THE AIR PROPELLER

Its working characteristics and theory, together with a brief discussion of the airplane engine and the power available for airplane propulsion

BY

FREDERICK BEDELL, PH.D.

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PREFACE

It is with some hesitation that the writer adds to the literature of the propeller. He has been lead to do so, however, because many discussions of the subject are unsatisfying and in some cases are not in accord with fact. Indeed, misconceptions of the behavior of a propeller are not uncommonly held even by those who are otherwise well-informed on aerodynamic subjects.

The author has endeavored to present a brief and simple treatment of the propeller for those who want a practical working knowledge of its characteristics and a general knowledge of its theory. It is believed that the treatment will at the same time serve as a general introduction for those who wish to pursue the subject further and to make a more detailed study of the propeller, either in its theoretical or practical aspects.

As the material herein is soon to be revised and republished* in another form, the author would welcome criticism, and would be pleased to have his attention called to any error or obscurity in presentation. He desires to thank Professor S. Noda, Honorary Fellow in Physics, Cornell University, for valuable assistance in the preparation of this book, particularly in the calculation of the characteristics of the propeller.

ITHACA, N. Y.,
August, 1919.

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*To be included in The *Airplane*, now in preparation; see notice preceding title page.

CONTENTS

POWER AVAILABLE FROM THE AIR PROPELLER AND THE AIRPLANE ENGINE

The **power required** for airplane flight at different velocities depends upon airplane structure, varying as the product of airplane velocity and the total airplane resistance. Neither the source of power nor the amount of power available is involved in the determination of power required, which is quite independent of propeller and engine. Curves for power required are shown in an appendix and will not be discussed here.

On the other hand, the power that is available for driving the airplane forward, called **power available** or **thrust horse power,** depends entirely upon the air propeller and the airplane engine. The power available is derived directly from the thrust of the propeller, being proportional to the product of propeller thrust and the forward velocity of the airplane; in horse power, it is equal to the product of thrust in pounds and velocity in miles per hour, divided by 375. The power necessary for driving the propeller in order to obtain this thrust is supplied by the airplane engine. Although the propeller and engine perform their separate functions, the conditions of operation of the one are dependent upon the operating characteristics of the other, for the power the propeller absorbs must exactly equal the power the engine delivers and the speed of rotation of the one must be the speed of rotation of the other.

Although no complete discussion of the airplane engine can be here undertaken, an outline will be given of its chief characteristics that have a bearing on the power available in airplane flight. This will be followed by a more complete discussion of the air propeller, its *Conditions of Operation*, its *Characteristics* and its *Theory*.

The Airplane Engine

The gas engine is the airplane engine in general use on account of light weight.

The internal combustion engine—or the "gas engine" as it is more popularly known—made flight possible; and, although some* of its characteristics are not the best for airplane flight, it meets the important requirement of *low weight per horse power.* Each year airplane engines have been made of greater power and less weight per horse power, a great advance† being made by the Liberty motor (1918) which gave 450 H.P. with a weight of only 1.8 lbs. per H.P.

Although other types of engine may hereafter be introduced,—possibly in huge aircraft requiring many thousand

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*Particularly undesirable is the decrease in the power developed by a gas engine at high altitudes, the power developed being in direct proportion to the density of the air, as discussed in a later chapter. At an altitude of about 20,000 feet, only half as much power is developed as near the ground. To obviate this decrease in power with altitude has been the aim of inventors. Methods for accomplishing this have been devised but are not in general use. (The chapter on altitude is not included in this volume.)

†*Size and weight of engines.*—The original motor of the Wright Brothers, used in the first airplane flight in 1903, gave 12 horse power, with a weight of 12.7 lbs. per horse power. The development of the airplane engine since then, until the 1918 Liberty motor, is shown by the following table. The numbers, except in the first and last column, are average values of principal engines for each year.

Year	1903	1910	1914	1915	1916	1917	1918
Horse power	12	54	112	133	185	243	450
Weight, lbs.	152	309	437	512	570	693	825
Lbs. per H. P.	12.7	5.7	3.9	3.8	3.1	2.8	1.8

To obtain greater power than can be obtained from a single engine, several engines (and usually as many propellers) are employed. As many as six engines, developing a total of 3000 H. P. have thus been used. The N C 4 hydroplane, in the first trans-Atlantic flight (1919), was equipped with four Liberty motors.

horse power,—the gas engine may be looked upon as *the standard type* of airplane engine and it only need be here considered.

Variation of engine power with speed.

The power developed by a gas engine, with throttle wide open or in other constant position, increases in proportion to the number of explosions in a given time and hence in proportion to the number of revolutions per minute, which hereafter will be referred to as the speed N. For a considerable range of speed this proportionality is quite close, power increasing in direct proportion* to speed; but for higher speeds the power increases less rapidly, and finally a speed is reached at which the power is a maximum and beyond which the power falls off. This falling off in power is due largely to the fact that the fuel-charge received in the cylinders for each explosion is reduced at high speeds on account of the increased friction through ports and passages.

The variation of power with speed for a typical engine† is shown in Fig. 44, in which the solid curve shows the brake horse power when the throttle is wide open. It is seen that power increases very nearly in proportion to speed until, in this case, a maximum of 106 H.P. is reached at a speed of 1240 R. P. M.

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*Power varies as torque x speed. When power varies in direct proportion to speed, torque is constant. The torque in a gas engine is nearly constant through the working range. As the power curve falls off from a straight line, the torque decreases.

†One hundred H. P. Gnome Monosoupape Motor. This particular motor is no longer made. Its performance, however, may be taken as typical.

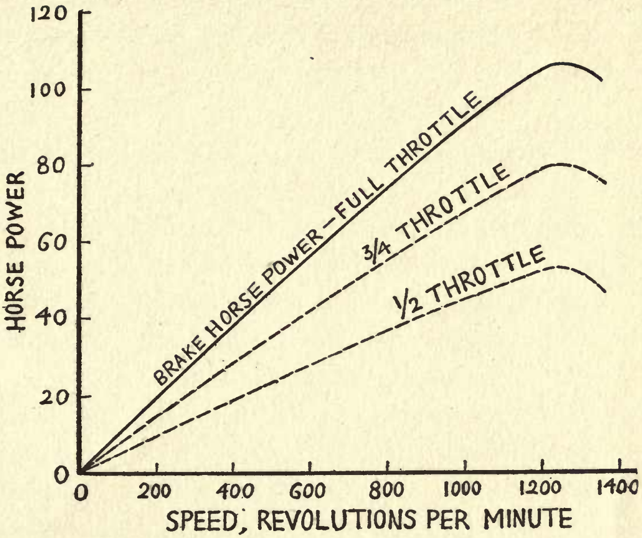

Fig. 44. Variation of brake horse power of a typical gas engine with speed. Dotted curves show reduction of power by throttle control.

Mechanical efficiency.

The entire power developed by the explosions in the cylinders of a gas engine is called the **indicated horse power** or **I. H. P.** Some of this power, however, is wasted in friction and other losses within the engine, so that the useful delivered horse power—called the **brake horse power** or **B. H. P.**—is, let us say, 10 or 15 per cent. less than the indicated horse power.

The mechanical efficiency of the engine is the ratio of the brake horse power to the indicated horse power; thus when the losses are 10 or 15 per cent., the mechanical efficiency is 90 or 85 per cent. The efficiency of an engine, as well as its power, varies with the speed at which the engine is run. The efficiency is low at low speed and at very high speed (*i. e.*, when the power delivered is low) and is nearly a maximum when power is a maximum. The speed for maximum efficiency is a little lower than the speed for maximum power, but the efficiency remains high (within a few per cent. of its maximum value) for a wide range of speed —a range, let us say, of twenty or thirty per cent. (In Fig. 44, this range extends roughly from the beginning of the word Throttle to the point of maximum power.)

Range of engine speed.

The best speed for engine operation is no one precise speed but extends through a moderate range of values just below the speed for maximum power. In this range, efficiency and power are both high; beyond this range, however, there is a large falling off both in efficiency and in power.

An engine is often run at a lower speed than this best range, when such lower speed and power is desirable, despite the lower efficiency; but it is rarely run at much higher speed, on account of increased wear and heating of the engine, as well as decrease in power and efficiency.

The best speed depends upon the design of the engine,—size of ports and bore, length of stroke, mass of moving parts, etc. As a usual thing, airplane engines are designed for a lower speed than automobile engines so as to permit of direct connection to the propeller. Structural and other reasons make high propeller speeds undesirable, the usual speeds being between 1200 and 1600 R. P. M.; but speeds beyond this range are not uncommon.

A propeller may be geared down, so as to gain the advantage of high engine speed with low propeller speed, but this gearing adds weight, introduces losses and is an added source of trouble.

Throttle control.

The solid curve for brake horse power in Fig. 44 shows the full power when all adjustments of throttle, spark and carburetor are made so as to give the greatest possible power at each speed. Usually, the pilot controls the power by means of the throttle, less power being obtained by partly closing the throttle. (In some engines, however, the only power control is the ignition switch, by which the power is turned either entirely on or off.)

Dotted curves in the same figure, marked "three-quarters throttle" and "half throttle," show the power obtained by throttling the engine so that, at each speed, the power is three-quarters or one-half the full power at that speed. To obtain precisely the same fraction of full power at each speed would require some adjustment of throttle (with constant throttle, the fractional power being not exactly three-fourths or one-half, or other definite proportion of full power, at all speeds), but this adjustment would not be great. The curves may, therefore, be considered as illustrating the variation of power with speed for various constant throttle positions; they are sufficiently correct for this purpose, although for exact computation they would require some modification. (These dotted curves practically show, also, the decreased power at higher altitudes, for, as discussed later under Altitude, the decrease in air density causes a decrease in power substantially the same as throttling.)

The curves in Fig. 44 are *engine characteristics* and show the power delivered by the engine at different speeds and with different amounts of throttle. Before we can determine how much power is available for flight, we must examine the characteristics of the air propeller.

The Air Propeller

(*a*) *Introductory*

The air propeller is mounted on or geared to the engine shaft,—either ahead of the engine as a **tractor,** or behind it as a **pusher.** The propeller is usually constructed with two blades, as in Fig. 45, but not uncommonly it is constructed with four and less commonly with three blades when propeller diameter is limited by the space available. The three-blade propeller is structurally difficult. The requisite strength is most readily obtained with two blades, which pass through the hub as one member.

The forward thrust required to overcome airplane resistance in flight is obtained by the propeller driving back a stream of air in a so-called **slip-stream;** the greater the backward velocity of this slip-stream and the greater its volume, the greater is the forward reaction or propeller thrust.

In the same way that an upward force or lift is obtained from a moving aerofoil because it deflects the air stream *downward,* a forward force or thrust is obtained from a moving propeller blade because it drives the air stream *backward.* In each case the force is a reaction obtained by deflecting or driving the air particles in a direction opposite to the force.

Although there are various ways of treating the propeller and it is commonly referred to and considered as an air screw, it is most satisfactory to consider the propeller blade—or each element thereof—as an aerofoil, with lift and drag determined by its cross-section and angle of incidence as for any aerofoil. The lift of a propeller blade as an aerofoil determines its thrust as a propeller; its drag as an aerofoil determines the torque necessary to drive it as a propeller, as discussed more fully later.

Screw definitions; pitch and pitch ratio.

Although the action of a propeller is very different from that of a screw, various terms that originated with the screw are applied to the propeller.

When a screw passes through a solid, the distance it moves forward in one revolution is called the **pitch** of the screw. This distance divided by the diameter of the screw is called its **pitch ratio.** The pitch and pitch ratio of a screw may be exactly determined from its dimensions (the distance between threads, and the diameter), the values thus determined being identical with the values determined by actually driving the screw through a solid or turning a bolt in a nut.

The terms pitch and pitch ratio are applied to a propeller as to a screw. It is found, however, that the **effective pitch*** of a propeller—the distance the propeller moves forward through the air in one revolution—is not the same as its **structural pitch** (also called **nominal pitch** or **geometrical pitch**) determined from its dimensions as a screw passing through a solid.

In propeller operation it is its effective pitch, rather than its structural pitch, in which we are most interested. As shown later, the effective pitch of a propeller varies with conditions of operation, being sometimes less and sometimes more than the structural pitch which has but one value fixed by its dimensions.

Definitions of torque horse power, thrust horse power and efficiency.

The power available for propelling an airplane through the air comes directly from the propeller thrust, the amount

*Called also "experimental pitch."

Fig. 45. Two-blade propeller.

of power thus furnished, as already pointed out, being proportional to the product of propeller thrust and airplane velocity. The propeller itself, however, does not create this power; it merely *transmits* power that it receives from the engine, the power it thus receives being proportional to the product of the torque* in the propeller shaft and its speed in revolutions per minute. The speed of the propeller is the speed of the engine, unless reduced by gearing. "Speed," here and elsewhere in this discussion, refers to speed of rotation, often referred to as "revs." or R. P. M., and not to the forward translation referred to as "velocity" or "miles per hour."

Of the three elements for flight,—engine, propeller and airplane,—the propeller is thus seen to be the intermediary or "middle-man," receiving power from the engine and delivering this power in a form available for propelling the airplane. The power the propeller receives is **torque horse power** and this is the brakehorse power of the engine already discussed. The power the propeller delivers is **thrust horse power** and this is the power available for airplane propulsion.

The **efficiency** of a propeller is the ratio of thrust horse power to torque horse power. The entire output of the engine would thus be available as thrust horse power for propelling the airplane, if the efficiency of the propeller were 100 per cent. On account of losses, however, the efficiency of a propeller is less than 100 per cent., so that not all of the engine output is thus available. Under best conditions,

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*Torque is a turning moment equal to the product Fr of a force F and the perpendicular distance r from the force to the center of rotation. If F is in pounds and r in feet, torque horse power is $2\pi N F r/33000$, for one horse power is 33000 ft. lbs. per min.

the efficiency of a propeller may be 80 or 85 per cent., but under working conditions it is usually less; thus, when the brake horse power of the engine is 100, perhaps only 60 or 70 horse power may be available for propeller thrust.

The air propeller, working in a compressible medium, is more efficient than the marine propeller working in a medium that is practically incompressible. The rarefaction and compression before and behind the blade of a propeller in air—as above and below an aerofoil—are factors not found in water. (In water, when a negative pressure created by the relative motion of blade and water exceeds the static pressure of the water, it is not possible for the water to become rarefied but a discontinuous flow occurs known as *cavitation*. To avoid this, the blades of a marine propeller are made short and wide, and not long and narrow as in an air propeller.)

A knowledge of how power* and efficiency are affected by different conditions of operation is most essential for the understanding of the propeller. Fortunately these relations, so far as results in operation are concerned are simple.

Let us first see what are the varying conditions of propeller operation. We will then see what are the characteristics of a propeller under these different conditions of operation, after which we will consider the theory of the propeller that accounts for these characteristics.

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*Power is of first importance. It makes little difference how efficient a propeller is, if it does not have enough power to do its intended work. A small desk fan, even were it 100 per cent. efficient, would not serve for propelling an airplane so well as a propeller with adequate power having an efficiency of only 50 per cent. Adequate power being assured, conditions of operation that give high efficiency should be sought.

(*b*) *Conditions of Propeller Operation*

V and N, the two variables in propeller operation.

During flight the two variables in propeller operation upon which other quantities depend are its forward velocity V and its speed or revolutions per minute N. (The effect of a third variable, the change of air density with altitude, is left for a later discussion.) The dimensions and shape of the propeller itself can only be changed by a change of propeller when not in flight.*

It will be found that propeller characteristics depend not only upon the absolute values of V and N but upon their relative values as well. The ratio of V to N, and the ratio V/ND, where D is propeller diameter, have special significance.

The values of V and N are known to the pilot by his air-speed meter and his revolution indicator. They are, furthermore, quantities that he directly controls. For these reasons, propeller characteristics are better understood—by a pilot at least—when expressed in terms of V and N than when expressed in terms of effective pitch, angle of blade incidence or slip, quantities that are only indirectly known and controlled by the pilot. It is well, however, to be able to interpret propeller characteristics when expressed in these various terms, for each has its significance; effective pitch and slip are convenient terms in the comparison of propellers of different diameter, while the angle of incidence the blade makes with the air is useful in propeller theory, as discussed later.

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*Adjustable propellers, in which the pitch can be changed during flight, have been used but have not been widely introduced.

V/N, the forward travel per revolution or effective pitch.

When a propeller making N revolutions per minute, is moving forward with a velocity of V ft. per minute, the distance that the propeller moves forward in one revolution is seen to be V/N feet. This distance, in feet or other unit of length, is called the **effective pitch** of the propeller; it varies with the relative values of V and N, under different conditions of operation, but is independent of their absolute values. (Thus, when $V = 5000$ ft. per min. and $N = 1000$ R. P. M., the propeller moves forward in one revolution a distance $V/N = 5$ ft., which is the effective pitch of the propeller; when $V = 6000$ and $N = 1200$, the effective pitch V/N is still equal to 5 ft.)

V/ND, the ratio of forward travel per revolution to diameter, or effective pitch ratio.

This forward travel per revolution, when expressed in term of propeller diameter D (instead of in feet) is V/ND and is called the **effective pitch ratio.** Thus, in the preceding example, if the propeller has a diameter of 8 feet, $V/ND = 5 \div 8 = 0.625$, which is the effective pitch ratio of the propeller and means that in each revolution the propeller travels forward a distance 0.625 times its diameter. V/ND is a number, independent of units; the units used, however, must be consistent.*

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*If N is expressed in R. P. M. and D in feet, V must be expressed in ft. per minute. For example, an 8 ft. propeller makes 1200 R. P. M. When $V/ND = 0.5$, $V = 0.5 \times 1200 \times 8 = 4800$ ft. per min. (54.5 MPH.); when $V/ND = 1$, $V = 9600$ ft. per min. (109 MPH.). The value of V/ND is frequently in this range (0.5 to 1.0), but these values are given for illustration and not as limits.

If N were revolutions per sec. and D meters, V must be meters per second; V/ND would be unchanged, being independent of units.

The value of V/ND indicates, to a certain extent, the conditions of propeller operation. Being independent of units, it is more useful for this purpose than V/N. Various propeller quantities (for example, efficiency, Figs. 55 and 56) are accordingly plotted in terms of V/ND.

Since the peripheral velocity of a propeller is πND, it is seen that V/ND is proportional to the ratio of the forward velocity to the peripheral velocity of the propeller tip.

Dynamic pitch and pitch ratio.

The effective pitch, or forward travel of a propeller per revolution, as just stated varies under different conditions of operation. It will be shown later, that as effective pitch increases, thrust decreases and finally becomes zero. The propeller then goes through the air smoothly, as a screw with no slip, without disturbing the air and without imparting velocity to the air particles.

The particular value of effective pitch that gives zero thrust is called the **dynamic pitch** of the propeller. It is characteristic of each propeller and like a dimension (expressed in feet or other unit of length) can not be changed.

The **dynamic pitch ratio** is the ratio of the dynamic pitch to the propeller diameter D, and is a number independent of units. Otherwise defined, it is the value of V/ND when there is no thrust and no slip.

As an illustration, if a 10 ft. propeller creates no thrust when its forward travel per revolution is $V/N = 9$ ft., the dynamic pitch ratio is $V/ND = 9 \div 10 = 0.9$. This is a constant of the propeller and is the same whether V and N be large or small. Practical values for dynamic pitch ratio are between 0.5 and 1.5.

Slip.

Positive thrust is obtained only when the forward travel per revolution, or the effective pitch, is *less** than the dynamic pitch. The difference between the dynamic pitch and the effective pitch, expressed as a percentage of the former, is called the **slip.** Thus, when a propeller with a dynamic pitch of 8 feet travels forward only 6 feet in one revolution, the slip is 25 per cent., or 0.25.

When the slip is s per cent., the forward travel per revolution is

$$V/N = \text{effective pitch} = (1 - s) \text{ dynamic pitch.}$$

As a ratio in terms of D, we have accordingly

$$V/ND = \text{effective pitch ratio}$$
$$= (1 - s) \text{ dynamic pitch ratio.}$$

It is seen that when the slip is zero, the effective pitch becomes equal to the dynamic pitch.

Dynamic pitch greater than structural pitch.

The dynamic pitch and pitch ratio of a propeller is greater† than the nominal or structural pitch and pitch ratio. In other words, the actual forward travel of a propeller through the air for no thrust is greater than its travel calculated as a screw passing through a solid, unyielding material. It is for this reason that the screw theory of the propeller is abandoned.

The explanation lies in the fact that the air through which the propeller is passing is a compressible gas and not an unyielding solid. The propeller blade in cutting through the air acts not as a screw but as an aerofoil—as discussed later

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*When the travel is greater than the dynamic pitch and the slip is negative (as in diving) a negative thrust is developed, the propeller then acting as a brake; see Fig. 51.

†Forty-eight propellers discussed by Durand in Report No. 14, referred to later, have values of dynamic pitch between 1.17 and 1.54 times the nominal pitch.

under propeller theory—and, like any aerofoil, gives rise to a rarefaction* on its upper surface (in front of the propeller) and a condensation on the lower surface (back of propeller). Calculations for a propeller as a screw take no account of this rarefaction and condensation of the air and for this reason calculated or nominal values for pitch and pitch ratio always differ from the actual dynamic values. The result in flight is much the same as though the whole body of air immediately surrounding a propeller were being carried forward with it, so that more than the calculated velocity is necessary in order to get zero thrust and this may serve as a rough explanation.

Dynamic pitch and pitch ratio can only be determined by experiment, where special facilities are available, whereas nominal pitch or structural pitch and pitch ratio can be determined by measurements described later on the propeller itself. For this reason the values for pitch and pitch ratio usually given are *nominal values*, and are always so understood *unless otherwise specified.*

The relation between V and N and the significance of slip, pitch and pitch ratio in propeller operation will be brought out more fully in the subsequent discussion of propeller characteristics and propeller theory.

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*See "Airplane Characteristics," p. 117.

(*c*) *Propeller Characteristics*

The behavior of a propeller under various conditions of operation will be understood by examining the characteristic curves that follow. These are working results, independent of any theory, the performance of the propeller being to many readers of first importance. A discussion of theory will follow, but some may prefer to read the theory before examining the performance.

The conditions of operation depend upon the relation between *V* and *N*, and this in turn requires first a study of torque horse power. Other characteristics will be studied in turn.

Torque horse power for different values of N and V.

The torque horse power required to drive a given propeller varies both with its speed *N* (revolutions per minute) and the forward velocity *V* (miles per hour) at which it is moving through the air.

For any constant value of *V*, torque horse power increases as the revolutions per minute increase; in other words, it is found, as might be supposed, that more power is required to turn a propeller fast than to turn it slowly. This is shown by the curves in Fig. 46 for the torque horse power of a particular* propeller at three different velocities, 50, 100 and 150 miles per hour.

By comparing these curves it is seen that the torque horse power is less for high than for low velocities.

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*The curves in Figs. 46 (and subsequent curves, unless otherwise stated) relate to a propeller 8′ 9″ in diameter, with nominal pitch ratio 0.9. The curves have been plotted from calculations based upon experimental data for Propeller No. 3, as given by W. F. Durand in Report No. 14, National Advisory Committee for Aeronautics, 1917. All curves relate to ground level, air density = 0.0789. The point *m* on any curve is the point of maximum propeller efficiency.

The decrease in torque horse power as V increases is better shown by the curves in Fig. 47 in which N is constant and V is variable. It takes less power to drive a propeller, at any given number of revolutions per minute, when the propeller has a forward velocity V than when it is stationary. Propeller thrust, as discussed later, is a maximum when the propeller is stationary; torque, also, is then a maximum, as well as torque horse power as shown by the curves.

As V increases, torque horse power continues to decrease and becomes zero when a certain velocity is reached. At higher velocities, torque horse power is negative; the propeller, instead of receiving power from the engine, then *drives the engine*, receiving power as an air motor from the air. This means that the airplane is descending in a glide or dive and that power is supplied by gravity. The airplane is being retarded by the propeller as by a brake.

Torque horse power is an important element in determining the relation between N and V.

Relation between N and V.

The velocity V of an airplane in flight is determined by its angle of incidence, as discussed in Chapter* II, and is controlled entirely by the elevator. *The revolutions per minute or speed N, although* controlled by the throttle, *depend not only upon engine throttle but also upon airplane velocity V.* Let us see in what way the speed N is determined.

For any given velocity, for example V = 100 M P H., we have a curve, as in Fig. 46, showing torque horse power for each value of speed N. But torque horse power received by the propeller must equal brake horse power delivered by the engine. The engine and propeller, accordingly, speed up

*See "Airplane Characteristics."

until a speed N is reached at which the propeller absorbs all the power output of the engine, that is, they speed up until torque horse power of the propeller and brake horse power of the engine are exactly equal.

This is made clear in Fig. 48, which shows a curve for engine brake horse power for a particular amount of throttle (reproduced from Fig. 44 with full throttle) and a curve for propeller torque horse power for a particular velocity (reproduced from Fig. 46 for $V = 100$ M P H.) The intersection* of these two curves determines the speed N and also the power, for the particular value of V and particular amount of throttle. The intersection will be shifted as either curve is shifted by control of throttle or change of V; or, both curves may be shifted simultaneously with a sort of scissors motion.

Value of N for different amounts of throttle.—The control of speed and power by throttle, for one value of V, is shown in Fig. 49. As the throttle is changed from "full throttle" to "¾ throttle" and "½ throttle," the intersection is changed from N' to N'' and N''', with corresponding change in speed and power.

Value of N for different values of V.—The change of speed and power for several different values of V, is shown in the same manner in Fig. 50. The speed and power corresponding to velocities of 50, 75, 100, 125 and 150 M P H., are determined for "full throttle," "¾ throttle" or "½ throttle," by the several intersections.

*Curves may be drawn for engine and propeller torque, instead of engine and propeller power, determining N by their intersection in the same manner. Curves for propeller torque, at different speeds N, are continuously rising curves, somewhat like the curves for torque horse power in Fig. 46. Curves for engine torque at different speeds are nearly horizontal, through a certain range of speed, dropping sharply at higher speeds.

It is seen that the speed N of engine and propeller depends not only upon engine throttle (which is directly controlled by the pilot), but also upon airplane velocity, which is indirectly controlled by the pilot by means of the elevator. For constant throttle, there is a definite speed N corresponding to each velocity V; and for constant velocity, there is a definite speed N for each position of the throttle.

The curves shown, Figs. 48, 49 and 50, relate to a particular propeller and engine; for other engines and propellers the general nature of the results would be the same, although numerical results would differ.

Thrust horse power at varying velocities.

A consideration of the thrust horse power delivered by a propeller under different conditions of operation is obviously of utmost importance, the sole purpose of a propeller being to produce thrust and thrust power. Like other propeller quantities these both vary as N and V are varied. It is, however, most satisfactory to plot their values for varying values of V, so that direct comparison can be made between curves for thrust power (power available) and curves for airplane power required, which are plotted in terms of V.

Before discussing thrust power, let us consider propeller thrust upon which thrust power depends.

Propeller thrust.—Thrust depends upon the backward velocity imparted to the air by the propeller, that is, the backward velocity of the slip stream *with respect to the surrounding stationary air.* The thrust developed by a propeller will, accordingly, vary with the forward velocity V of the propeller and will be a maximum when V is zero, namely, when the airplane is stationary), for the velocity of the slip stream, with respect to the surrounding air, is then a maximum. The thrust, when the airplane is stationary, is called the **static thrust.**

When the propeller is moving forward with a velocity V, the backward velocity of the slip stream (which remains unchanged with respect to the propeller) is less with respect to the surrounding stationary air and the thrust is accordingly less. **Thrust decreases as V increases,** as shown in Fig. 51.

Thrust continues to decrease as V increases, and finally thrust becomes zero when the propeller has a forward velocity V just equal to the backward velocity of the slip stream relative to the propeller. The velocity of the slip stream, with respect to the stationary air, is then zero and no thrust is created, for no velocity has been imparted to the air by the propeller. Slip is then zero.

The solid curve in Fig. 51 shows the variation of thrust with velocity for a particular propeller when driven at 1200 R.P.M. The dotted curves show the thrust at 1000 and 800 R.P.M. In all cases zero slip corresponds to zero thrust; 100 per cent. slip corresponds to zero velocity.

Thrust horse power derived from thrust.—Thrust horse power is readily derived from thrust, being equal to the product of thrust and velocity, divided by 375 when thrust is in pounds and velocity is in miles per hour.

Fig. 52 shows curves for thrust and velocity, and a curve for thrust power thus obtained from their product. It is seen that thrust power is zero when $V = 0$, at 100 per cent. slip; thrust is then a maximum. It is seen, also, that thrust power is zero when thrust is zero, at zero slip; V then has a certain definite value. These curves are drawn for a constant speed, $N = 1200$ R.P.M.

A curve for torque horse power, reproduced from Fig. 47, is shown in Fig. 52 for comparison; this makes possible a determination of efficiency, discussed later.

For the case shown in Fig. 52, maximum thrust power is obtained when the slip is 44 per cent.; maximum efficiency, at the point *m*, when the slip is 28.7 per cent.

Thrust horse power for different values of speed N.

The curves in Fig. 53 show the variation of thrust horse power with velocity for a propeller driven at different speeds *N*. They strikingly show that, for each speed, there is a certain velocity at which the power is a maximum, and that the value of this maximum is greater for greater values of speed *N*.

These are the so-called curves for **power available** which —when compared with the curves for power required— have an important bearing upon power relations in flight. They are the most useful of propeller curves and should be carefully studied so that a picture of them may be kept in mind. Although plotted for a particular propeller, they are typical of the curves for power available for any propeller. They are independent of the motor used, for *any* motor (not necessarily a gas engine) may be used provided it has sufficient power to drive the propeller. (Curves for propeller thrust horse power, when a particular engine is used, are shown later in Fig. 57.)

A propeller delivers its maximum power when the slip is, say, 40 to 50 per cent. (in this case about 45 per cent.); it has its maximum efficiency —discussed in a later paragraph —when the slip is, say, 25 to 40 per cent. (in this case about 30 per cent.). There is considerable variation in these values with different propellers, but maximum power always occurs at a greater slip than maximum efficiency. *The best range for propeller operation is between the point for maximum power and the point for maximum efficiency.*

Thrust horse power for propellers of different diameters D.

Greater thrust horse power can be obtained by increasing *N* as just shown, but is often better obtained by using a propeller of larger diameter *D*, the greater power in this case being due to the greater volume of the air stream. The curves in Fig. 54 show the power obtained, at different velocities, from propellers of different diameters.

An airplane should be designed for as large a propeller as space permits, for a large propeller at moderate speed is (generally speaking) better than a smaller propeller at very high speed; but the larger propeller is objectionable if it necessitates an undue elevation of the center of gravity of the airplane. On account of this limitation and the necessity of having sufficient clearance between the propeller and the ground, the huge propellers satisfactorily used on airships are not used on airplanes. A clearance as little as 10 inches has been found sufficient in some types of planes.

Assured of sufficient thrust power delivered by the propeller, we next inquire as to the efficiency of the propeller under different conditions of operation.

Propeller efficiency for different values of V /ND.

The efficiency of a propeller is equal to thrust horse power delivered divided by torque horse power received. Note the curves for torque and thrust power in Fig. 52; a comparison of these is very interesting.

It has been found that efficiency depends upon the ratio *V* /*N* and not upon the absolute values of *V* or *N*; if *V* and *N* are both changed in the same proportion, efficiency remains unchanged. Furthermore, in comparing propellers of the same design but with different diameters D, it is found that efficiency depends not upon V/N but upon V/ND, namely, the effective pitch ratio which varies with the slip. Propeller efficiencies are, therefore, plotted for various values of V/ND or for various values of slip. Both scales are shown in Fig. 55.

Referring to Fig. 55, and to Fig. 52 which relates to the same propeller, it is seen that when $V/ND = 0$, corresponding to 100 per cent. slip, thrust power is zero and hence propeller efficiency is zero. As V/ND increases, propeller efficiency increases until a maximum efficiency of 80 per cent., or so, is reached. As V/ND is further increased, the efficiency decreases, and again becomes zero when V/ND reaches a certain value (the dynamic pitch ratio of the propeller) corresponding to zero thrust and zero slip. It is seen, from Fig. 55, that this propeller has a dynamic pitch ratio 1.2, whereas the nominal pitch ratio is 0.9.

Every propeller has an efficiency curve of the type shown in Fig. 55. It is seen that for a given number of revolutions per minute there is a certain airplane velocity V, or for a given airplane velocity V there is a certain number of propeller revolutions N, at which the efficiency of a particular propeller is a maximum.

A propeller should, accordingly, be selected* that has high

*The same care in selection has to be taken in case of a marine propeller. Take as an illustration two tug boats, with identical hulls and engines, but different propellers. One boat, with propeller that gives full power when travelling at high velocity, far outstrips the other in the race to an incoming steamer, but when it comes to pulling a load it is inferior to the other boat equipped with a propeller that gives full power when travelling at low velocity.

efficiency and power at the operating values of V and N. A propeller that is very good for a certain airplane and engine may be very poor for another airplane or engine. In other words, the propeller, engine and plane *must fit*, so that, each will be operating under good conditions.

It is well to operate a propeller at a value of V/ND somewhat lower (rather than higher) than the value of maximum efficiency, in order to obtain greater power. The points for maximum power* and maximum efficiency are marked on the curve. As already stated, maximum efficiency occurs when the slip is, say, 25 to 40 per cent., and maximum power when the slip is, say, 40 to 50 per cent.

A *wide range* of high efficiency is usually more desirable than a narrower range of slightly higher efficiency.

Pitch ratio and efficiency.

The efficiency curves for three propellers with different pitch ratios but otherwise similar are shown in Fig. 56. The nominal pitch ratios of the three propellers are 0.5, 0.7, and 0.9; the dynamic pitch ratios (shown by the values of V/ND when the efficiency curves fall to zero) are 0.76, 0.96 and 1.2, respectively. Which propeller is the best to use is seen to depend upon what is the value of V/ND under working conditions. Thus, when V/ND is less than 0.47, the propeller with pitch ratio 0.5 is seen to be the most efficient of the three; when V/ND is more than .052, this same propeller is the least efficient.

Pitch ratio and power.

Pitch ratio does not affect efficiency alone. In Fig. 57 are

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*The point for maximum power depends upon D and pitch ratio. The point is marked here for $D = 8' 9''$ and pitch ratio = 0.9.

shown curves of thrust power for the same three propellers, having nominal pitch ratios 0.5, 0.7 and 0.9. It is seen that for maximum power, as well as for maximum efficiency, the value of V/ND must be greater for the propeller of greater pitch. For the three propellers here shown, maximum power is seen to increase with pitch ratio, but this is true only for a limited range of pitch ratio

Combined engine and propeller characteristics.

We have discussed various propeller characteristics independent of the motor used to drive the propeller, the separate study of engine and propeller being for most purposes preferable. Thus, in Fig. 53, was shown the thrust horse power obtained from a certain propeller driven at specified constant speeds by any motor. This constant speed is obtained by throttle adjustment, when a gas engine is used.

In Fig. 58 are shown curves for thrust horse power for a given propeller driven by a particular gas engine, these curves being not for constant speed as in Fig. 53, but for constant throttle.

It was shown in Fig. 50 how the brake horse power and speed N is determined for full throttle (or for ¾ or ½ throttle) when V is 50, 75, 100, 125 or 150 M P H. Thrust horse power may be obtained by multiplying brake horse power, as here shown, by efficiency, which is known from Fig. 55 when V, N and D are known. The curves in Fig. 58 were thus determined.

The chief propeller characteristics have now been shown, most important being the power available curves in Fig. 53, useful for direct comparison with curves of power required.

Let us now examine briefly the basis for propeller theory.

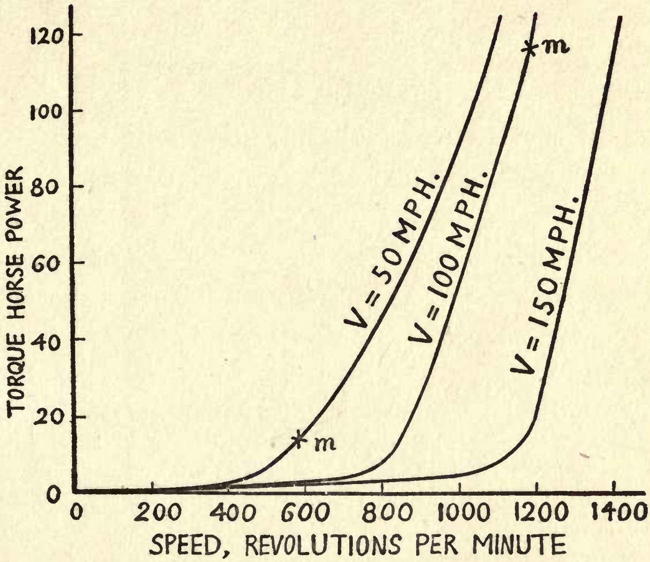

Fig. 46. Torque horse power required to drive a particular propeller at different speeds (revolutions per minute) when travelling through the air at 50, 100 and 150 M P H., at ground level. Propeller diameter, 8′ 9″; pitch ratio, 0.9. Maximum propeller efficiency is at *m*.

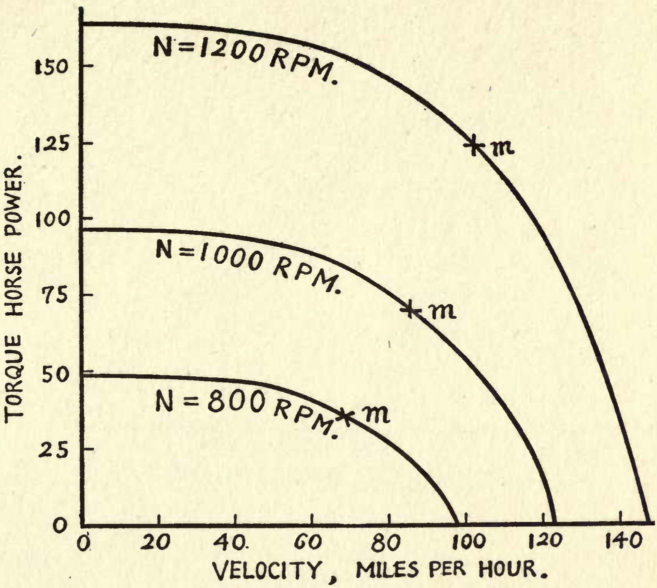

Fig. 47. Variation of propeller torque horse power with velocity when propeller is driven at constant speed. Same data as Fig. 46. Maximum efficiency at *m*.

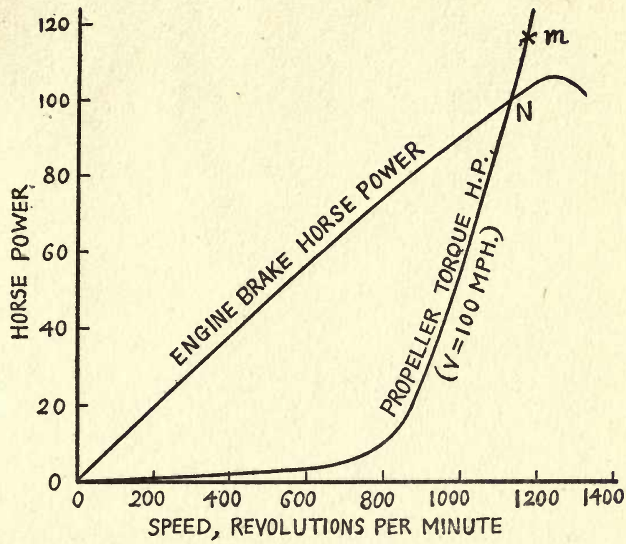

Fig. 48. Speed N and power, of particular engine and propeller, determined by intersection of curves for engine brake horse power and propeller torque horse power.

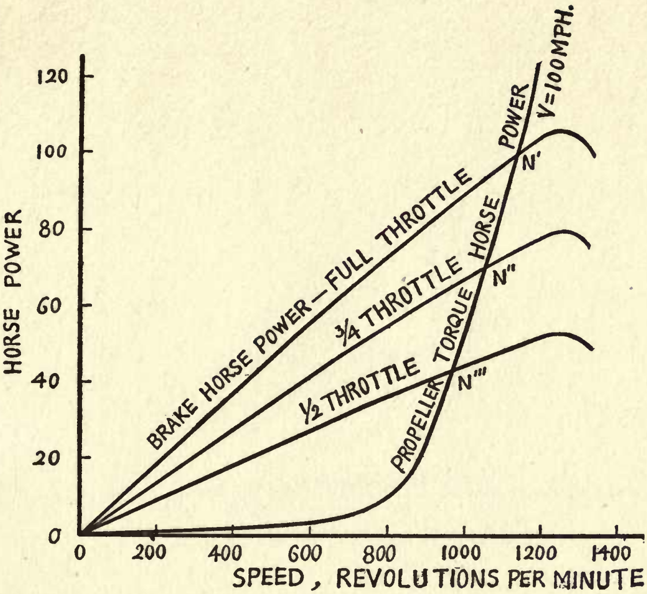

Fig. 49. Speed N', N'' and N''' and corresponding power, for particular engine and propeller, determined for three different amounts of engine throttle, when velocity is 100 MPH.

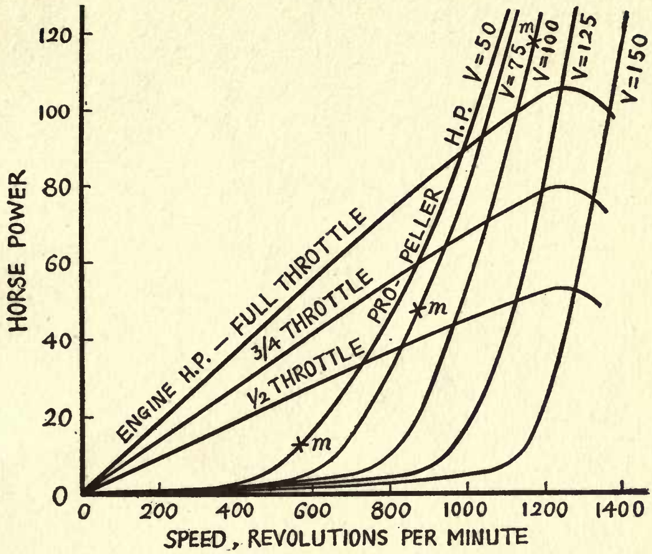

Fig. 50. Curves for engine brake horse power for different amounts of throttle and propeller torque horse power for different velocities. Intersections determines speed and power for each velocity and amount of throttle. Maximum efficiency at *m*.

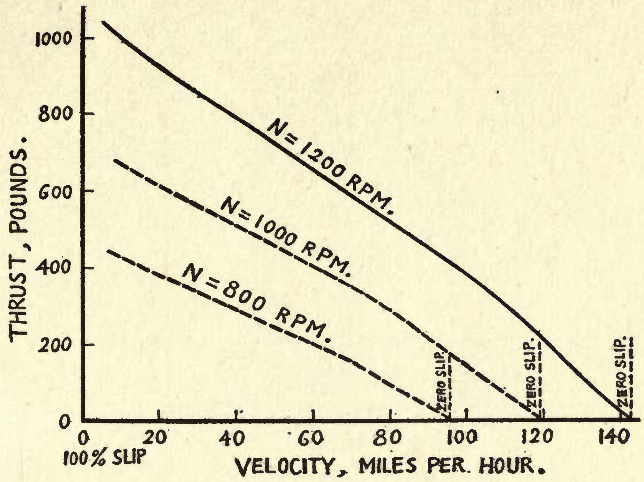

Fig. 51. Variation of thrust with velocity, for a particular propeller, when driven at constant speed. Pitch ratio 0.9, diameter 8′ 9″.

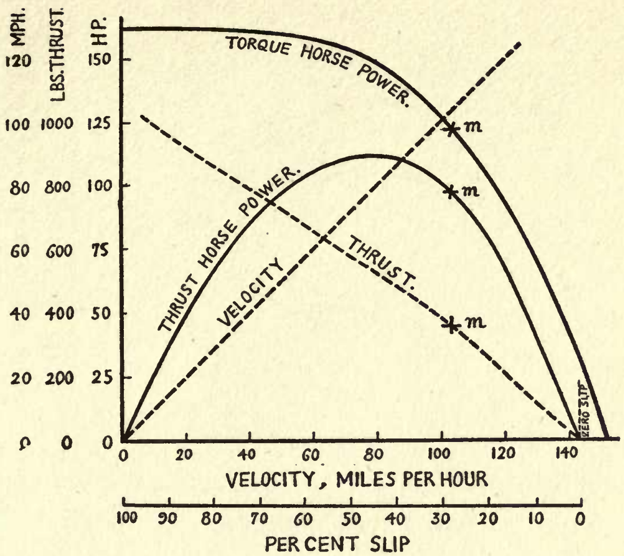

Fig. 52. Variation of thrust horse power with velocity for a particular propeller when driven at 1200 R. P. M. Dotted curves show thrust and velocity. The upper curve, reproduced from Fig. 47, shows torque horse power.

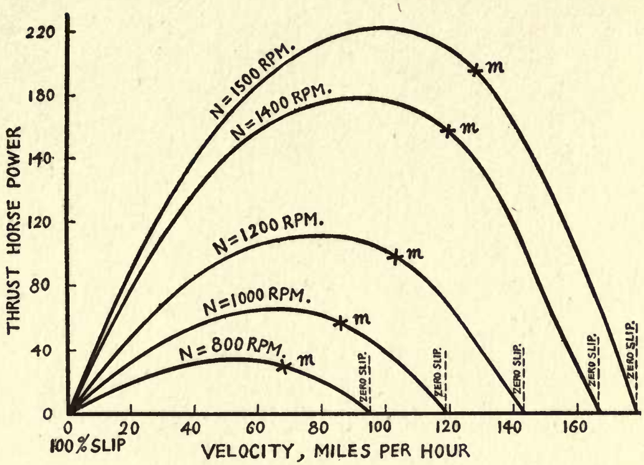

Fig. 53. Curves for thrust horse power (usually called power available) for particular propeller driven at different speeds *N*, by any engine. Maximum propeller efficiency is at *m*.

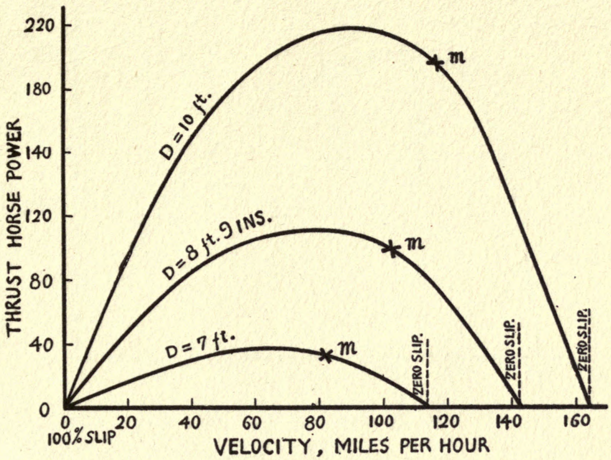

Fig. 54. Thrust horse power of similar propellers with different diameters, at constant speed $N = 1200$ R. P. M. Pitch ratio 0.9. Maximum efficiency at *m*.

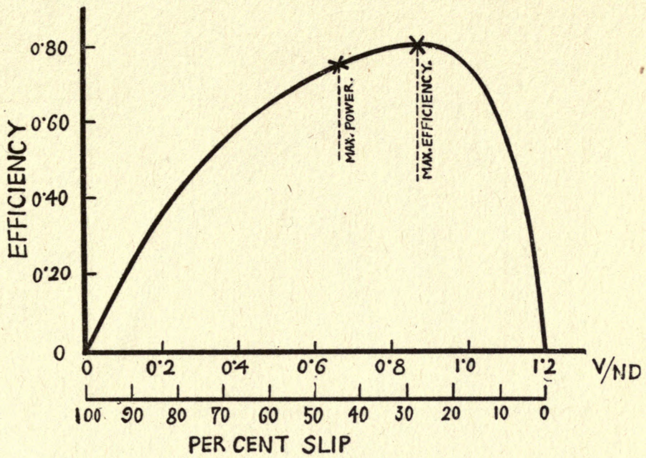

Fig. 55. Propeller efficiency for different values of V/ND. Efficiency is equal to thrust horse power divided by torque horse power; see Fig. 52. Pitch ratio, 0.9. Values for V, N or D are not fixed.

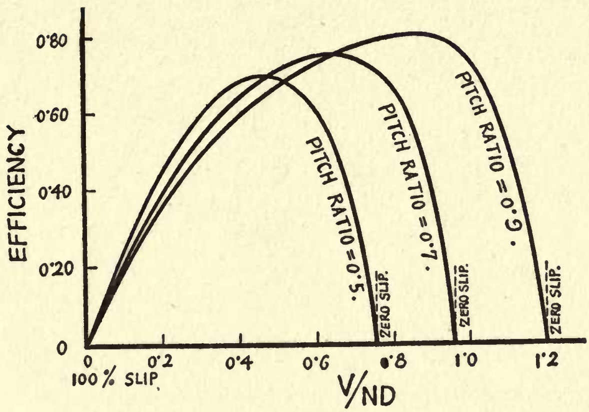

Fig. 56. Efficiency of three similar propellers with different pitch ratios.

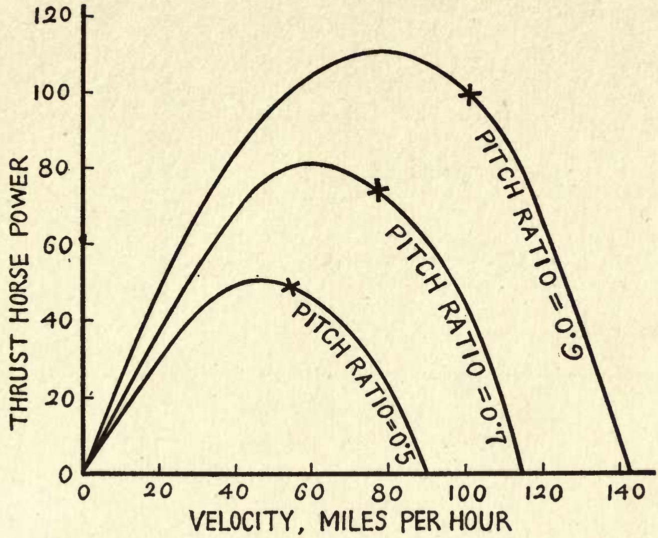

Fig. 57. Thrust horse power of three similar propellers with different pitch ratios. Point of maximum efficiency is marked by x.

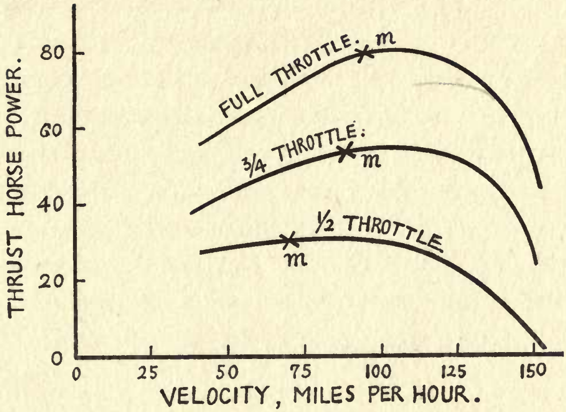

Fig. 58. Combined engine and propeller characteristic. Thrust horse power, or power available, for constant throttle; a particular propeller (pitch ratio 0.9, diameter 8′ 9″) driven by a particular engine. Maximum efficiency at *m*. For engine curves, see Fig. 45.

(*d*) *Propeller Theory*

The foregoing discussion of the characteristics of a propeller in operation shows working results in simple form; these are the facts that can be easily understood, independent of any theory that may be used to explain them.

The oldest theory of the propeller treats it as a screw, which moves forward as it turns, and upon this conception are based many propeller terms in common use. In an incompressible fluid, as water, the screw theory is fairly satisfactory and the marine propeller is, accordingly, commonly treated as a screw. When, however, the medium is air, that can be compressed and rarefied as any gas and has a density only 1/800 the density of water, the screw theory is far from satisfactory and, as a theory for the air propeller, has been practically abandoned.

Aerofoil theory of the propeller.

The most satisfactory theory of the air propeller considers the propeller blade as a rotating aerofoil. When the propeller is merely rotating and has no forward velocity, each element of the blade moves in a circle, the plane of rotation being perpendicular to the propeller shaft. When the propeller makes N revolutions per minute, the velocity of rotation of any element at a distance r feet from the center of the shaft is $2 \pi r N$ feet per minute.

In flight the propeller has a forward velocity in addition to its rotation, and the path of any element is a cork-screw curve or helix and not a circle. The velocity of any element along this path is then the resultant of its forward velocity V and its velocity of rotation, $2 \pi r N$.

Fig. 59 shows the plan of a propeller blade and several sections at different distances from the center. The similarity of these sections to the section of an airplane wing and the justification of the aerofoil theory is obvious.

Fig. 60 is an illustrative diagram (not to scale) of one section of a propeller blade, developing more fully the aerofoil theory. Each section or "element" of the blade may thus be treated as an aerofoil.

The **angle of incidence i,** at which any blade element or section attacks the relative air due to its motion, is the angle between the chord of the element and its resultant flight path, as shown in Fig. 60.

The **blade angle** or **pitch angle** (nominal or structural pitch angle) for any particular section is the angle a between its chord and the direction of its rotation in a plane perpendicular to the propeller shaft. As shown in the previous figure, this angle decreases for the various sections of a blade as we proceed from hub or **boss** to tip; that is, the blade angle a decreases* as the distance r from the hub increases.

When a propeller is rotating, but has no forward velocity, its motion is in the plane of rotation and the angle of incidence of a blade element is obviously equal to the pitch angle a, for this is then the angle at which the blade element attacks the relative air due to its rotation.

In flight, when there is a forward velocity V, the resultant motion or flight path of a blade element is a helix and the angle of incidence of a blade element with the relative wind is the angle i between its chord and this heliacal path. OP, in Fig. 60, shows a short portion of this path. It will be seen that *as the forward velocity V increases (relative to N) the angle of blade incidence decreases.*

**Determination of pitch from propeller measurement.*—The tangent of a is equal to the structural pitch divided by $2 \pi r$. The structural pitch of a propeller is, accordingly, equal to $2 \pi r \tan a$ and can be determined by measuring the pitch angle at any distance r from the hub.

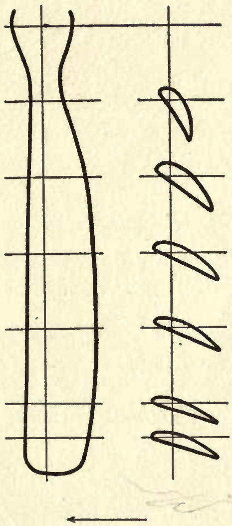

Fig. 59. Plan and section of propeller blade.

The **effective pitch angle,** as shown in the figure, is the angle e which the resultant flight path makes with the plane of rotation. The effective pitch angle varies with different conditions of operation and increases as V/N increases, the tangent of e being equal to $V/2\pi r N$. The effective pitch angle thus determines the forward travel of the propeller per revolution. The effective pitch angle and effective pitch are zero when $V = 0$, corresponding to 100 per cent. slip and maximum thrust; the angle of blade incidence is then a maximum and the thrust is a maximum.

Lift and drag.—As in the case of any aerofoil, each blade element has a lift perpendicular to, and a drag or resistance in the direction of, the flight path. The direction of L and D are indicated in the diagram. Their values are

$$\text{Lift} = L = K_L S V_R^2;$$
$$\text{Drag} = D = K_D S V_R^2.$$

Here S is the area of the blade element; V_R its resultant velocity along its heliacal path; K_L and K_D are the usual coefficients which depend upon aerofoil shape and vary with the angle of blade incidence.

Thrust and torque.—The component of force parallel to the shaft of the propeller gives **thrust;** the component of force in the direction of rotation gives **torque.** Although thrust results from lift, it is seen that thrust is not precisely equal to lift; nor is torque precisely equal to drag.

The total thrust and torque for the propeller as a whole is the sum of the thrust and torque of the separate blade elements.

Angle of blade incidence.—The angle of incidence i varies during flight from, say, 2° or 3° in horizontal flight to, say, 10° or perhaps 12° in climbing. As the angle of incidence increases (with an increase in slip and decrease in V/N) the lift, and so the thrust*, increases. The increase in thrust, with increase in slip and decrease in V/N, has been shown by the curve in Fig. 51. This increase, in climbing, may be obtained by a decrease in V or an increase in N, or both.

Negative blade incidence for zero thrust.—As the angle of incidence decreases (with decrease of slip and increase of V/N) the lift, and so the thrust, decreases; but at zero incidence there is still some lift and thrust. As with any aerofoil there is a certain negative incidence at which there is no lift (as shown in Fig. 11, page† 18), so with a propeller element there is a certain negative incidence at which there is no thrust. The resultant path of a blade element is then as indicated by the dotted line *OF* in Fig. 60, in advance of the chord of the blade element, instead of back of it as shown by *OP* for positive incidence.

The angle between *OF* (the resultant path for zero thrust) and the direction of rotation *OB*, is the **dynamic pitch angle,** and the corresponding pitch is the **dynamic pitch.**

To obtain positive thrust, the effective pitch angle e must be less than the dynamic pitch angle, by an amount dependent upon the slip.‡

L/D ratio for propeller.—The L/D ratio for a propeller section has a maximum value of about 20, when the blade incidence is, say, 4° or 5°. It is sought in propeller design

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*Thrust is equal to the component of L parallel to the shaft, less the component of D in that direction. Torque is the sum of the components of L and D in the plane of rotation. Thus,

$$\text{Thrust} = L \cos e - D \sin e.$$
$$\text{Torque} = L \sin e + D \cos e.$$

†See "Airplane Characteristics."

‡Slip varies as the difference between the tangents of the two angles.

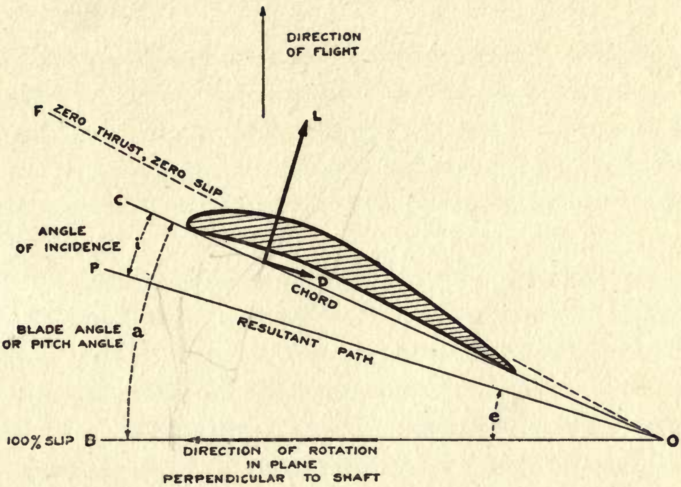

Fig. 60. Particular section of propeller blade at distance of *r* from center of shaft, showing the behavior of a propeller blade as an aerofoil, attacking the air at an angle of incidence *i*.

and operation to approach a maximum value in this ratio (or rather in the thrust/torque ratio) but there are limitations in structure that make this difficult.

Blade shape.

The problem of determining the several sections for a propeller blade is much the same as that of determining the section for any aerofoil, although there are differences due to the heliacal path in one case and the straight path in the other, and consequent differences in the eddies and vortices produced.

The front surface of a propeller blade (the upper surface, considered as an aerofoil in the usual manner) is highly cambered. The amount of this camber and its distribution depends somewhat upon the intended service. The back surface is flat, or nearly so, for it is found that there is little or no gain in shaping this surface. Aspect ratio enters in blade design much as in the design of any aerofoil. To obtain the advantage of high aspect ratio, a long and narrow blade is used for an air propeller. (Not so for a marine propeller.)

The greatest thrust and torque in a propeller blade is obtained toward the tip, the maximum being about 4/5 the way from hub to tip.

Mechanical strength is an important consideration in propeller design. Changes in blade shape, that produce little change in aerodynamic efficiency, may have a large effect upon strength. In fact in propeller design the question of strength is foremost. Particularly true is this as the hub is approached, for this part of the propeller—on account of its lesser velocity of rotation—contributes little to thrust, so that strength is here practically the entire problem. High polish is given the blade to reduce resistance. The surface is given a waterproof finish to avoid absorption of moisture and consequent warping.

Very important is a proper **propeller balance,** a slight unbalancing at high velocities of rotation causing forces that soon become destructive.

Uniform and variable pitch; mean pitch.

When a propeller is constructed with the same pitch at all parts, from hub to tip, the pitch is said to be **uniform.** When the pitch varies from hub to tip, the pitch is said to be **variable.** A mean value for pitch is then sometimes given, but the determination of mean pitch is somewhat arbitrary. It has been found that a variable pitch gives no gain in aerodynamic efficiency.

Scientific basis of aerofoil theory.

The aerofoil theory has put the theory of the propeller on a scientific basis and has removed much that was formerly mysterious or, at least, not well understood. Recourse, of course, must be made to experiment for fundamental data, but when the theory is understood these experiments may be made systematically and not blindly.

Although a knowledge of the working characteristics of the propeller is all that is needed for many purposes, some knowledge of the theory of the propeller as an aerofoil proves a valuable aid in explaining its behavior under different conditions and in understanding the relations between the various quantities involved in its operation. The foregoing discussion, prepared primarily for this purpose, should also serve as a general introduction to a more detailed study of the propeller, either practical or theoretical.

APPENDIX

GLOSSARY*

AEROFOIL: A winglike structure, flat or curved, designed to obtain reaction upon its surface from the air through which it moves.

AEROPLANE: See Airplane.

AILERON: A movable auxiliary surface used to produce a rolling moment about the fore-and-aft axis.

AIRCRAFT: Any form of craft designed for the navigation of the air—airplanes, balloons, dirigibles, helicopters, kites, kite balloons, ornithopters, gliders, etc.

AIRPLANE: A form of aircraft heavier than air which has wing surfaces for support in the air, with stabilizing surfaces, rudders for steering, and power plant for propulsion through the air. This term is commonly used in a more restricted sense to refer to air-planes fitted with landing gear suited to operation from the land. If the landing gear is suited to operation from the water, the term "seaplane" is used. (See definition.)

Pusher.—A type of airplane with the propeller in the rear of the engine.

Tractor.—A type of airplane with the propeller in front of the engine.

AIR-SPEED METER: An instrument designed to measure the speed of an aircraft with reference to the air.

ALTIMETER: An aneroid mounted on an aircraft to indicate continuously its height above the surface of the earth.

ANEMOMETER: Any instrument for measuring the velocity of the wind.

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*From Report No. 15, on "Nomenclature for Aeronautics," by the National Advisory Committee for Aeronautics.

Angle:

Of attack or *of incidence of an aerofoil.*—The acute angle between the direction of the relative wind and the chord of an aerofoil; *i. e.*, the angle between the chord of an aerofoil and its motion relative to the air. (This definition may be extended to any body having an axis.)

Critical.—The angle of attack at which the lift-curve has its first maximum; sometimes referred to as the "burble point." (If the "lift curve" has more than one maximum, this refers to the first one.)

Gliding.—The angle the flight path makes with the horizontal when flying in still air under the influence of gravity alone, *i. e.*, without power from the engine.

Appendix: The hose at the bottom of a balloon used for inflation. In the case of a spherical balloon it also serves for equalization of pressure.

Aspect ratio: The ratio of span to chord of an aerofoil.

Aviator: The operator or pilot of heavier-than-air craft. This term is applied regardless of the sex of the operator.

Axes of an aircraft: Three fixed lines of reference; usually centroidal and mutually rectangular.

The principal longitudinal axis in the plane of symmetry, usually parallel to the axis of the propeller, is called the fore and aft axis (or longitudinal axis); the axis perpendicular to this in the plane of symmetry is called the vertical axis; and the third axis, perpendicular to the other two, is called the transverse axis (or lateral axis). In mathematical discussions the first of these axes, drawn from front to rear, is called the X axis; the second, drawn upward, the Z axis; and the third, forming a "left-handed" system, the Y axis.

Balancing flaps: See Aileron.

Ballonet: A small balloon within the interior of a balloon or dirigible for the purpose of controlling the ascent or descent, and for maintaining pressure on the outer envelope so as to prevent deformation. The ballonet is kept inflated with air at the required pressure, under the control of a blower and valves.

BALLOON: A form of aircraft comprising a gas bag and a basket. The support in the air results from the buoyancy of the air displaced by the gas bag, the form of which is maintained by the pressure of a contained gas lighter than air.

Barrage.—A small spherical captive balloon, raised as a protection against attacks by airplanes.

Captice.—A balloon restrained from free flight by means of a cable attaching it to the earth.

Kite.—An elongated form of captive balloon, fitted with tail appendages to keep it headed into the wind, and deriving increased lift due to its axis being inclined to the wind.

Pilot.—A small spherical balloon sent up to show the direction of the wind.

Sounding.—A small spherical balloon sent aloft, without passengers, but with registering meteorological instruments.

BALLOON BED: A mooring place on the ground for a captive balloon.

BALLOON CLOTH: The cloth, usually cotton, of which balloon fabrics are made.

BALLOON FABRIC: The finished material, usually rubberized, of which balloon envelopes are made.

BANK: To incline an airplane laterally—*i. e.*, to roll it about the fore and aft axis. Right bank is to incline the airplane with the right wing down Also used as a noun to describe the position of an airplane when its lateral axis is inclined to the horizontal.

BAROGRAPH: An instrument used to record variations in barometric pressure. In aeronautics the charts on which the records are made indicate altitudes directly instead of barometric pressures.

Basket: The car suspended beneath a balloon, for passengers, ballast, etc.

Biplane: A form of airplane in which the main supporting surface is divided into two parts, one above the other.

Body of an airplane: The structure which contains the power plant, fuel, passengers, etc.

Bonnet: The appliance, having the form of a parasol, which protects the valve of a spherical balloon against rain.

Bridle: The system of attachment of cable to a balloon, including lines to the suspension band.

Bullseyes: Small rings of wood, metal, etc., forming part of balloon rigging, used for connection or adjustment of ropes.

Burble point: See Angle, critical.

Cabane: A pyramidal framework upon the wing of an airplane, to which stays, etc., are secured.

Camber: The convexity or rise of the curve of an aerofoil from its chord, usually expressed as the ratio of the maximum departure of the curve from the chord to the length of the chord. "Top camber" refers to the top surface of an aerofoil, and "bottom camber" to the bottom surface; "mean camber" is the mean of these two.

Capacity: See Load.
The cubic contents of a balloon.

Center: *Of pressure of an aerofoil.*—The point in the plane of the chords of an aerofoil, prolonged if necessary, through which at any given attitude the line of action of the resultant air force passes. (This definition may be extended to any body.)

Chord:

Of an aerofoil section.—A right line tangent at the front and rear to the under curve of an aerofoil section.

Length.—The length of the chord is the length of the projection of the aerofoil section on the chord.

CLINOMETER: See Inclinometer.

CONCENTRATION RING: A hoop to which are attached the ropes suspending the basket.

CONTROLS: A general term applying to the means provided for operating the devices used to control speed, direction of flight, and attitude of an aircraft

CONTROL COLUMN: The vertical lever by means of which certain of the principal controls are operated, usually those for pitching and rolling.

CROW'S FOOT: A system of diverging short ropes for distributing the pull of a single rope.

DECALAGE: The angle between the chords of the principal and the tail planes of a monopolane. The same term may be applied to the corresponding angle between the direction of the chord or chords of a biplane and the direction of a tail plane. (This angle is also sometimes known as the longitudinal V of the two planes.)

DIHEDRAL IN AN AIRPLANE: The angle included at the intersection of the imaginary surfaces containing the chords of the right and left wings (continued to the plane of symmetry if necessary). This angle is measured in a plane perpendicular to that intersection. The measure of the dihedral is taken as 90° minus one-half of this angle as defined.

The dihedral of the upper wing may and frequently does differ from that of the lower wing in a biplane.

DIRIGIBLE: A form of balloon, the outer envelope of which is of elongated form, provided with a propelling system, car, rudders, and stabilizing surfaces.

Nonrigid.—A dirigible whose form is maintained by the pressure of the contained gas assisted by the car-suspension system.

Rigid.—A dirigible whose form is maintained by a rigid structure contained within the evnelope.

Semirigid.—A dirigible whose form is maintained by means of a rigid keel and by gas pressure.

Diving rudder: See Elevator.

Dope: A general term applied to the material used in treating the cloth surface of airplane members and balloons to increase strength, produce tautness, and act as a filler to maintain air-tightness; it usually has a cellulose base.

Drag: The component parallel to the relative wind of the total force on an aircraft due to the air through which it moves.

That part of the drag due to the wings is called "wing resistance" (formerly called "drift"); that due to the rest of the airplane is called "parasite resistance" (formerly called "head resistance").

Drift: See Drag. Also used as synonymous with "leeway," *q. v.*

Drift meter: An instrument for the measurement of the angular deviation of an aircraft from a set course, due to cross winds.

Drip cloth: A Curtain around the equator of a balloon, which prevents rain from dripping into the basket.

Elevator: A hinged surface for controlling the longitudinal attitude of an aircraft; *i. e.*, its rotation about the transverse axis.

Empannage: See Tail.

Entering edge: The foremost edge of an aerofoil or propeller blade.

Envelope: The portion of the balloon or dirigible which contains the gas.

Equator: The largest horizontal circle of a spherical balloon.

Fins: Small fixed aerofoils attached to different parts of aircraft, in order to promote stability; for example, tail fins, skid fins, etc. Fins are often adjustable. They may be either horizontal or vertical.

Flight path: The path of the center of gravity of an aircraft with reference to the earth.

Float: That portion of the landing gear of an aircraft which provides buoyancy when it is resting on the surface of the water.

Fuselage: See Body.

Gap: The shortest distance between the planes of the chords of the upper and lower wings of a biplane.

Gas bag: See Envelope.

Glide: To fly without engine power.

Glider: A form of aircraft similar to an airplane, but without any power plant.

When utilized in variable winds it makes use of the soaring principles of flight and is sometimes called a soaring machine.

Gore: One of the segments of fabric composing the envelope.

Ground cloth: Canvas placed on the ground to protect a balloon.

Guide rope: The long trailing rope attached to a spherical balloon or dirigible, to serve as a brake and as a variable ballast.

Guy: A rope, chain, wire, or rod attached to an object to guide or steady it, such as guys to wing, tail, or landing gear.

Hangar: A shed for housing balloons or airplanes.

Helicopter: A form of aircraft whose support in the air is derived from the vertical thrust of propellers.

Horn: A short arm fastened to a movable part of an airplane, serving as a lever-arm, *e. g.*, aileron-horn, rudder-horn, elevator-horn.

Inclinometer: An instrument for measuring the angle made by any axis of an aircraft with the horizontal, often called a clinometer.

Inspection window: A small transparent window in the envelope of a balloon or in the wing of an airplane to allow inspection of the interior.

KITE: A form of aircraft without other propelling means than the towline pull, whose support is derived from the force of the wind moving past its surface.

LANDING GEAR: The understructure of an aircraft designed to carry the load when resting on or running on the surface of the land or water.

LEADING EDGE: See Entering edge.

LEEWAY: The angular deviation from a set course over the earth, due to cross currents of wind, also called drift; hence, "drift meter."

LIFT: The component perpendicular to the relative wind, in a vertical plane, of the force on an aerofoil due to the air pressure caused by motion through the air.

LIFT BRACING: See Stay.

LOAD:

Dead.—The structure, power plant, and essential accessories of an aircraft.

Full.—The maximum weight which an aircraft can support in flight; the "gross weight."

Useful.—The excess of the full load over the dead-weight of the aircraft itself, *i. e.*, over the weight of its structure, power plant, and essential accessories. (These last must be specified.)

LOADING: See Wing, loading.

LOBES: Bags at the stern of an elongated balloon designed to give it directional stability.

LONGERON: See Longitudinal.

LONGITUDINAL: A fore-and-aft member of the framing of an air-plane body, or of the floats, usually continuous across a number of points of support.

MONOPLANE: A form of airplane whose main supporting surface is a single wing, extending equally on each side of the body.

MOORING BAND: The band of tape over the top of a balloon to which are attached the mooring ropes.

NACELLE: See Body. Limited to pushers.

NET: A rigging made of ropes and twine on spherical balloons, which supports the entire load carried.

ORNITHOPTER: A form of aircraft deriving its support and propelling force from flapping wings.

PANEL: The unit piece of fabric of which the enevelope is made.

PARACHUTE: An apparatus, made like an umbrella, used to retard the descent of a falling body.

PATCH SYSTEM: A system of construction in which patches (or adhesive flaps) are used in place of the suspension band.

PERMEABILITY. The measure of the loss of gas by diffusion through the intact balloon fabric.

PITOT TUBE: A tube with an end open square to the fluid stream, used as a detector of an impact pressure. It is usually associated with a coaxial tube surrounding it, having perforations normal to the axis for indicating static pressure; or there is such a tube placed near it and parallel to it, with a closed conical end and having perforations in its side. The velocity of the fluid can be determined from the difference between the impact pressure and the static pressure, as read by a suitable gauge. This instrument is often used to determine the velocity of an aircraft through the air.

PONTOONS: See Float.

PUSHER: See Airplane.

PYLON: A mast or pillar serving as a marker of a course.

RACE OF A PROPELLER: See Slip stream.

RELATIVE WIND: The motion of the air with reference to a moving body. Its direction and velocity, therefore, are found by adding two vectors, one being the velocity of the air with reference to the earth, the other being equal and opposite to the velocity of the body with reference to the earth.

Rip cord: The rope running from the rip panel of a balloon to the basket, the pulling of which causes immediate deflation.

Rip panel: A strip in the upper part of a balloon which is torn off when immediate deflation is desired.

Rudder: A hinged or pivoted surface, usually more or less flat or stream lined, used for the purpose of controlling the attitude of an aircraft about its "vertical" axis, *i. e.*, for controlling its lateral movement.

Rudder bar.—The foot bar by means of which the rudder is operated.

Seaplane: A particular form of airplane in which the landing gear is suited to operation from the water.

Serpent: A short, heavy guide rope.

Side slipping: Sliding downward and inward when making a turn; due to excessive banking. It is the opposite of skidding.

Skidding: Sliding sideways away from the center of the turn in flight. It is usually caused by insufficient banking in a turn, and is the opposite of side slipping.

Skids: Long wooden or metal runners designed to prevent nosing of a land machine when landing or to prevent dropping into holes or ditches in rough ground. Generally designed to function should the landing gear collapse or fail to act.

Slip stream or propeller race: The stream of air driven aft by the propeller and with a velocity relative to the airplane greater than that of the surrounding body of still air.

Soaring machine: See Glider.

Span or spread: The maximum distance laterally from tip to tip of an airplane wing, or the lateral dimension of an aerofoil.

STABILITY: A quality in virtue of which an airplane in flight tends to return to its previous attitude after a slight disturbance.

Directional.—Stability with reference to the vertical axis.

Dynamical.—The quality of an aircraft in flight which causes it to return to a condition of equilibrium after its attitude has been changed by meeting some disturbance, *e. g.*, a gust. This return to equilibrium is due to two factors; first, the inherent righting moments of the structure; second, the damping of the oscillations by the tail, etc.

Inherent.—Stability of an aircraft due to the disposition and arrangement of its fixed parts—*i. e.*, that property which causes it to return to its normal attitude of flight without the use of the controls.

Lateral.—Stability with reference to the longitudinal (or fore and aft) axis.

Longitudinal.—Stability with reference to the lateral axis.

Statical.—In wind tunnel experiments it is found that there is a definite angle of attack such that for a greater angle or a less one the righting moments are in such a sense as to tend to make the attitude return to this angle. This holds true for a certain range of angles on each side of this definite angle; and the machine is said to possess "statical stability" through this range.

STABILIZER: Any device designed to steady the motion of aircraft.

STAGGER: The amount of advance of the entering edge of the upper wing of a biplane over that of the lower, expressed as percentage of gap; it is considered positive when the upper surface is forward.

STALLING: A term describing the condition of an airplane which from any cause has lost the relative speed necessary for control.

STATOSCOPE: An instrument to detect the existence of a small rate of ascent or descent, principally used in ballooning.

STAY: A wire, rope, or the like used as a tie piece to hold parts together, or to contribute stiffness; for example, the stays of the wing and body trussing.

STEP: A break in the form of the bottom of a float.

STREAM-LINE FLOW: A term in hydromechanics to describe the condition of continuous flow of a fluid, as distinguished from eddying flow.

STREAM-LINE SHAPE: A shape intended to avoid eddying and to preserve stream-line flow.

STRUT: A compression member of a truss frame; for instance, the vertical members of the wing truss of a biplane.

SUSPENSION BAND: The band around a balloon to which are attached the basket and the main bridle suspensions.

SUSPENSION BAR: The bar used for the concentration of basket suspension ropes in captive balloons.

SWEEP BACK: The horizontal angle between the lateral axis of an airplane and the entering edge of the main planes.

TAIL: The rear portion of an aircraft, to which are usually attached rudders, elevators, stabilizers, and fins.

TAIL CUPS: The steadying device attached at the rear of certain types of elongated captive balloons.

THIMBLE: An elongated metal eye spliced in the end of a rope or cable.

TRACTOR: See Airplane.

TRAILING EDGE: The rearmost edge of an aerofoil or propeller blade.

TRIPLANE: A form of airplane whose main supporting surface is divided into three parts, superimposed.

TRUSS: The framing by which the wing loads are transmitted to the body; comprises struts, stays, and spars.

UNDERCARRIAGE: See Landing gear.

WARP: To change the form of the wing by twisting it.

WASH OUT: A permanent warp of an aerofoil such that the angle of attack decreases toward the wing tips.

WEIGHT: Gross. See Load, full.

WINGS: The main supporting surfaces of an airplane.

WING FLAP: See Aileron.

WING LOADING: The weight carried per unit area of supporting surface.

WING MAST: The mast structure projecting above the wing, to which the top load wires are attached.

WING RIB: A fore-and-aft member of the wing structure used to support the covering and to give the wing section its form.

WING SPAR OR WING BEAM: A transverse member of the wing structure.

YAW: To swing off the course about the vertical axis.

Angle of.—The temporary angular deviation of the fore-and-aft axis from the course.

POWER REQUIRED

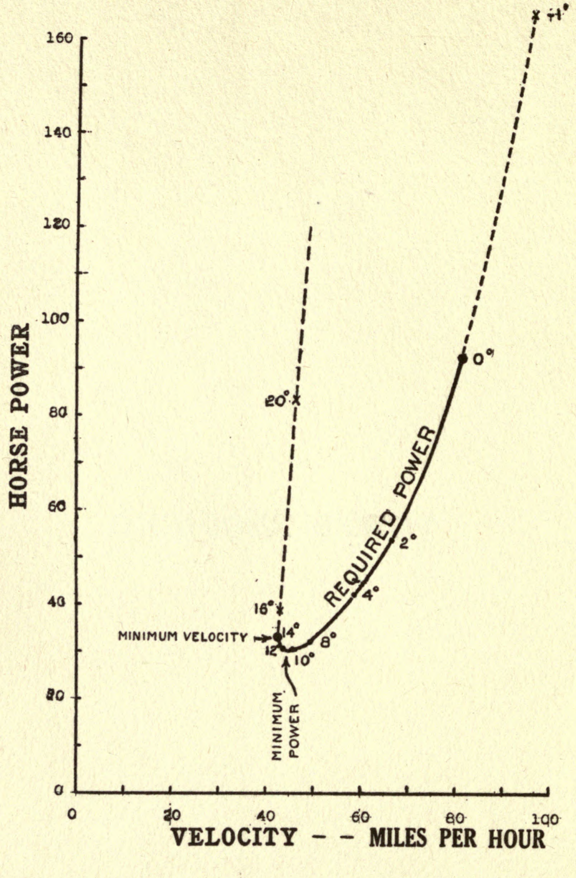

Fig. 39. Required power at different velocities, when $W = 2000$ lbs.; $W/S = 6$; parasite resistance $= 0.04 V^2$.

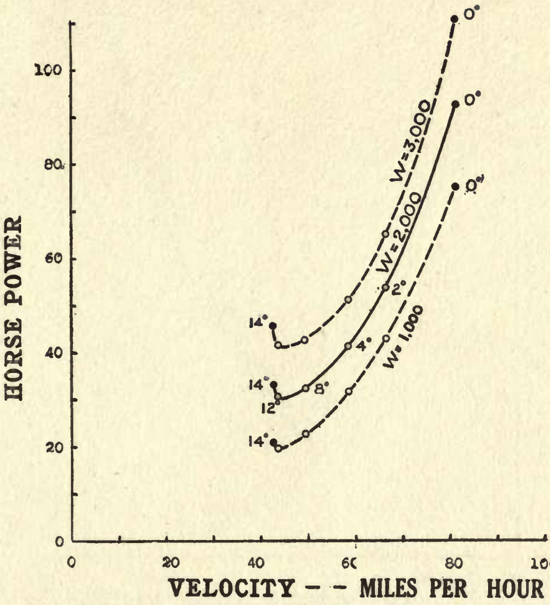

Fig. 40. Variation of required power with velocity. The three curves show effect of changing weight (W = 1000, 2000 and 3000 lbs.) when loading is kept constant ($W/S = 6$); parasite resistance = $0.04 V^2$.

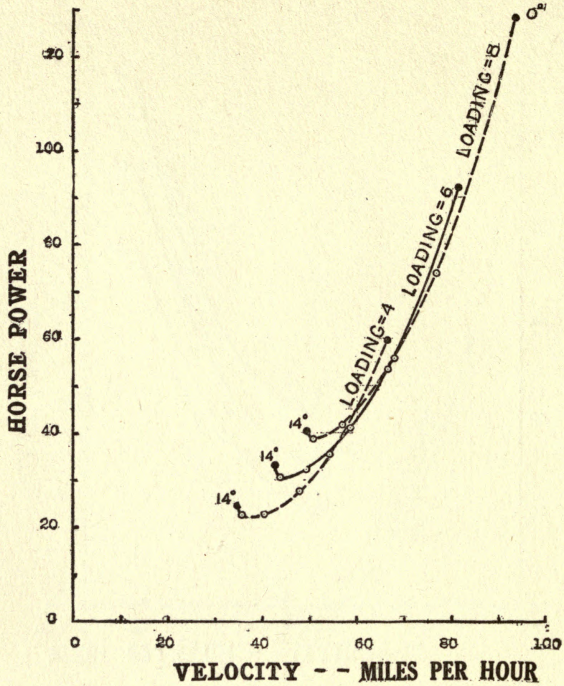

Fig. 41. Variation of required power with velocity. The three curves show effect of changing loading (W/S = 4, 6 and 8) when weight is kept constant (W = 2000 lbs.); parasite resistance = $0.04 V^2$.

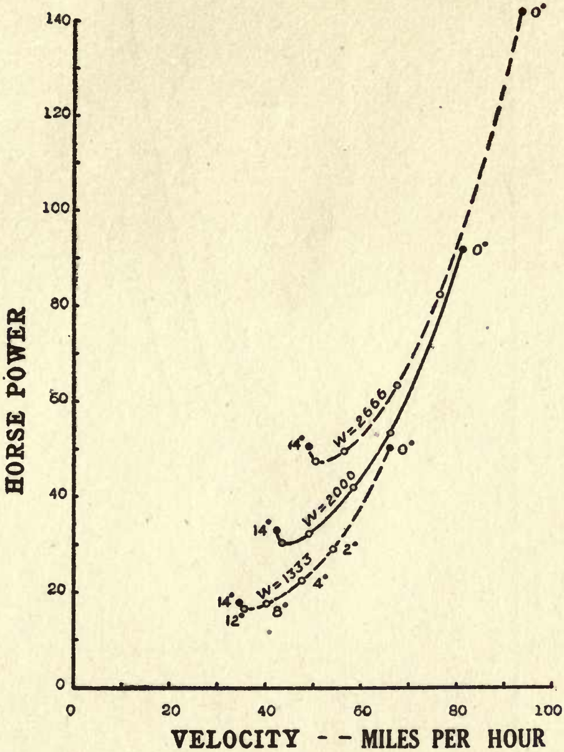

Fig. 42. Variation of required power with velocity. The three curves show effect of changing weight (W = 1333, 2000 and 2666 lbs.) and loading in proportion (W/S = 4, 6 and 8), wing-area being constant; parasite resistance = $0.04\,V^2$.

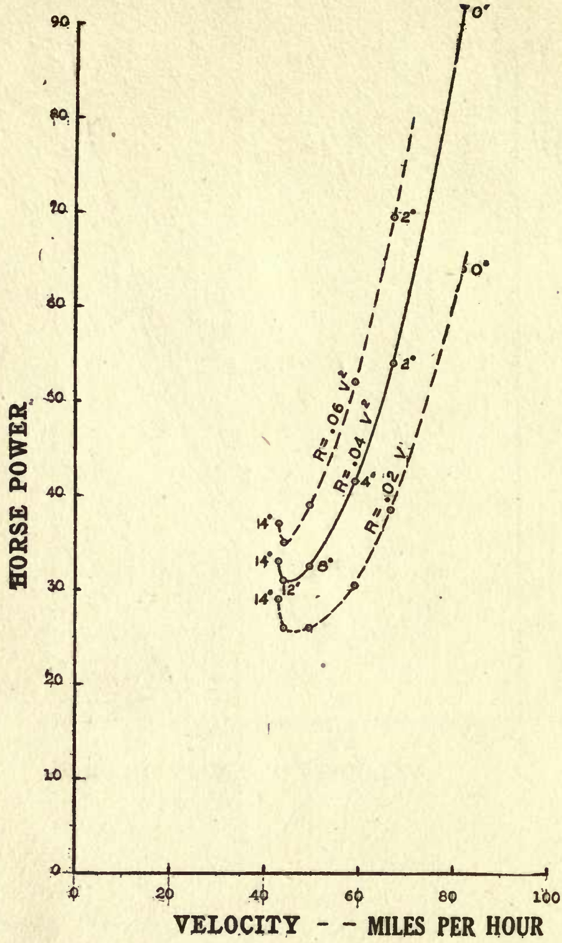

Fig. 43. Variation of required power with velocity. The three curves show effect of changing parasite resistance ($R = 0.02\,V^2$, $R = 0.04\,V^2$ and $R = 0.06\,V^2$); weight and loading constant ($W = 2000$ lbs.; $W/S = 6$).