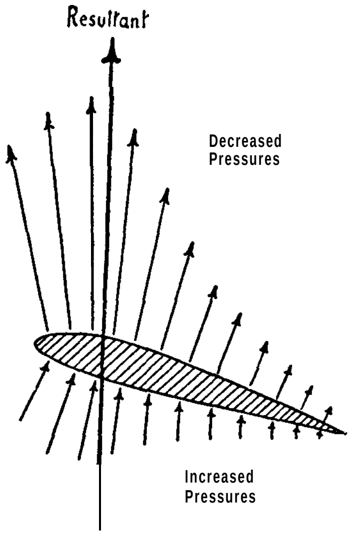


Fig. 27. **Distribution of pressure over a wing section**

connected to glass tubes, or manometers, in which there is a column of liquid, the glass tubes being connected at the bottom to a common reservoir (Fig. 26). If the liquid in any tube is sucked upwards, it means that the pressure at the corresponding hole on the surface of the wing has been reduced; similarly, if the liquid is forced downwards, the pressure has been increased. In this way a kind of map can be drawn to show the pressures at different parts of the surface of the wing. The diagram shows such a map for a typical wing section (Fig. 27). Have a good look at it; it will tell you a lot about the mystery of flight. Notice, first, that over most of the *top* surface the *pressure is* decrease&-this is due to the downward curvature of the air;

on the *bottom* surface, however, the air is pressed downwards, and there is an *increase of pressure.* Notice that the decrease in pressure on the top surface is much more marked than the increase underneath, and thus the *top surface contributes the the largest proportion of the lift.* This is only another way of saying what we had already noticed, namely that it is the top surface which is chiefly responsible for the downwash. The diagram of pressure distribution also confirms another previous discovery: it is quite clear that the majority of the lift, both at top and bottom surfaces, comes from the front portion of the wing, and therefore when we replace all this distributed pressure by a single force, we must think of that force as acting in front of the centre of the aerofoil-in other words, the centre of pressure is well forward (notice how we showed this in the earlier diagrams). All this confirmation of what we had already discovered should give us confidence, and we need confidence in this subject because, although it is all founded on simple laws of mechanics, it is full of surprising results and unexpected happenings.

I do not want, in this book, to worry you with formulae, figures or mathematics of any kind. You will find all that in more advanced books on the subject. But there has been so much misconception as to the *values* of the pressures round an aerofoil that I would like to put your mind at rest on that point at any rate. The misconception arises chiefly owing to the habit of describing the decreased pressure on the top surface of an aerofoil as a “vacuum” or “partial vacuum”. Now, a vacuum means the absence of all air pressure; a vacuum on the upper surface would cause water in the corresponding tube in the manometer to be “sucked up” to a height of about 36 ft. In actual practice, the column of water rises three or four inches, so it is not much of a vacuum, hardly even worthy of the name of “partial” vacuum. Another way of looking at it is that a vacuum on the top surface would result in an effective upward pressure--from *the top surface only-of* nearly 15 lb/sq in, whereas the actual lift from an aeroplane wing may not even be as much as 15 lb/sq ft-and there are 144 square inches in a square foot. No, the truth of the matter is that the pressures round an aeroplane wing are but small variations in the usual atmospheric pressure of about 15 lb/sq in, and that is why such a large wing surface is necessary to provide the lift required.

Perhaps we ought also to explain that where you see the arrows on the top surface pointing upwards you must not think that there is really a kind of upward negative pressure on this surface-it is impossible to have a pressure less than nothing. What these upward arrows mean is that the pressure is reduced *below the normal atmospheric pressure,* and this, *in effect,* is producing an upward pressure. The normal atmospheric pressure is about 14·7 lb/sq in, so that when the wing is *not* moving through the air there will be a *downward* pressure on the *top* surface of 14·7 lb on every square inch, and an *upward* pressure on the *bottom* surface of the same amount. These two cancel out, and the net effect of the pressures is nil. Now, when the aerofoil is pushed through the air, the pressure on the top surface is still downwards, but it is *less than* 14·7 lb/sq in, whereas the pressure on the bottom surface is still upwards but *more than* 14·7 lb/sq in, and so there is a net upward pressure equal to the difference between these two, and the arrows are intended to show that this upward pressure is contributed both by the decrease on top and by the increase underneath-more by the former than the latter.

17. The Venturi Tube

The reader may feel that he would like a little more explanation as to *why* the pressure is decreased above the aerofoil and increased below it. All we have said so far is that it is due to

the downward curvature of the air flow, and this is certainly one way of looking at it. But perhaps a better way is to compare it with similar examples of the same sort of thing. Do you know what a *venturi tube* is? In case you do not, here is a picture of one (Fig. 28). It is a tube which has an inlet portion, gradually narrowing, then a throat or neck, followed by the outlet, which gradually widens. In a well-designed venturi

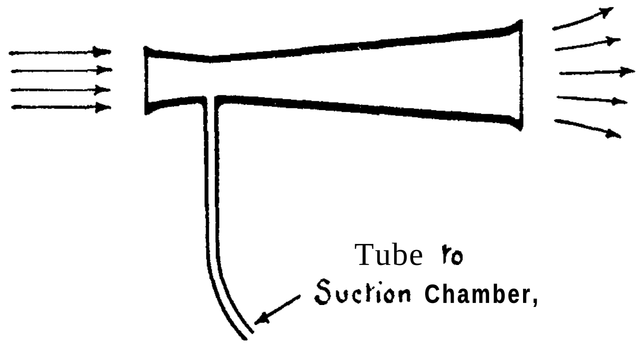


Fig. 28. **A venturi tube**

tube the outlet is usually longer than the inlet. The tube is so shaped-and it must be done very carefully-that air or other fluid which passes through it continues in steady streamline flow; if large eddies are formed, the whole idea of the tube breaks down. Now, it is quite clear that the same amount of air must pass through the throat as passes into the inlet and out of the outlet. Therefore, since the cross-sectional area of the tube at the throat is less than at inlet and outlet, it follows that one of two things must happen-either the fluid must be compressed as it passes through the throat, or it must speed up. The throat is after all what is commonly called a bottle-neck, and we all know from numerous examples in ordinary life the sort of things that can happen at a bottle-neck. Think, for instance, of a gate or narrow passage at the exit from a football ground. The badly disciplined crowd will try to push through the gate, they will be compressed, and, quite apart from the discomfort, the whole process of getting away from the ground will be delayed. The well-disciplined crowd, however—if there is such a thing-will move faster as they approach the gate, pass through it at a run, then slow down again as the path widens. Contrast, too, the way in which the traffic tries to push its way through some of the notorious bottle-necks in

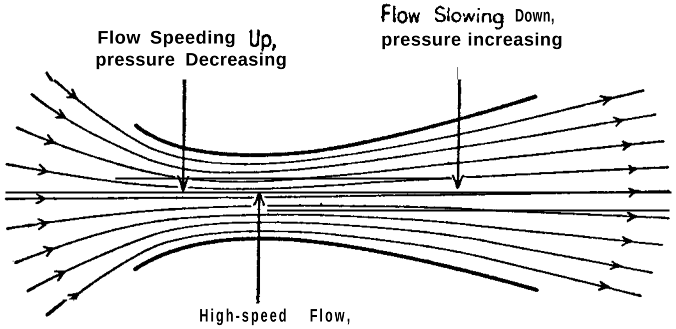


Fig. 29

the London streets, and the well-disciplined speed-up through the Mersey tunnel.

Now which of these two things happens when a fluid passes through the venturi tube? Is it compressed at the throat, or does it flow faster? The answer, in the case of water, is clearly that it flows faster; first, because water cannot be compressed (appreciably, at any rate); secondly, and perhaps more convincingly, because there are so many practical examples in which we can watch water and see how it speeds up as it passes through the throat-stand on a bridge and watch the water as it flows between the supporting pillars. The reader may not be so easily convinced about air, but the fact is that the patterns of air and water flow through a venturi tube are almost exactly the same (Fig. 29)-so much so that indistinguishable photographs can be taken-and measurements of

the speeds show that air speeds up just like water, and, as already explained, behaves as though it were incompressible—provided always that we are considering a speed of flow well below that at which sound travels.

And what is the result of this speed-up of the flow at the throat? Our pressure plotting experiment, now applied to the venturi tube, gives a convincing answer to that question, though it is not so easy to explain *why* it happens. At the throat the pressure which the air exerts on the sides of the tube is less than at outlet or inlet; in fact as the ***velocity increases, the pressure on the walls of the tube decreases,*** and vice versa. Why ? The answer you will usually be given is simply ***Bernoulli's theorem.*** That doesn't sound very convincing; and what is Bernoulli's theorem? Well, you have probably heard of the idea of the conservation of energy-that energy may be transformed from one form into another but that the sum total of all energy in the universe remains the same. Some people will tell you that it isn't true ; but don't worry about that, it is true enough for the purposes for which we are concerned with it. Well, Bernoulli's theorem is a kind of special application of this principle in so far as it concerns the flow of fluids-or rather the streamline flow of fluids, because if the flow is turbulent the theorem breaks down. In effect, the theorem states that, in streamline flow, the sum of the pressures exerted by the fluid remains constant. Now, a fluid can exert pressure for two reasons: first, because of its movement-this is the pressure that we feel when wind blows against our faces—secondly, because of the energy stored in it which makes it exert pressure on the sides of a vessel even when it is not moving-this is the pressure exerted on the envelope of a balloon, on the walls of a pneumatic tyre, or, to use the most common example, the ordinary atmospheric or barometric pressure. The pressure due to movement we will call ***dynamic pressure,*** the other the ***static pressure.***

So, according to Bernoulli's theorem, the sum of the dynamic and static pressures remains constant-therefore, as the velocity (and the dynamic pressure) goes up, the static pressure must come down. We cannot prove the theorem here, but, what is perhaps more convincing, we can give several examples of its truth in practice. This is probably advisable, because it is one of those scientific principles which some people think are contrary to common sense-which seems to suggest that common sense is more common than sense, but that is by the way. Have you noticed how the dentist attaches a tube to an ordinary tap and in that tube is a small glass venturi, from the throat of which another tube leads to your mouth? The flow of water through the venturi causes a decrease in pressure which sucks moisture out of your mouth. Have you ever noticed how wind blowing through a narrow gap tends to suck in leaves and dust towards the gap? Have you seen a draught through a slightly open door close the door, rather than open it, as common sense might suggest? Have you noticed how in a whistle, or in most wind instruments, air is sucked in towards the throat in the instrument? Two ships passing close to each other tend to be sucked together, and this has often been the cause of collisions; similarly a ship passing close to a wharf tends to be sucked in towards the wharf.

But the best examples of all are from our own subject. Consider the wind tunnel, for instance. When the air is rushing through it, the pressure of the air outside is greater than the pressure at the narrowest part of the tunnel where the air is flowing fastest. If you doubt this, try to open a window or door in the tunnel, and you will soon know all about it. Venturi tubes themselves-sometimes double venturi tubes, a little one inside a big one-are used for all kinds of suction instruments, for measuring air speed by suction, for driving gyroscopes by suction. The choke tube in a carburettor is a perfect example of the practical use of a venturi tube, And

last, the aerofoil which we are trying to explain. Here there is no obvious venturi, but by looking carefully at the way in which the air flows (Fig. 24) you will notice that the decreased pressures are where the streamlines are close together, where the air is flowing with higher velocity as at the narrower portions of the venturi. As a general rule, the air flows faster all over the top surface, and slower all over the lower surface. The greatest velocity of all is at the highest point of the camber on the *top* surface, and here is the least pressure, as at the throat of the venturi. But-let us emphasize this once again, because it is important-the best results will only be obtained if the streamlines are kept flowing close to the surface; as soon as they break away, on both aerofoil and venturi, there will be less decrease of pressure, less suction.

One of the best ways of thinking about air, or water, flowing through a venturi tube or over an aerofoil is to think of how the changes of pressure affect the flow rather than-as we have done so far-of how the flow affects the pressure. It is, after all, rather like the chicken and the egg-one doesn't know which came first. A fluid flows easily from high pressure to low pressure; there is, in technical terms, a favourable pressure gradient-it is flowing downhill so far as pressure is concerned. This is what is happening between the entrance to the venturi and the throat, or over the top surface of the aerofoil as far as the maximum camber-the air is free-wheeling, it likes it. But after the throat, or the point of maximum camber, the pressure is increasing, the pressure gradient is adverse, the air is trying to go uphill, if we are not careful it will stall-yes, just that!

18. Why the Centre of Pressure Moves

If we follow up this "pressure plotting" idea we shall find not only confirmation, but explanation, of another phenomenon that may have puzzled us. If we plot the pressure round the aerofoil at different angles of attack we shall find that the pressure distribution changes, and that it changes in such a way that as we increase the angle (up to a certain limit) the tendency is for the most effective pressures to move forward, thus causing the *resultant* forces to move forward, and so accounting for the instability of the aerofoil (Fig. 23). On the other hand, if we plot the pressure round a flat plate-not an easy thing to do-we find that the pressure distribution changes in a different manner, the resultant force tending to move backward as the angle increases, making the flat plate stable (see Section 14).

19. Stalling or Burbling

In Section 15 we mentioned that the angle of attack used in flight was a small one because "although a larger angle would give more lift, it would create more disturbance and cause more drag." The question of what is the best angle needs a little further investigation.

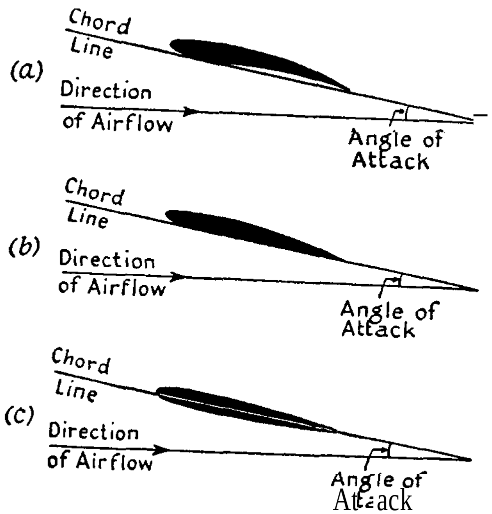


***Fig*. 30. Chord line and angle of attack**

Before going into this we ought to mention that it is not so easy to define what we mean by "angle of attack" now that we have the curved aerofoil surfaces instead of our original flat plate. Clearly we must choose some straight line to represent the aerofoil-but what straight line? It sounds a simple

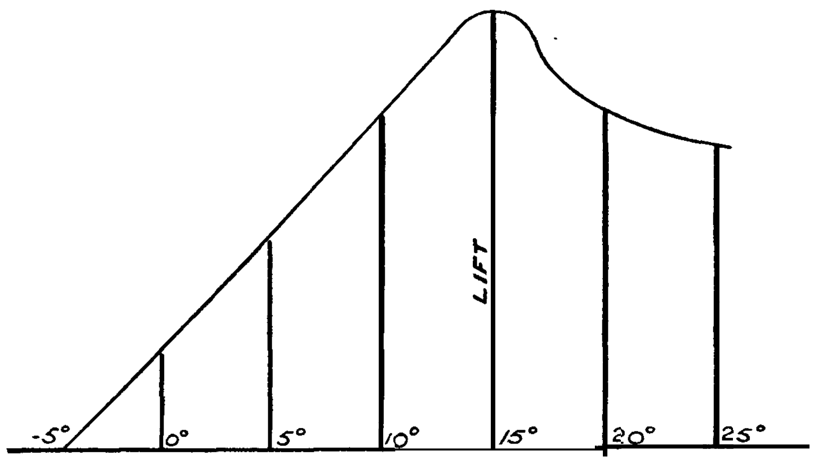


***Fig*. 31. Variation of lift with angle of attack when the air speed remains constant**

question, but it has not been at all easy to solve, largely because methods which are satisfactory when considering the subject theoretically are quite impracticable to those whose duty it is to take actual measurements on the aeroplane. To cut short a long story, we can only say that different ***chord lines*** are used for different-shaped aerofoils (see Fig. 30), and the ***angle of attack (for aerofoils) is defined as the angle which the chord line makes with the air flow.***

Now, if we increase this angle, what will happen?

Again it is not quite such an easy question as it sounds, and an enormous amount of experimental investigation has been made in order to answer it. So far as the lift is concerned, it increases as we increase the angle (provided that the air speed remains constant) *but **only** up to a certain **limit***; after this it begins to fall off. Although the actual amount of lift given by the wing when this maximum limit is reached varies tremendously according to the shape of the aerofoil section, it is rather curious that most wings, whatever their shape of section and whatever the air speed, reach their maximum lift at about the same angle, usually between 15" and 20" (Fig. 31).

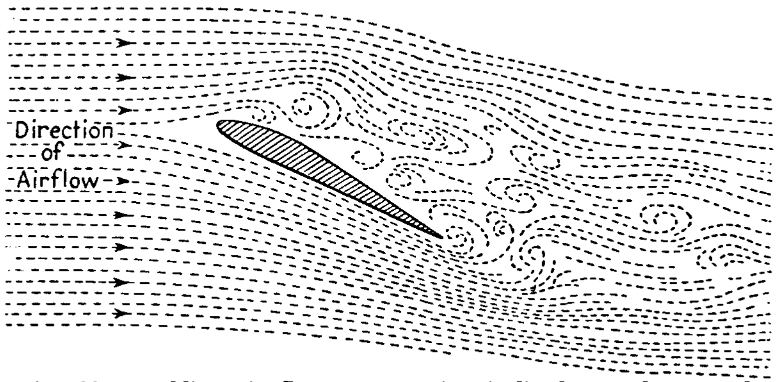


Fig. 32. Burbling air flow over a wing inclined at a large angle

Now, why does the lift fall off after this angle has been reached? One would think that the increasing angle would create more downwash and consequently more lift. It is rather natural that aeronautical engineers should have spent much time and study on this phenomenon, because flight would become very much easier and very much safer did it not occur. By watching the flow of air over the wing-using smoke or streamers so that they can see the type of flow-they have discovered that *when this critical angle is reached **the flow** over the top surface changes-quite suddenly-from a steady **streamline flow** to a violent eddying motion, with a result that much of the downwash, and consequently the **lift**, is lost* (Fig. 32). As

one might expect, the drag, by the same token, suddenly increases.

Exactly the same thing happens in a venturi tube if we make the throat too narrow, or try to expand the tube too suddenly after the throat. In this connection it is interesting to note that, although the front part of the wing section, and the entry and throat of the venturi tube, seem to experience nearly all the effect so far as reduction of pressure is concerned, they are entirely dependent for this effect on the shape and angle of the rear portion of the wing and the expanding exit portion of the venturi. It is no good saying the front part gives the results, therefore why worry about the rear part; why not, even, cut it off? It is the front part that will suffer if you do.

The truth is that the flow is very sensitive to the exact shaping and angle and attitude of the whole system, whether it be a wing section or a venturi tube, and immediately we attempt to go too far it shows its objection by breaking down into turbulent flow-and so spoiling everything. If the hill is too steep, it just won't go up it!

This phenomenon is called *stalling* or, rather appropriately, burbling-it is one of the greatest problems of flight.

20. Lift and Drag again

Now, it is the air flow and the consequent pressures, as described in the preceding sections, that give us at one and the same time the *lift* which enables us to fly, in heavier-than-air craft, and the *drag* which tries to prevent us from doing so. Both are really part of the same force, but owing to their very different effects it is important to distinguish between them.

One of the unfortunate aspects of this subject, from the point of view of those who learn it or teach it, is that one constantly has to correct or modify one's original ideas. What I am going to tell you now is a glaring example of this. You will have gathered from what you have read that lift is an upward force and drag is a backward force. You will probably claim-not without justice-that I have told you so (see Section 6). Now I have got to tell you that that idea isn't true-or, rather, that it is only true in one particular case, i.e. when the aeroplane is travelling horizontally (even then the lift may be downwards, as it was on the model in Fig. 18). The real definition of lift is that it is *that part of the force on a wing (or an aeroplane or whatever it may be) which is at right angles to the direction of the air* flow-or, what comes to the same thing, at right angles to the direction in which the aeroplane is travelling. Similarly, *drag is that part of the force which is parallel to the direction of the airflow.* So you will see that the upwards idea of lift and the backwards idea of drag are only true for horizontal flight. In a nose-dive it is lift which will be horizontal and drag vertical. So far as lift is concerned, the correct definition is a rather silly one, because in ordinary language the word lift surely implies *upwards;* that is really my excuse for not telling you the truth earlier, because I did not want you to get the impression that it was a silly subject. Perhaps, by now, you have already realized that it is!

21. Effects of Speed

Both lift and drag increase with speed. Everyone knows this—at any rate so far as drag is concerned; one has only to try to pedal a cycle against winds of different velocities, and there can no longer be any doubt. In view of such common experience, it is rather surprising that most people seem to underestimate *how much* the resistance increases as the speed increases. They will usually tell you that if the speed is doubled they would think that the drag would be about doubled, perhaps a little more, perhaps a little less. This is very much of an underestimate, the truth being that for double the air

Plate 3. The British Aerospace 146 is quieter than any other jetliner, and can also operate from much shorter runways. Thanks to high-bypass-ratio turbofan engines it is propelled by relatively slow-moving quiet jets. Note the lack of sweepback.

Plate 4. The surprising thing about the Airbus A320 is how ordinary it looks. Internally it is packed with new technology, including a digitally controlled automatic flight-control system (using electrically signalled "fly by wire" connections to the control surfaces) which, for example, can sense dangerous atmospheric conditions such as wind-shear and downbursts and fly the aircraft to its safe limits, where earlier jetliners might have had little chance of survival.

speed the drag and the lift are about four times as much ; for for three times the speed they are nine times and for ten times the speed they are multiplied by a hundred (Fig. 33).

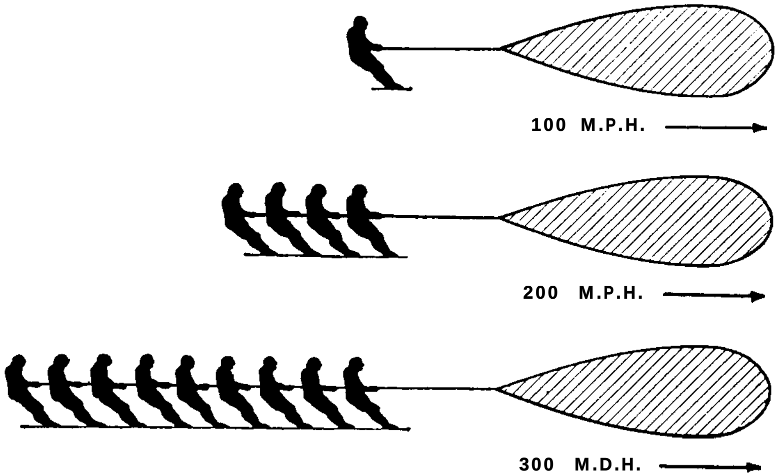


Fig. 33. **The "speed squared" law**

The men represent the resistances holding the bodies ***back*** at the various speeds; there must, of course, be corresponding forces pulling the bodies forward.

This is called the *speed squared law-the lift and the drag are proportional to the square* ***of*** *the speed.* It is one of the fundamental laws of the whole subject.

22. Effects of Size

Both lift and drag also depend on the size ***of*** *a body;* large bodies have more drag than small ones of the same shape; large wings have more lift. Probably everyone knows this too and it might even be said to be rather obvious, but there is a little more in it than that. From this point of view "size" used to be taken as meaning *frontal area,* i.e. what you see of a body when viewing it from the front-in other words, its cross-sectional area when viewed from this position. For an airship it would mean the area of the largest frame, for a strut the maximum breadth times the length. The greater the frontal area, the greater would be the drag-in direct proportion.

This, however, is another aspect of the subject in which modern development is leading to a change in ideas. When bodies were badly shaped, it was true enough that the frontal area was the best way of thinking of the size of a body moving through the air, but now that so much has been accomplished in the direction of cleaning up and streamlining aeroplane design, now that skin friction has become of so much relative importance compared with form drag, it is more correct to say that resistance is proportional to surface *area* or, as the naval engineer would speak of it, to the wetted surface, the surface which is washed by the air passing over it.

Provided bodies are of similar shapes it really makes no difference whether we compare frontal areas or surface areas ; for instance, a flat plate two inches square will have four times the frontal area of a flat plate one inch square, and it will also have four times the surface area, and therefore, by both laws, four times the resistance (at the same speed). If, however, either flat plate is **faired** to form a streamline body, the form drag will, of course, be very much reduced because of the better shape, but we must not forget that there will be an actual *increase in the skin friction* owing to the larger wetted surface and the greater velocity of air flow over it. Think over this, because it is important, and it is apt to be forgotten in view of the decrease in *total* drag. What it means, in practice, is that it may not be worth while polishing a flat plate or a "dirty" aeroplane, but it is very much worth while polishing a perfect streamline shape or a "clean" modern aeroplane, in which skin friction has become the major type of drag. In the case of lift it is usual to consider the *plan area* of the wing.

Notice that the area of a full-scale machine is 25 times the area of a one-fifth scale model (Fig. 34) and 100 times that of

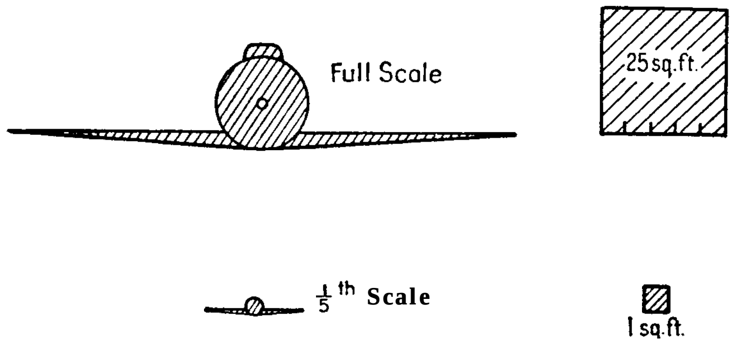


***Fig.* 34. Frontal area**

a one-tenth scale model. This applies whether we consider frontal area or wetted surface, or plan area.

23. Effects of Air Density

Lastly, *the lift and drag depend upon the density*, or "thickness" of the air. The denser the air, the greater the forces it produces; this, too, one would expect.

Now, as we noticed when considering the atmosphere, the air density decreases very rapidly as we climb. Even at 20,000 ft (by no means a great altitude for modern aeroplanes) the air density is only about one-half what it is near the ground, and for this reason the drag-other things being equal-should only be half the drag at ground level, so obviously (that dangerous word again!) it will pay us to fly high and thus reduce resistance. But will it? What about the lift? And what about "other things being equal"? That, of course, is where the catch comes in; "other things" at 20,000 ft are far from being equal to what they were near the ground, and it becomes a very debatable question, and a fascinating problem, whether to fly high or to fly low. We shall say more about it later. In the meantime let us remember that *lift and drag depend on the air density-other things being equal.*

24. Lift/Drag Ratio

So when we try to get more lift by increasing the speed, or by increasing the wing area or size of the aircraft, or even by flying in denser air, we also-other things being equal-get more drag, and, moreover, get it in the same proportion; e.g. if we double the lift we also double the drag. But if we try to get more lift by increasing the camber of the wing section, or by increasing the angle of attack, we shall still get more drag, though not necessarily in the same proportion-and this is rather important. The increase in lift is obviously a good thing-the increase in drag is obviously a bad thing-but what is the net result?-good or bad? Of course, there are times when we want lift even at the cost of increased drag (we shall find later that this is so when we are out for low landing speeds) ; there are other times when we will sacrifice everything, even lift, for a decrease in drag (that sounds like speed records); but in the average aeroplane we shall get a clearer idea of what we are after if we consider the *ratio of lift to drag,* rather than the two quantities separately.

An example will make this clear; the figures are taken from tests on actual wing sections. A certain shape of section gives maximum lift 30 per cent greater than a rather thin section; but, on the other hand, the best ratio of lift to drag of the thinner section is 30 per cent greater than that of the thick section. This is typical of the kind of results which are obtained when wings are tested, and it accounts for the wide variety of shapes of wing section which are in practical use. What it means is that the thicker section would be more suitable for a

particular kind of aeroplane, probably a fairly slow weight-carrier or bomber, while the thinner section would suit a more general-purpose machine, and some other shaped section altogether would be needed for a high-speed machine.

Or again, considering the effect of changing the angle of attack of a wing (keeping the speed constant), whereas the lift increases steadily from 0” to about 15°, at which it reaches a maximum, the drag changes very little over the smaller angles with the result that the ratio of lift to drag is greatest (and may be as much as 24 to 1) at about 4”; it then falls off to, say, about half this value at 15” when the lift is a maximum. Of course, once burbling occurs, the lift drops rapidly, the drag increases rapidly, and the lift/drag ratio tumbles to something like 3 to 1 at, say, 20”.

25. Analysis of Drag

Having considered the main factors on which lift and drag depend, let us concentrate for a moment on the unpleasant force-drag.

Why is it unpleasant? Well, lift is what we are seeking; it is what lifts the weight and thus keeps the aeroplane in the air, it makes flight possible, and is the friend of flight. Drag, on the other hand, is a bitter enemy. This backward force contributes nothing towards lifting the aeroplane, and it opposes the forward motion of the aeroplane which is necessary to provide the air flow which in turn provides the lift. This forward motion is produced by the *thrust* and the *thrust* is provided by the *power* of the engine. This applies whether the engine drives a propeller or merely exhausts itself as a jet, or whether the engine is a rocket. The greater the drag, the greater the thrust and the greater the power needed. But more engine power means more weight, more fuel consumption, and so on. and therefore it is fairly clear that for economical flight we must make every possible effort to reduce the drag. So let us analyse it—split it up if we can into its various parts (Fig. 35).

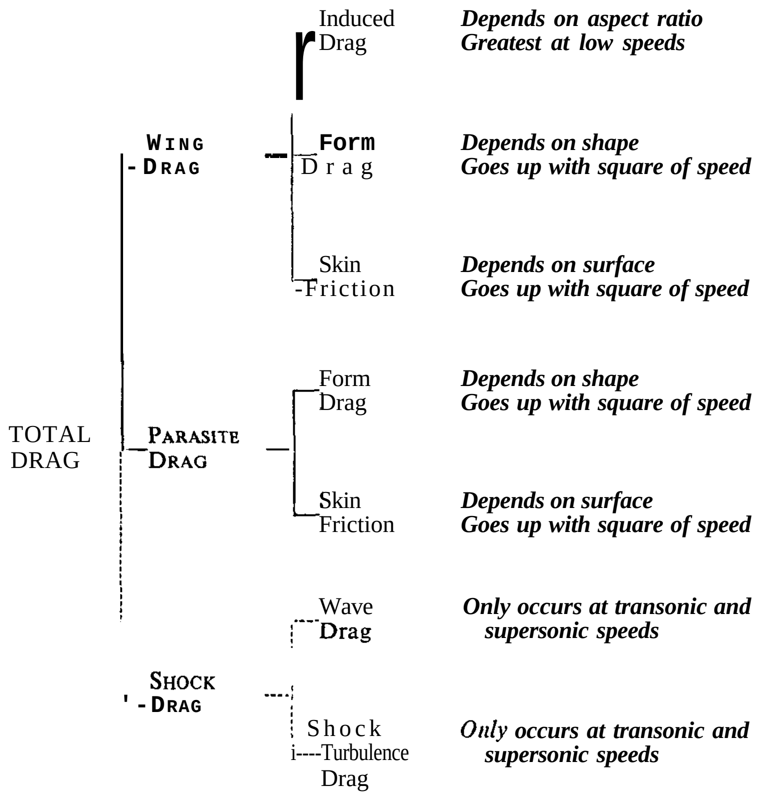


Fig. 35. **Analysis of drag**

Shock drag only occurs at high speeds and will be considered in the later sections of the book.

Unfortunately, the drag of a wing is a necessary evil. In the very nature of things, if we are going to deflect the air flow in order to provide lift, we are bound to cause a certain amount of drag. It is true that if the camber is small and the angle of attack is small, the drag will be small-but so will

the lift. However, it is no good complaining about this, and we become so resigned to this drag from the wings that it has sometimes been called ***active drag.*** This is rather too flattering a term, but it really implies that it is caused by those parts of the aeroplane which are "active" in producing lift; the term is comparative, it is the lesser of two evils, the greater being its brother of Section 27, and it is really better to call it ***wing drag.***

26. Induced Drag

But active drag, or wing drag, the drag of the wings, is in itself made up of various kinds of drag, and the story of the first and most important of these is a fascinating study.

If we tie streamers on to the wing tips of an aeroplane, we shall discover that they whirl round and round as shown in the sketch (Fig. 36). Notice that they rotate in opposite

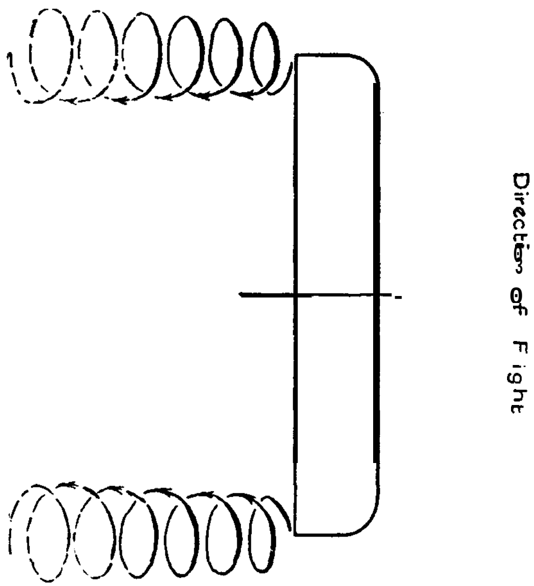


***Fig.* 36. Wing-tip vortices**

directions at the two wing tips, the right-hand one going anti-clockwise (when watched from the back) and the left one gonig clockwise. These curious whirls, *or vortices* as they are called, happen with all aeroplanes, but it was a long long time before practical men realized their existence, let alone their significance. What a pity we cannot see air; if we could, all pilots from the beginning of flying would have seen, and talked about, these wing-tip vortices; we can easily illustrate them with our piece of cardboard. The author has vivid memories of an incident just after the end of the first war when, on a festive occasion, long streamers were attached to the wing tips of his flying boat. When taxying on the water these streamers rotated violently, and they continued to do so in the air until, after a few minutes, they were nothing but shreds. The author and his colleagues dismissed the whole affair with some such silly remark as "That was funny, wasn't it?" Had they been a little more intelligent they would have realized that a phenomenon of this kind does not occur without good reason, and they would have followed it up by further experiment-and maybe it would have slowly dawned on them that this was one of the most significant facts of aviation and one that was to influence the whole trend of aeroplane design. But that discovery was left to others and, even then, it took some time.

But what is the real significance, and what is the cause of these vortices? We can answer the first question quite simply and shortly by saying that we cannot stir up whirlpools without doing work; this work must be done by the engine, and the whirlpools are nothing more or less than a form of drag tending to hold the aeroplane back.

The cause of the vortices is that the air tends to flow around the wing tip from the region of high pressure below the wing to the region of low pressure above. A fluid always tends to flow from high pressure to low pressure. This flow round

the wing tips causes all the air over the top surface to flow slightly inwards and that over the bottom surface to flow outwards (Fig. 37). Thus the streams meeting at the trailing

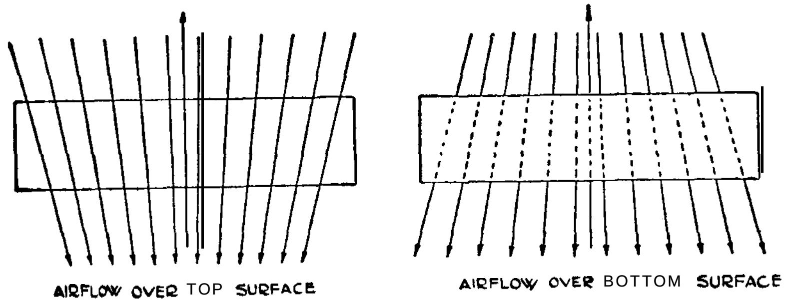


Fig. 37. The cause of trailing vortices

edge cross each other and form what is really a series of eddies called *trailing vortices,* which roll up to one big vortex at each wing tip (Fig. 38). As a result of the wing-tip vortices

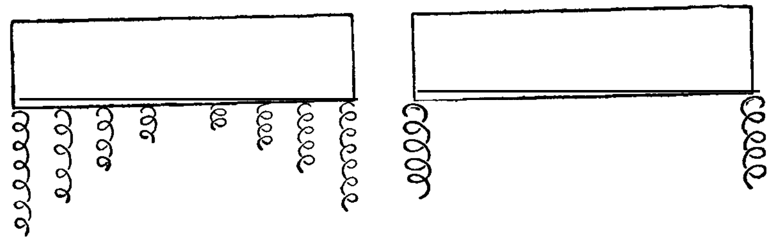


Fig. 38. **Trailing vortices which become wing-tip vortices**

the air behind the wing is deflected downwards, that outside the span being deflected upwards. Thus the net direction of the air which actually passes the aerofoil is in a downward direction, and so the lift-which is at right-angles to the air flow-is slightly *backwards,* and so contributes to what we call the drag (Fig. 39). This is another, and perhaps more scientific, way of thinking of the drag caused by the wing-tip vortices. The drag thus formed is called *induced drag* (another term which the highbrows claim for themselves) because it is a result of the downward velocity "induced" by the wing-tip vortices. In a sense, induced drag is part of the lift, and thus it can never be eliminated, however cleverly we design our wings. This, nuisance as it may be, is really the part of the drag which best deserves the name of "active" because it is

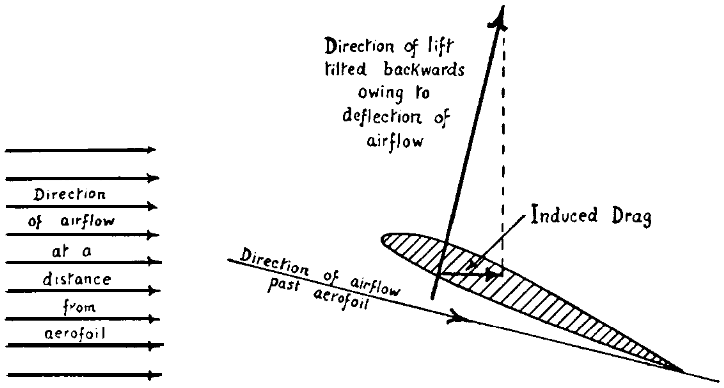


Fig. **39. Induced drag**

essential to lift. So long as we have lift we must have induced drag.

But before we leave this fascinating part of the subject we must make a confession, prompted not so much, I'm afraid, by a conviction that honesty is the best policy as by the knowledge that we will be found out sooner or later! *Induced drag does not increase with the square of the speed;* on the contrary, *it is greatest when the aeroplane is flying as slowly as it can,* i.e. just before the stalling angle is reached and we are getting the maximum lift for the minimum speed.

27. Parasite Drag

The ideal aeroplane would be *all wing;* it has, in fact, been termed a "flying wing." Even modern aeroplanes often fall a long way short of this ideal; at best they have fuselages, tails,

and various projections and protuberances, while at worst they are more like Christmas trees than flying wings. These extra parts, engines, radiators, dynamos, guns, bombs, aerials, wheels, petrol tanks, or whatever they may be, all produce drag, but, except in a few instances of clever design, *do not contribute towards the lift.* Their drag, therefore, is considered to be of a very vicious type, and is given the appropriate name of*parasite drag.* The ideal aeroplane would still have a certain amount of active drag, but it would have no parasite drag. We should get better performance; speed, climb, weight-lifting, all would be improved, and at the same time fuel consumption would be reduced. Obviously, therefore, it is well worth the while of those responsible for producing aeroplanes to study this problem of parasite drag, and to see how it can be reduced to a minimum, if not banished altogether.

There are two distinct methods of reducing parasite drag. One is to eliminate altogether those parts of the aeroplane which cause it; the other is so to shape them and smooth their surfaces that their drag is as small as possible. The first is the most effective, but it has its limitations, and progress has been made by trying a bit of each method. The problem of eliminating struts, wires, and projections is really a structural one, and it has largely been solved in modern aircraft (Plates 27 and 28). It is a question of getting strength by internal rather than external bracing, and by having "clean lines" generally.

At one time it was considered that the extra weight required for making an undercarriage *retractable* during flight would be such as to outweigh the advantages which would be gained by the reduction of parasite drag. We do not think like this today; the undercarriage is one of those parts which is useless during flight-worse than useless, it is a parasite spoiling the performance of the aeroplane. Even if it does mean some increase in weight, even if pilots do forget (in spite of various alarm signals) to lower them for landing, the fact is that nearly all modern undercarriages are of the retractable type. The tail wheel has gone the same way or has been eliminated altogether in the tricycle or nose-wheel undercarriage, while radiators were first retracted and then disappeared; the "flying wing" may still be a long way off, but it is a great deal nearer than it was twenty or thirty years ago.

The problem of reducing the drag of those parts which we cannot eliminate forms a fascinating study, so let us now turn our attention to that side of the question.

28. Form Drag

In this age, when even motor cars, railway trains, and ships are streamlined, there is no need to explain what streamlining means ; but, perhaps for the very reason that we have become so accustomed to the idea, it is rather hard for us to realize that efficient streamlining took a long time to come, and that even nowadays very few people fully appreciate how effective it is.

The sketches give some idea of the nature of the air flow past bodies of various shapes, and at the same time an indication is given of their comparative resistances (Fig. 40). It

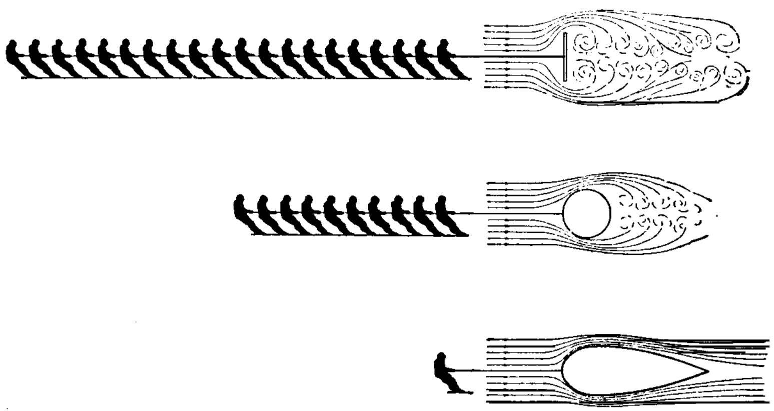


Fig. 40. **The effect of streamlining**

will be noticed that the more turbulent the air flow the greater is the resistance, and streamlining really means so shaping a body that air (or water) will flow past it in streamlines, i.e. without eddying, and thus the resistance is reduced to a minimum. Streamlining is another instance in which an attempt to avoid figures altogether would leave us in the dark. How many people realize that by carefully streamlining a flat plate, such as, for instance, a coin held at right-angles to the wind (Fig. 41), we can reduce its resistance not by 20 per

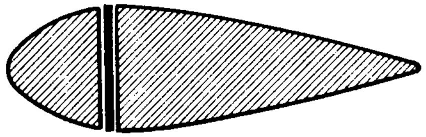
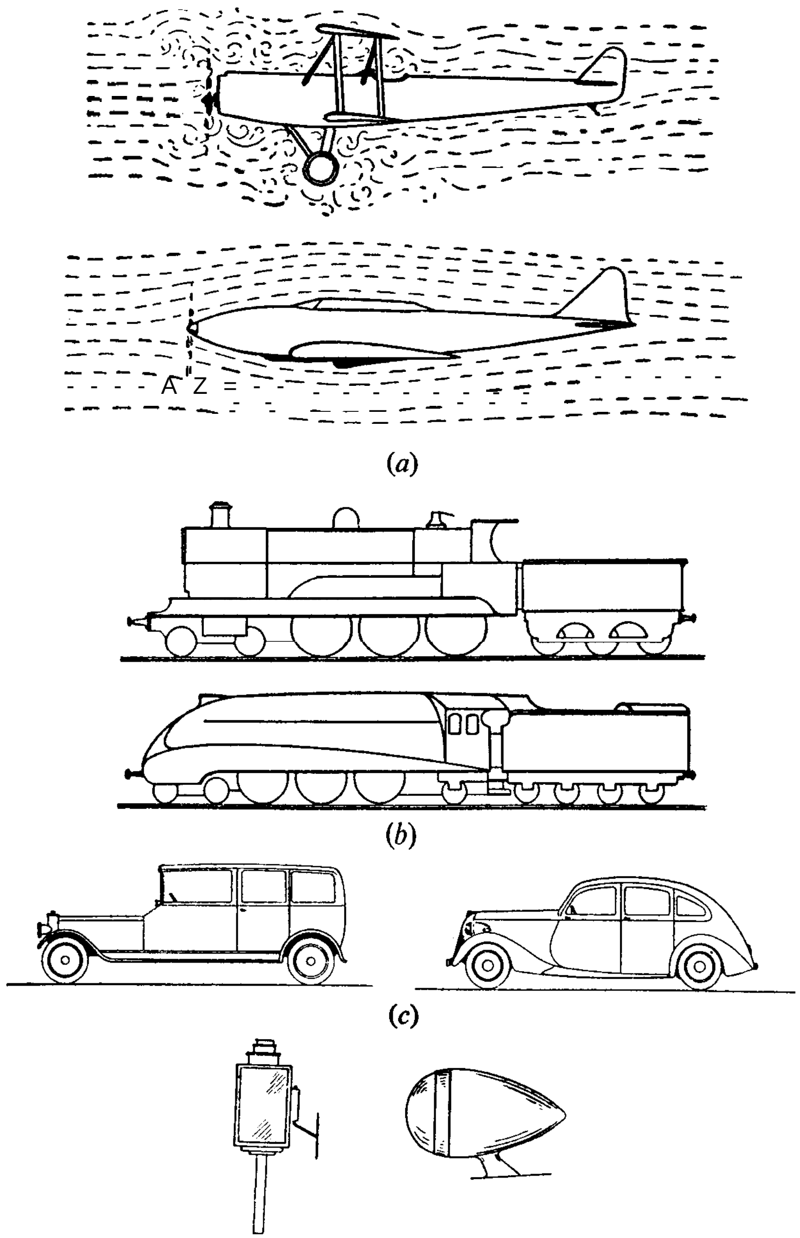


Fig. 41. **Streamlining a coin**

cent or 30 per cent or even 50 per cent, but to less than one-twentieth of its original resistance, a reduction of 95 per cent?

That part of the drag which is due to the shape or "form" of a body, and which can be reduced by streamlining, is called ***form drag.***

The sketches show how, in course of time, aeroplanes (Fig. 42*a*), railway locomotives (Fig. 42*b*), motor cars (Fig. 42*c*), and even motor-car lamps (Fig. 42*d*) (until they became incorporated in the body of the car itself, which is better still) were streamlined so as to reduce their head resistance, or form drag. Advantage is often taken of the fact, clearly shown by Fig. 40, that most of the benefit is due to the shaping or "fairing" of the trailing edge of the body and that it makes comparatively little difference whether the nose portion is flat, round or streamlined. This brings back memories of our old friends the venturi tube and the wing section.



(*a*) (*b*) (*c*) (*d*)

Fig. 42

The ratio of length (a) to breadth (b), as shown in Fig. 43, is called the fineness ratio of a streamlined body. For best results it should be about 4 to 1, but it really depends on the air speed; the higher the speed, the greater should be the fineness ratio, but experiments show that there is not much variation in the drag for quite a large range of fineness ratios.

An aeroplane is made up of various distinct parts such as fuselage, wings, undercarriage and so on. If one could imagine

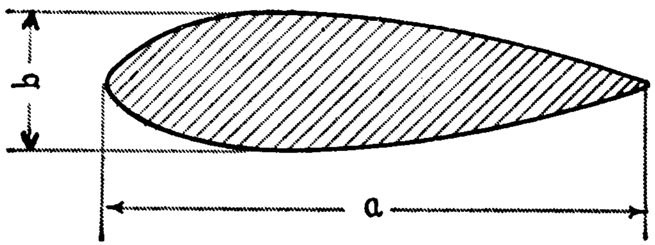


Fig. **43. Fineness ratio**

each of these parts so shaped in itself as to give the least possible resistance it does not follow that when they are joined together the combination will give the minimum resistance. Resistance caused by the effect of one part on another is called interference drag, and much care has to be taken in modern design to reduce this portion of the drag by careful fairing of one shape into another.

29. Skin Friction

Not only the shape of a body, but the nature of its surface also, affects the drag. It can easily be understood that a rough surface will cause more friction with the air flowing over it than will a smooth surface. This surface friction is called skin friction. Figures are not so convincing in this case, partly because no parts of an aeroplane are likely to be very rough, and therefore we can only compare a surface like that of ordinary doped fabric with a highly polished metal surface. The former is certainly rough in comparison with the latter; but the difference is not great, and the effect on the total resistance of a highly polished wing surface in place of a fabric surface is not very noticeable-or was not until recently.

For there are two modern tendencies which are making the study of skin friction become of increasingly greater importance. One is *speed*. Whereas at 100 m.p.h. there may be only a negligible difference between the polished metal and the fabric, at 400 m.p.h. the difference is such that it becomes of immense practical importance. The second tendency which affects skin friction is the *improvement in streamlining*. That sounds rather paradoxical, but the point is that in a badly shaped body the form drag is so great that the difference in total resistance between a rough surface and a smooth one is hardly noticeable -it is swamped by the large resistance due to eddies. On the other hand, when a body is so perfectly streamlined that its form drag almost disappears, then the skin friction becomes not only noticeable but important. Clearly, then, high-speed aeroplanes need to have both streamlined shapes and highly polished surfaces. There appears, however, to be a limit to the degree of polish which makes any difference-perhaps that is just as well for those who will be expected to maintain the polish. A surface is said to be *aerodynamically smooth* when further polishing will not have any appreciable effect on its skin friction.

Modern theory seems to suggest yet another reason for the importance of reducing skin friction. Apparently two and two do not make four-in other words, the total parasite drag is not the sum of the skin friction and the form drag, but it is more nearly the greater of the two. Thus by reducing one part of the drag only, we do not notice much effect on the *total*. The only way is to reduce *both*.

We know another example of this sort of thing in the case of noise. Two equal noises occurring at the same time do not make double the noise; actually they make very little more than one noise. The two chief sources of the noise of an aeroplane are the engine exhaust and the propeller. The former can be silenced, at any rate in piston engines; but it is hardly worth while, because it makes little difference to the total noise.

A part of the drag which might seem to be a necessary evil is what is called the *cooling drag*, i.e. the resistance caused by the air flowing over radiators (in liquid-cooled engines), over cylinders and cowling (in air-cooled piston-driven engines), and through and over turbine engines. This cooling drag is made up of both form drag and skin friction. Much ingenuity has been spent in trying to reduce it; the wings themselves have been used as radiators, and for air-cooled engines special cowlings and ducts have been devised. Results have been good; so good that it has been possible to reduce this portion of the drag to nothing, or even to less than nothing, the heat of the engine being used to help the aeroplane forward. There is nothing miraculous about this; it is simply a little bit of jet propulsion in piston-driven engines and in turbines driving propellers, while in pure jet engines it is, in effect, the *thrust* instead of being drag at all.

30. The Boundary Layer

The study of skin friction has led to an interesting investigation. We have talked about air "flowing over a surface," but probably air never flows over a surface. However smooth the surface may be, the particles of air which are actually in contact with the surface remain stationary relative to the surface and do not move over it. The next layer of air slides over the stationary layer at a small velocity (Fig. **44)**, the next layer slides over that one at a slightly higher velocity, and so on, until eventually the air is moving at what we would call the "velocity of the air." This region (in which the velocity changes from zero at the surface of the body to the full velocity at the outside) is called the ***boundary layer***. Its thickness may be only of the order of one-hundredth of an inch or so; yet, when the rest

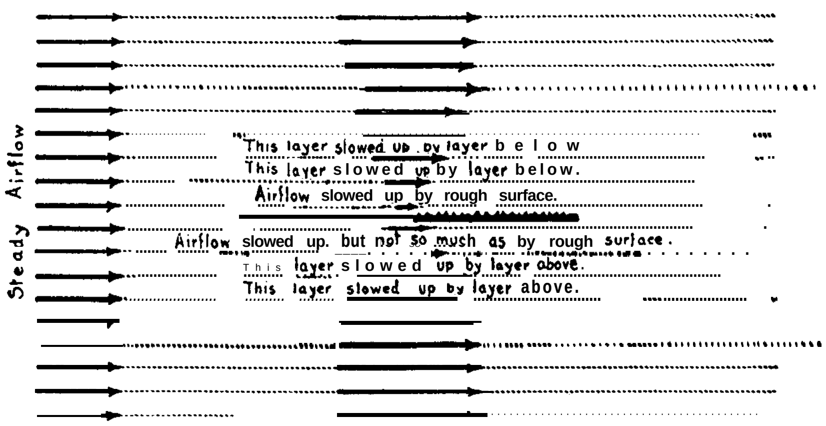


Fig. 44. **Skin friction**

of the air is flowing smoothly, the boundary layer must be in a state of turmoil-called turbulence-and thus cause a lot of drag, which is nothing more or less than the skin friction we have been talking about. It is also the break-away of the boundary layer from the surface which leads to stalling. If we can learn to control this boundary layer, to keep it smooth, to keep it close to the surface, and so on, we may succeed in reducing drag considerably. This can be done by having small holes in the surfaces of wings and other parts, and suction inside the wings (Fig. 45), or alternatively by blowing air out and so smoothing the air flow in the boundary layer-the efflux from jet engines has even been used for this purpose.

It is in the boundary layer that the property of viscosity of the air is important. It is rather difficult to explain what this

term means except by saying that *treacle is very viscous.* It is the tendency of one layer of the fluid to "stick" to the next layer and to prevent relative movement between the two. One can feel this in treacle, one can imagine it in water; but one

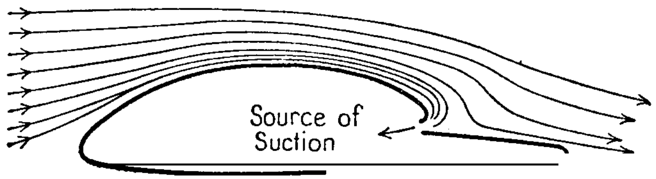


Fig. **45. Control of boundary layer by suction**

would hardly think of air as being "sticky"-yet sticky it is, though of course to a much less degree than water, let alone treacle. It is this property of viscosity that causes skin friction, and in fact it is ultimately the cause of all turbulence, all eddies and all drag. Yet it is only really effective in this small boundary

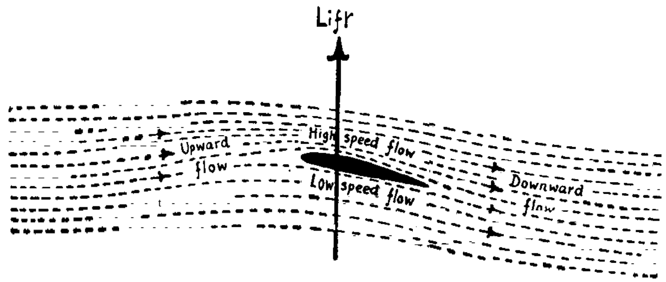


Fig. **46. Flow of air past an aerofoil**

layer, outside which the air behaves almost as though it were not viscous.

Now that we understand something about the boundary layer and viscosity, we can think of lift from a different point of view. If, by means of smoke or other device, we watch the flow of air over a wing inclined at a small angle, we now know that it will look rather like the flow shown in Fig. 46.

'Notice that the streamlines are closer together above the aerofoil than below it, which means that the air must be *flowing faster above the aerofoil and slower below.* Notice also that there is an *upwash in front of the leading edge* and a *downwash behind the trailing edge.* If we could float along in the air stream past the aerofoil, it would almost look as though air was travelling round the aerofoil, because whereas we should be travelling at the same speed as the main body of the air

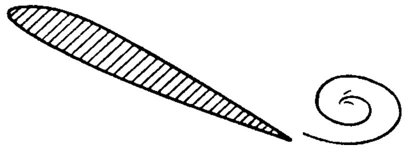


Fig. **47. Starting vortex**

stream, the air in front of the aerofoil would be moving upwards relative to us; the air over the top would be flowing backwards, i.e. faster than us; the air behind would be flowing downwards and on the under surface forward, i.e. slower than us. This idea of flow round the wing is called *circulation* and it is really this circulation that is responsible for the lift. *But it must not be imaginedfrom what has been said that any particles of air actually travel round the aerofoil-it* is all a question of *relative* motion once again.

Of course, this flow of air is outside the boundary layer, which under such conditions of steady flow is of very small thickness, expecially over the front portions of the aerofoil. Yet, in a way which we cannot properly explain here, it is this thin boundary layer which is responsible for setting up the circulation and so causing the lift. It is interesting to note that, when an aerofoil *starts* to move through the air, the boundary layer causes an *opposite* circulation in the form of an eddy shed from the trailing edge (Fig. 47). Such an idea amuses some people, who think it is a fanciful theory-but it is not, it is a

fact, and one which you can very easily see for yourself by moving an inclined surface through water, or even the piece of cardboard through smoke.

When the angle of attack of the wing is increased, the boundary layer becomes thicker and of increasing turbulence, and this turbulence gradually spreads towards the leading edge. Eventually the main flow breaks away altogether from the top surface, large eddies are set up, and stalling, or burbling,

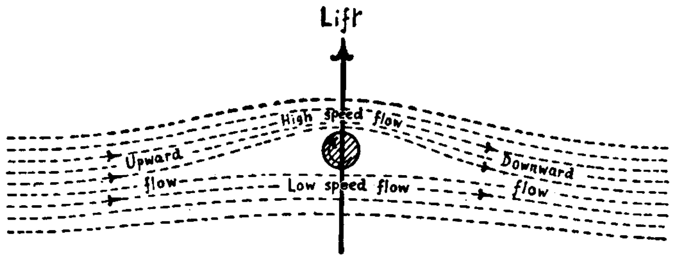


Fig. 48. **Flow of air past a rotating cylinder**

results. Much of the circulation is lost, and so the lift falls off.

Our ideas of circulation become more convincing if we think of a rotating cylinder moving through the air (Fig. 48). The boundary layer will tend to rotate with the cylinder, thus causing an increased speed above and a decreased speed below it (assuming that it rotates in the direction shown in the diagram while it moves from right to left). Also there will be an upwash in front and a downwash behind. In short, we have the same state of affairs as on the aerofoil, and for the same reasons a decrease of pressure above and an increase underneath, and thus a net lift. At first, it sounds a strange idea that a round cylinder can *lift*. It may sound strange, but once again it is no idle theory but a simple everyday fact. If I tell you that it was the principle of Flettner's Rotor Ship, with its large rotating funnels, you may not be much the wiser or the more convinced. But it is much more than that. Do you play golf, football, tennis, cricket, table tennis or any ball game? If so, you will know what is meant by putting "top" or "bottom" spin on a ball, you know how balls are made to swerve accidentally or intentionally as they travel through the air. It is all caused by this mysterious lift (notice once again that lift need not be upwards, but may be sideways or even downwards) ; it is all a question of boundary layer and circulation.

31. Shape of Wing Section

Having considered lift, and drag in its various forms, let us now see if we can discover what shape of wing section will give the best results.

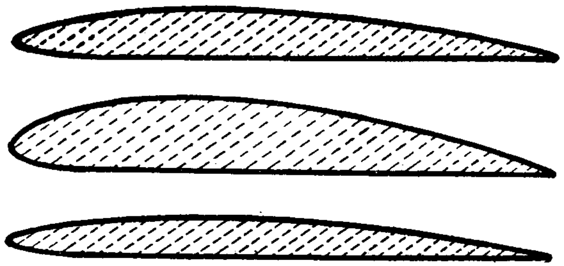


Fig. 49. **Wing shapes with different cambers on upper surface**

Assuming that the wing is to be a double cambered surface, we still have to decide how much the camber shall be. Fig. 49 shows three typical sections with different top-surface cambers and so different thicknesses. Generally speaking, a large camber on the top surface will produce good lift but large drag, not only induced drag, but form drag; for wings too have form drag and skin friction in addition to their induced drag. Different cambers on the under surface do not make so much difference to the lift and drag properties of the aerofoil, but

the modern tendency has been to change from the very much concave cambers of the early aircraft to much flatter cambers, and even to convex cambers as shown in the diagrams. One would think that cambering the under surface in this way would tend to spoil the downwash and thus affect the lift, and this is to a certain extent true; but, on the other hand, the convex under surface has two advantages which probably outweigh any small loss of lift. In the first place, the depth of the wing is increased, and the deeper the wing the lighter can be its construction; and this reduction in weight is more valuable than the loss in lift. Secondly, the convex under

Fig. **50. Laminar-flow aerofoil section**

surface has an appreciable effect on the movement of the centre of pressure, tending to make its movement stable, or at any rate less unstable.

Fig. 50 shows another tendency in what is called a ***laminar-flow wing section:*** notice how thin this section is and how much farther back is the point of greatest thickness than in the more conventional section.

32. Variable Camber

Some advantages result from large camber, others from small camber, and the reader may wonder whether it is not possible to *alter* the camber of a given wing section so as to meet the varying requirements of flight. To do so is certainly a practicable proposition, but it raises a problem which we shall always be coming up against in this subject-whether it is worth while; that is to say, whether we shall gain enough to make up for (perhaps I should say, to *more* than make up for) what we shall lose by the increase in weight of the mechanism involved and the increase in complication. All such devices mean something more to go wrong, some extra lever for an already harassed pilot to worry about.

Many ideas have been suggested, and many ingenious devices patented, in attempts to provide the wing with a "smoothly variable" surface, or even with a variable area. Few of these, however, have got beyond the stage of being ideas, and the only devices that have proved really successful in practice may be summed up under the headings of slots, *slats* and *flaps*. These are perhaps more crude than a smoothly variable wing would be, but they have won the day because they combine effectiveness with simplicity-a combination of qualities that is all too rare in modern aircraft but all the more welcome when it can be found.

33. Slots, Slats and Flaps

Flaps at the trailing edge date back to the First World War, or even before that, but then they were only used on special types of aircraft for special purposes, as for instance on aircraft used in the early experiments in landing on decks of ships. Now, however, flaps are considered to be almost a necessity and, in one form or another, are incorporated in the design of nearly all modern aircraft.

The effect of the trailing edge flap is to increase the camber by lowering the rear portion of the wing, which is made in the form of a hinged flap-similar to an *aileron* (Section 54), except that it probably extends along most of the span of the wing.

The kink thus caused in the top surface may be eliminated by using a *split flap*. In this device the flap portion is split inof two halves, the top half remaining fixed and the bottom half dropping like a lower jaw of a mouth. Many other kinds to special flap have been invented, including some fitted at the

leading edge of the wings, and merits are claimed (by their inventors) for all of them. For some it is claimed that they give the greatest increase in lift, for others that they give the greatest increase in the ratio of lift to drag, and for others that

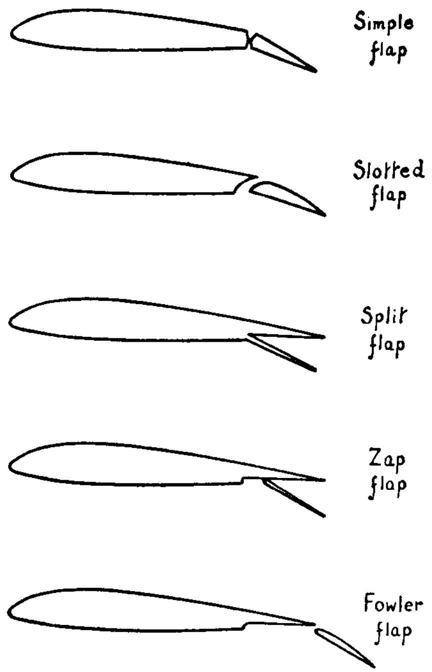


Fig. 51. **Types of flap**

they give the greatest increase in drag. Since all these qualities -even the increase in drag-may be needed for varying circumstances, there may be something in all the claims put forward.

We shall have more to say about various types of flap in a later paragraph (Section 65). In the meantime, have a look at Fig. 51, which illustrates some of the main types.

Slots have not had quite such a long history as that of flaps, and in view of their early promise, have proved somewhat disappointing. The original object of the slot was to delay the stall of a wing and so obtain greater lift from it.

It has already been explained that the cause of the stall is the airflow breaking away from the top surface and forming eddies. In a slotted wing this is prevented, or rather postponed, by allowing the air to pass through a gradually narrowing gap near the leading edge, so that it picks up speed (a venturi in fact) and is kept close to the surface of the wing (Fig. 52). The

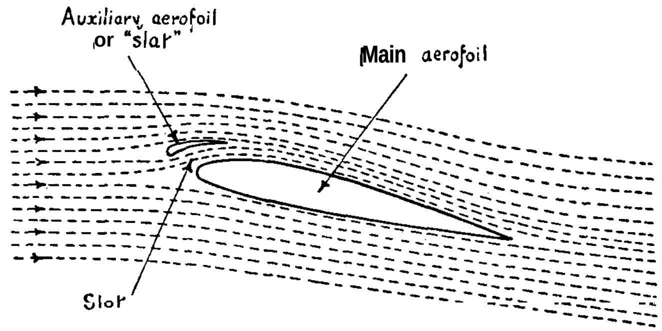


Fig. 52. **Slotted wing**

gap is really the slot-the small auxiliary aerofoil which forms the top surface of the gap is called a ***slat.***

The effectiveness of slots varies with the type of wing section to which they are fitted; in some instances the increase in maximum lift reached may be as much as 100 per cent, while the stalling angle is increased to 25" or 30". From many points of view the increased angle is a disadvantage, as will be explained when we are considering landing, and perhaps this has been one of the main causes of disappointment.

Of course slots, like flaps, should be put out of the way when they are not required ; otherwise they would tend to cause excessive drag. Fortunately this can be done automatically; at small angles of attack, i.e. at high speed, the air pressure on the

slat causes it to close while at high angles of attack, i.e. at low speed, the air pressure causes the slat to move forwards and so open the slot. Sometimes, however, slots are controlled by a lever in the cockpit, sometimes they are combined with flaps, and sometimes they remain open all the time.

34. Aspect Ratio

In addition to the cross-sectional shape of a wing, we must consider its ***plan*** shape, especially the ratio of its ***span (or length) to ifs chord (or breadth).*** This is called the ***aspect ratio*** of the wing. Fig. 53 shows how it is possible to have wings of

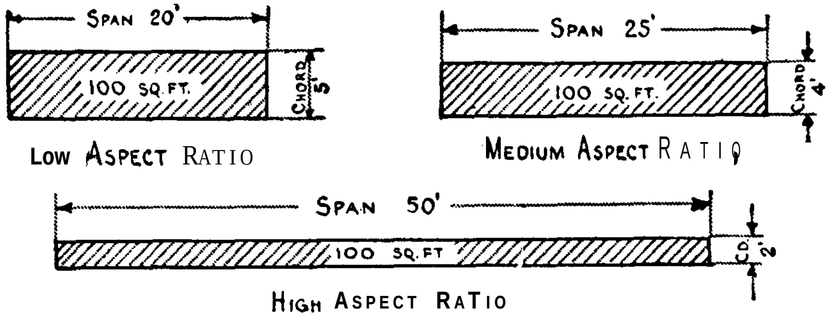


Fig. 53. **Aspect ratio**

the same area but very different aspect ratios. We have said that induced drag cannot be altogether eliminated-because it is an inevitable result of lift. But it can be reduced, even without reducing the lift, and that is where aspect ratio comes in. Experiments indicate that there is a small but quite definite increase in efficiency as we increase the aspect ratio, keeping the area the same. That is why you will notice the very high aspect ratios used on the wings of gliders, sailplanes, and aeroplanes designed for long-distance flying; all cases where efficiency of the wing is of primary importance. But of this we shall have more to say later.

At first it was rather difficult to explain why aspect ratio should be so important, because the elementary theory had led us to believe that the lift of a wing depended on its area, and yet an aeroplane with a high aspect ratio wing was found to be more efficient than an aeroplane with a wing of the same area but lower aspect ratio. The answer to this puzzle is ***induced drag,*** the wing with the higher aspect ratio having less induced drag.

Why does aspect ratio affect the induced drag? To answer that let us go back to the fundamental cause of induced drag, the flow round the wing tip from the high pressure underneath to the low pressure on top, and the consequent outward flow over the lower surface and inward flow over the upper surface of the wing. Imagine a wing that gradually becomes longer and narrower, the wing tips becoming farther and farther apart. Clearly-I nearly fell into the trap of writing "obviously"!—the influence of the flow round the wing tip on the flow over the remainder of the wing will become less and less until, if we reduce the thing to an absurdity by imagining a wing of infinite aspect ratio, there would be no flow round the wing tips for the simple reason that there would be no wing tips. This state of affairs is not quite so absurd as it sounds because we can, in a wind tunnel, fake conditions of infinite aspect ratio. In a closed tunnel we can do this by making the span of the aerofoil such that it just fits into the tunnel and the tunnel walls effectively prevent any flow round the wing tips; in an open tunnel we can do it even more convincingly by testing a wing of which the span is greater than the width of the jet of air, so the wing tips are outside the jet altogether. Fakes of this kind are, in fact, extremely valuable because they enable us to confirm the theory by taking it to its limits; something that

we cannot do in actual flight. As it happens, theory and experiment give extraordinarily similar results in this part of the subject, and prove convincingly that the greater the aspect ratio the less is the induced drag.

As so often happens in the study of flight, we find a fly in the ointment-a high aspect ratio has its disadvantages. These are chiefly structural-adding to the weight and thus eventually cancelling out the effect of increased lift. Another bad point is that a high aspect ratio makes a machine more difficult to manoeuvre, whether in the air or on the ground, and it takes up more space in a hangar.

Thus we must compromise on the question of aspect ratio, just as we had to in deciding the amount of camber. Values used in practice vary from 5 or 6 to 1 for fighters, which must be manoeuvrable, to as much as 20 to 1 for sailplanes, but there are certain rather freak examples right outside these limits-in both directions.

We shall mention later the very low aspect ratios of wings used in flight at supersonic speeds.

Before leaving the subject of induced drag-for the time being; we can never leave it altogether-we must once again modify an impression that may have been left by an earlier remark to the effect that it was a long time before practical men realized the significance of wing-tip vortices, and so of induced drag. If by practical men we mean the men who fly, and perhaps even the men who design aeroplanes, then the remark is substantially true, but it is only fair to say that there were other men, the greatest of whom were Lanchester in Great Britain and Prandtl in Germany, who studied, wrote about and preached the principles of induced drag-though they didn't call it that-in the very early days of aviation ; it can even be claimed that Lanchester did so before any aeroplane ever flew! When one realizes that those principles explain the importance of high aspect ratio, the advantages of the monoplane over the biplane, and the modern ideas about economical flying, it seems rather hard that in their day these men were not considered as practical men, or even listened to by those who considered themselves to be so. But there it is.

35. Biplanes

And *so we* come to ***biplanes.*** It is not easy to discover who first thought of the idea of a biplane, i.e. of using two aerofoils, one placed above the other. Some people, of course, have thought of putting even more planes on top of one another. Many of our ideas about flight have, very naturally, come from birds, but the biplane idea seems to be a purely man-made invention, though some naturalists claim that there are biplane insects. At any rate, the first aeroplane to fly was a biplane, so the idea is at least as old as the history of flight.

We noticed in an earlier paragraph that very large wing areas are required for flight, and the advantage of the biplane was that this large wing area could be arranged in a more compact fashion, making the finished aeroplane more convenient to handle both on the ground and in the air. The biplane structure seemed more suited than the monoplane to give us what we most required: strength without weight. So far the biplane seemed to have all the advantages; why, then, has it proved the loser in the long run?

It is as a wing, as an aerofoil, that the monoplane has always been superior. Remembering how the pressure is distributed round a wing section, let us put two such sections together, one above the other, and observe the effect (Fig. 54). We find that the increased pressure on the under surface of the upper wing is not so effective as it was when it was alone-still less is the decreased pressure above the lower wing

so effective; thus both upper and lower wings suffer. There is, in fact, an interference between the two wings and this is called ***biplane interference.*** Another way of thinking of it is to consider the induced drag, which is greater on a biplane—with its four wing tips-than on a monoplane of the same

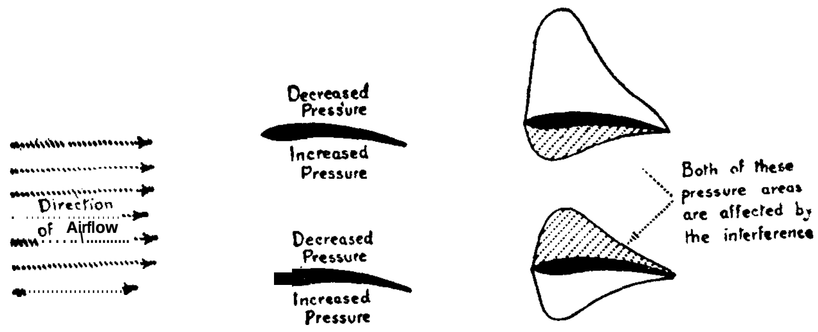


Fig. **54. Biplane interference**

wing area, and so the overall lift/drag ratio of the monoplane is better than that of the biplane.

The biplane enthusiast, full of confidence owing to the structural superiority of the biplane, persistently endeavoured to minimize this disadvantage.

His first idea was naturally to increase the ***gap,*** i.e. the distance between the two wings. This expedient had its effect in reducing interference, but very large gaps were needed to make the effect appreciable, and very large gaps meant an increase in structure weight, which, after a limit had been reached, outbalanced the advantage gained.

But our biplane fan was not yet baffled. He next tried to eliminate the interference by ***staggering*** the planes, in other words separating them horizontally rather than vertically. When the leading edge of the upper plane was in front of the leading edge of the lower plane it was called ***forward*** or *positive*

stagger; when behind it, it was called ***backward or negative stagger.*** Forward stagger definitely served its purpose, and there was a small but appreciable increase in lift when compared with an unstaggered biplane of the same gap. Backward stagger, although it appeared hopeful, was most disappointing from this point of view; in fact it actually did more harm than good.

Stagger, however, had certain practical advantages, and for this reason was adopted on most biplanes. Access to cockpits was usually improved, and, above all, the view of the pilot became more extensive. This latter point is very clearly shown in Fig. 55.

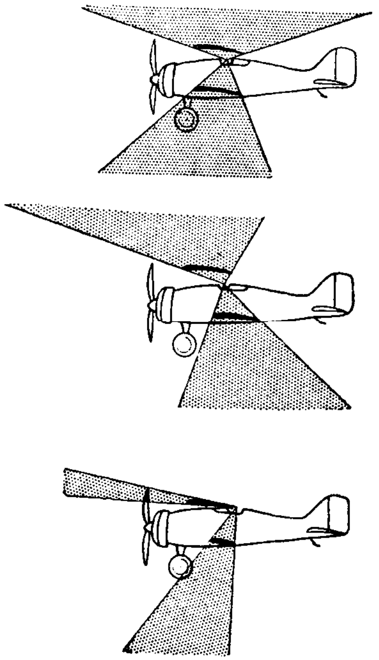


***Fig. 55.* Angles of view**
The shaded areas shows the blind spots

The reader who is not used to flying may not realize the seriousness of this question of field of vision. On the other hand, the reader who flies frequently has probably become so accustomed and resigned to seeing only a little less than nothing during flight that he does not realize how many "blind spots" there are in the average aeroplane-whether biplane or monoplane.

Anything that can be done to enlarge the pilot's field of vision is a step in the right direction, and may well have turned the balance in favour of stagger.

The ***sesquiplane***—or one and a half plane-was really a compromise between a monoplane and biplane. The reader may have noticed that we are frequently using that word "compromise" ; no wonder, because it crops up in every part of aeroplane design. A finished aeroplane ***is*** a compromise from beginning to end. We want this, we want that; but we cannot have both this and that, so we end up by having a bit of each. The sesquiplane was a bit of a monoplane and a bit of a biplane. The structure was that of a biplane and had its consequent advantages; on the other hand, the lower plane was so small that it caused hardly any interference with the upper plane, which was therefore "almost a monoplane." Plates 3 and 5 illustrate this tendency towards a large upper plane and small lower plane.

But even in a sesquiplane there were struts and wires to connect the two planes, and when, further to tip the balance, experience in structural design and the improvement of structural materials, together with other advances in aeroplane design, made it possible for a monoplane structure to be as efficient as that of a biplane, designers came slowly but surely round to the opinion that the monoplane was the best type. So perhaps the birds, not to mention Lanchester and Prandtl, were right after all.

36. Lift and Drag-A Summary

We have so far considered the forces that act upon bodies due to their movement through the air, and how they experience lift, or drag, or both, according to their shape, speed, and so on. We are now in a position to study something even more interesting-the flight of the aeroplane as a whole-but, before doing so, let us sum up what we already know about lift and drag :

(a) A body that is pushed or pulled through the air causes a disturbance in the air and, in consequence, experiences a force.
(b) The amount of this force depends on the shape of the body,
(c) on its speed through the air (actually, speed squared),
(*d*) on its size,
(e) on the smoothness of its surfaces,
(*f*) and on the density of the air through which it passes.
(g) That part of the force which is parallel to the direction of the air flow, that is to say which acts against the motion of the body, is called drag.
(h) That part of the force which is at right-angles to the direction in which the body is travelling is called lift.
(k) A wing is designed to give as much lift as possible with as little drag as possible.
(I) Other parts of the aeroplane, if they cannot be eliminated altogether, are designed to give as little drag as possible—the drag of these parts is called parasite drag.
(m) Drag caused by the shape of a body is called form drag—this is reduced by streamlining.
(n) Drag caused by roughness of surface is called skin friction.
(*o*) Wings also experience induced drag, as an inevitable consequence of their lift.

(*p*) The wing is pushed or pulled through the air at a small angle called the angle of attack or angle of incidence.
(*q*) This motion produces a downwash which in turn causes the upward reaction or lift.
(*r*) As the angle increases the lift increases up to a certain angle called the stalling angle.
(s) Wing sections are curved or cambered, usually on both top and bottom surfaces.
(t) The decrease in pressure on the top surface is caused by the speeding up of the flow over that surface-as in a venturi tube.
(*u*) Slots and flaps are the most practical means of producing variable camber.
(*v*) The top surface of a wing contributes more lift than the bottom surface, the front portion more than the rear portion.
(w) The centre of pressure is therefore well forward.
(*x*) As the angle changes, the centre of pressure may move in a stable or unstable way-with most aerofoils the tendency is unstable.
(*y*) Wings of high aspect ratio are the most efficient, because they have less induced drag.
(z) After a long struggle the monoplane has won the day over the biplane.

Yes, we have exhausted the alphabet and, what is more important, we have already learnt the main principles on which flight depends.

37. Straight and Level Flight

Let us now apply these principles to the flight of the aeroplanes as a whole. This is where it all becomes more interesting; it is where the practical men, namely those who build and