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AERIAL PROPELLER

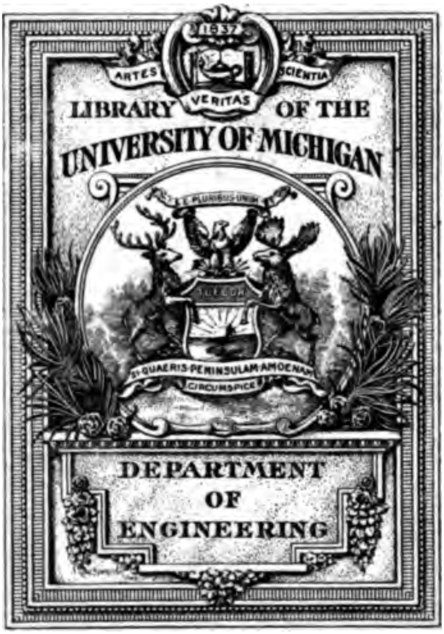
AMERICAN SCHOOL of CORRESPONDENCE
CHICAGO ILLINOIS

AERIAL PROPELLER

Volumes have been written on the theory and design of the screw propeller as applied to marine practice, yet after so many years of actual use there are still many things that remain to be definitely settled. A change in the condition of operations renders previous data of little value, as in the case of the adoption of the high-speed turbine for marine propulsion, the "Mauretania" having been equipped with no fewer than three different sets of screws since she was first put in service. It is, accordingly, not to be greatly wondered at that there should be a conflict of opinion where the aerial propeller is concerned. Obviously, the propeller is no less important an essential than the planes themselves, for support in an aeroplane is entirely dependent upon speed. To obtain speed, thrust is necessary, and it is the function of the propeller to produce it. How this may be done most efficiently is the object of an endless amount of research that is being carried on at the present time. The purpose of the present subject is to reflect current practice—to give as far as possible the data upon which the designs of the most successful propellers are based, to show how the propellers themselves are made, and why they are so made, as drawn from actual experience rather than from purely theoretical ideas.

In view of the imperfect engineering knowledge extant on the subject at this late day, it appears rather marvelous that the scientist-philosopher Leonardo da Vinci should have proposed the use of the propeller in one of the aerial navigation schemes which came up in his day—more than four hundred years ago. Of course, the propeller as it exists today was not known then, but the screw principle upon which it is based is centuries old. In fact, General Meusnier's conception of the *turning oars* in his plan for a dirigible balloon antedates the actual use of the propeller for marine service by many years, and was likewise a strikingly approximate anticipation of the aerial propeller of the present day.

Factors in Propeller Action. *Pitch.* Before taking up the design or construction, the essential features of a propeller should be


1837
ARTES
SCIENTIA
VERITAS
E PLURIBUS UNUM
TUEBOR
SI QUAERIS PENINSULAM AMOENAM
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per second times the slip velocity in feet per second. This is *dynamic thrust.* The effort of the same propeller on the column of air in which it acts when standing still, is termed *static thrust.* An illustration of the difference between the two may be drawn from the starting of an aeroplane from the ground. While held prior to running over the ground, the screw is exerting static thrust. The moment the machine is released, it begins to exert dynamic thrust in that it is then forcing the aeroplane ahead. It is generally conceded that the amount of static thrust a certain propeller is to exert affords no definite measurement of what it is capable of doing when driving the machine through the air, or rather that its static thrust will be much greater than its dynamic, although Sir Hiram Maxim states that, as the result of his experiments, both were found to be the same. The thrust of the propeller in question was said not to vary whether it was traveling through the air at a velocity of 40 miles an hour, or standing stationary, the r. p. m. rate of the motor remaining constant. The explanation is that when traveling, the propeller is constantly advancing on to undisturbed air and that while the slip velocity is reduced, the undisturbed air is equivalent to acting upon a greater mass.

The factors affecting the thrust given by a propeller are: *First,* the diameter, blade area, and pitch or blade angle, which may be termed propeller characteristics; *second,* the speed of revolution, which is proportionate to the engine driving power; and *third,* the rate at which the characteristics of the vessel will allow the propeller to move through the fluid. The propeller which is the most efficient is naturally the one which will produce the greatest amount of thrust in proportion to the power transmitted it by the engine, both when revolving in a fixed position on the ground and when traveling through the air. Each of the factors mentioned must be provided for in the design. A propeller which is too large or of too great a pitch for a given motor, will effectually prevent the motor from developing its normal power by retarding the r. p. m. rate. Propeller blades that are not given sufficient area or pitch will permit the engine to race through not imposing sufficient load on it, and if the speed becomes greatly excessive, the blades are likely to burst or fly apart through centrifugal force. Should the engine be too powerful for the propeller, the blades may bend and break under the strain.

Pitch Ratio. Another characteristic having an important bearing on the result is the *pitch coefficient*, or *pitch ratio*, as it is frequently termed. There is a certain analogy between the propeller and the main planes in that both are intended to drive through the air easily and at the same time exert a sufficient hold on the air either for the purpose of support, as in the latter instance, or for driving, as in the former. Pitch ratio is consequently analogous to aspect ratio. It is the ratio that the pitch bears to the diameter, or length of the propeller. The pitch coefficients of eighteen well-known monoplanes and biplanes vary from 0.4 to 0.2, the mean value being 0.62, which, as it so happens, is exactly that of the Farman propeller. The pitch ratio of the Wright propeller is said to be 1, and its unusually high efficiency is generally conceded, though very few builders have apparently considered it expedient to adopt the means that make this efficiency possible, *i.e.*, propellers of large pitch and diameter turning at the very slow speed of 450 r. p. m. The propeller of the Bleriot XI has a pitch ratio of 0.4, but it is designed to run at 1,350 r. p. m.

Diameter. The diameter is affected by structural considerations, the placing of the motor and other conditions, which restrict the size of propeller that can be employed on a certain machine. Different experimenters have widely-differing standards in this respect, as witness the use of 4-foot extremely high-speed propellers on some machines and 8-foot slow-speed propellers on others. The disadvantage of using a very small propeller is now generally recognized, however, and few, if any, of less than 6-foot diameter are employed. The question of efficiency is so largely dependent upon the diameter, that we may look for an *increase* rather than a *decrease* in the machines of the future. In fact, the whole question of the efficiency of the 2-bladed aerial propeller seems to be one of *diameter* and *speed.* Speaking in general of properly-designed concave propellers, a propeller of large size and slow speed is always more efficient, all other things being equal. Reduce the diameter and increase the speed and the efficiency drops off very rapidly—from as high as 50 pounds thrust per horse-power to as low as 6 pounds per horse-power, these figures being the result of experiments carried out especially to establish the effect of altering the relation of these two essentials of design. The falling off in the efficiency at high speeds is remarkable, for while it seems possible with the best designs to obtain as high as 40 to 50 pounds thrust per horse-power, the average modern aeroplane has a screw of one-sixth this efficiency, or about 7 pounds per horse-power.

Peripheral Speed. The limiting factor in the propeller is its peripheral rather than its rotational speed, since it is upon this that the centrifugal stresses, which are by far the most severe of all involved, depend. The propellers of practically all aeroplanes built so far run at peripheral speeds ranging from 12,000 to 40,000 feet per minute, with occasional instances of speeds as high as 50,000 feet per minute, the rotational speeds being so adjusted to the diameters of the propellers as to produce little variation outside of the range given. At the higher of the speeds mentioned, nearly 570 miles per hour, centrifugal force is so great as to test to its utmost the quality of the finest structural material obtainable.

That it is better to gain permissible peripheral speeds by the use of large diameter propellers at low-rotational speeds, rather than with small propellers at high-rotational speeds, becomes very evident with a little study. Take, for example, the case of a portion of a propeller surface, 1 foot long and 1 foot wide, traveling edgewise round a 30-foot circumference, 600 times a minute, it being assumed that a peripheral speed of 18,000 feet per minute is the maximum permissible in the case in question. Under the conditions stated, the surface passes any given point 10 times per second—often enough to produce a material disturbance of the air worked against. Now assume the circumference reduced to 15 feet by a corresponding halving of the propeller diameter, and immediately it becomes apparent that a doubling of the rotational speed is allowed without increasing the peripheral speed.

But, under the new conditions, the assumed propeller surface passes any given point 20 times per second, twice as often as before with a correspondingly reduced assurance of finding undisturbed air to work against. Moreover, since the blade surface travels the same distance in the same time in both cases, there is no opportunity to reduce its area on account of the higher rotational speed in the smaller propeller. The result is that the blade which is of a width only $\frac{1}{30}$ the length of its path in the large propeller, is in the smaller one $\frac{1}{15}$ its length—a condition that operates directly against maximum effectiveness. Of course, it may be urged that when a propeller is traveling through the air under its normal condition of operation, instead of revolving in a circle, as when kept from advancing, the blades travel separate helical paths, wholly distinct from one another. But these paths are, nevertheless, closely adjacent and become more so with every increase in the number of blades and every decrease in the pitch. From these considerations, it will be evident that large diameters and a minimum number of blades reduce the frequency of the air disturbance and tend to eliminate interference. The largest propeller built thus far, to the writer's knowledge, was turned out in the fall of 1910 for a monster 2,200-pound aeroplane at that time building in California. This propeller measured 14½ feet in diameter, with a corresponding coarse pitch, as compared with the 6- to 8-foot propellers commonly employed.

The air acted on by the propeller is limited to that which flows through the circle described by the tips of the blades, frequently referred to as the *disk*, Fig. 3. The amount acted upon, therefore, increases with the diameter, and as the thrust depends directly upon the volume of air and the velocity at which it is displaced to the rear, it follows that the greater the diameter the less the rearward velocity need be to obtain a given thrust. Thus approximately the same thrust will be obtained from an 8-foot propeller which imparts a 5-mile velocity to the air, as from a 4-foot propeller that imparts a 20-mile velocity. It is self-evident that of the total power developed by the motor only a part is actually utilized in forcing the machine ahead through the air—the remainder does no useful work and is lost. A considerable portion of this lost energy is contained in the air which has been pushed to the rear by the propeller. The amount of such lost power increases as the square of the velocity at which it is pushed astern. In the 4-foot and 8-foot propellers compared above, it is found that when developing the same thrust at a speed of 40 miles per hour, the amount of lost power in the case of the smaller one is about three times as great as in that of the larger one. This is the underlying

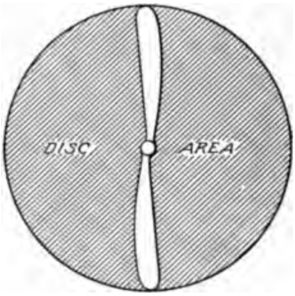

Fig. 3. Diagram Showing Effective Area of Propeller Influence

reason why small propellers are inefficient when used to develop relatively high thrust.

Power of Propellers. To obtain thrust from a propeller, it must waste some power, for reasons that have already been mentioned —it is essential to thrust some air at least to the rear. The smallest quantity that it is necessary to waste can be figured out, and this added to the useful power gives the minimum amount of power which would be required with a perfect and frictionless propeller.

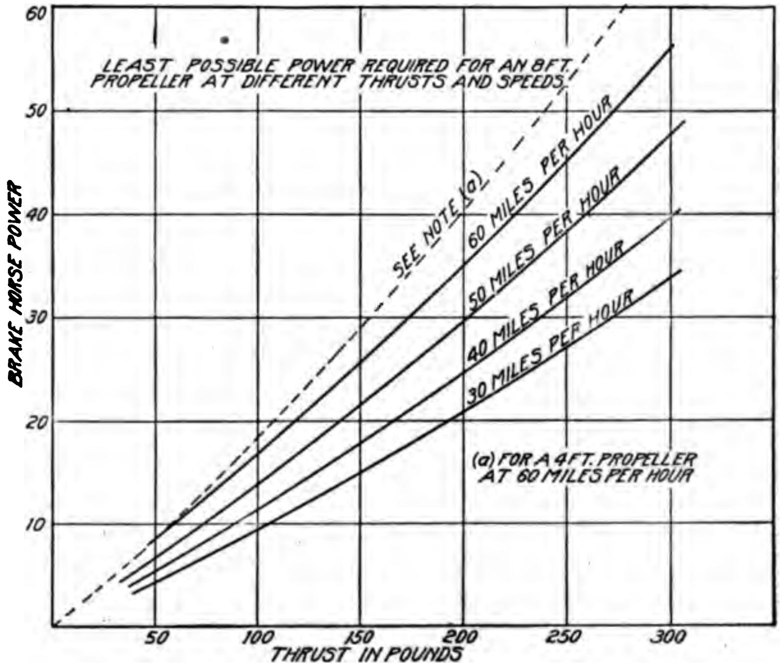

Fig. 4. Minimum Power Required for 8-Foot Propeller at Various Thrusts and Speeds

The curves in Fig. 4 show this least power for an 8-foot propeller at different thrusts and at speeds of from 30 to 60 miles an hour. As a matter of fact, no propeller can be expected to reach the theoretical limit. Many of the best air propellers require about 25 per cent more power than that shown by the curves in Fig. 4, and in fact, the curves in Fig. 5, which show the power which will be needed for a good type of propeller, have been prepared by adding 25 per cent to the theoretical power required in each case. For example, from the curves in Fig. 5, at a speed of 40 miles, a thrust of 100 pounds should be obtained with 14.7 brake horse-power. The Wright Brothers obtain this thrust with about 15 horse-power, which agrees practically with the above.

In Fig. 4, the dotted line shows the minimum power theoretically necessary for a 4-foot propeller at a speed of 60 miles and at different thrusts. At a thrust of 200 pounds, 41 horse-power is necessary, while for an 8-foot propeller only 35 horse-power is required. That is, at this speed and thrust, the smaller propeller requires 20 per cent more power than the larger one.

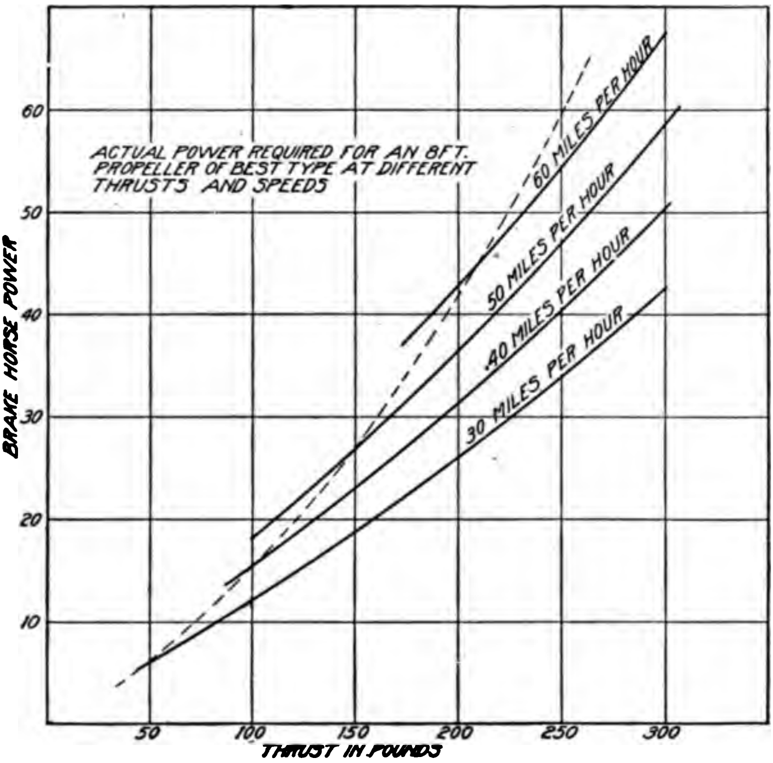

Fig. 5. Actual Power Required for 8-Foot Propel er at Various Thrusts and Speeds

This particular compromise of using a small-diameter, high-speed screw to suit the rest of the design has cost the present-day aeroplane an enormous toll. It makes it necessary to carry a motor several times more powerful and heavy than it should be, with a consequent increase in the size of the aeroplane itself in order to carry the extra weight. The large-diameter, slow-speed screws of the Wright machines are undoubtedly the chief basis of the unusually high efficiency that they show. Langley demonstrated that 1 horse-power, properly applied, could carry 200 pounds at 40 miles per hour. But what machine approaches this? On the same basis, the Wright machine should theoretically be able to fly with a 7-horse-power motor, 2 horse-power being allowed for overcoming the resistance of the non-supporting surfaces, such as the struts, guy wires, and the like, while 5 horse-power would be all that is needed to drive it through the air at its usual speed. But this would entail propellers of great diameter, turning at a slow speed, and they are not compatible with the rest of the design. If they were, it seems that a tremendous saving could be effected; the weight of the engine could be greatly reduced and the radius of action of the machine increased at least threefold.

If allowance be made for the difference in the weights of a cubic foot of water and a cubic foot of air, and the speed is changed from knots to miles per hour, the corresponding formula for air propellers is

$$d=\frac{33\sqrt{T}}{V}$$

For a thrust of 100 pounds and a speed of 40 miles per hour, the diameter would be

$$d=\frac{33\times\sqrt{100}}{40}=8\tfrac{1}{4}\text{ feet}$$

This agrees in practice with the results obtained by the Wright Brothers, who use an 8¼-foot propeller for this thrust and speed. The dotted line in Fig. 5 shows this relation for an 8-foot propeller. The line crosses the power curve for a speed of 60 miles at a thrust of 210 pounds, and that should be the thrust of about the best efficiency. At a speed of 40 miles the best efficiency would be obtained with a thrust of about 95 pounds.

From the above it appears that the larger the diameter the better, and this would be true but for friction and head resistance of the air to the propeller blades. This increases as the diameter is increased, and the power lost from this cause soon becomes as great or greater than that carried away by the air in the propeller race or wake. With other conditions equal and developing the same thrust, an 8-foot propeller will lose from frictional and head resistance about twice as much power as a 4-foot propeller. This makes it apparent that the relation between the diameter, speed, and thrust is an important one. If the diameter is small, there is excessive loss of power in the propeller race, while if too large, the frictional losses are very high, so that a compromise is necessary. In water it has been found that when cavitation does not occur, the most effective diameter is given by the formula

$$d=\frac{\sqrt{T}}{V}$$

where d is the diameter in feet, T the thrust in pounds, and V the speed of the vessel in knots.

Propeller Blades. The next characteristic is the blade. Leonardo's propeller was a screw or helix of a single *worm* or *thread*—being practically all *worm*, and constituting an entire convolution, of which the modern equivalent would be a single-bladed screw, blades being a much later development. It is easy to realize how the original screw propeller came to be of the single *worm* type, and why one complete turn was deemed essential. It was first discovered by actual experiment that half a convolution was fully as efficient as a whole turn, then that a quarter turn was more efficient than half, but with this curtailing of the helix a formidable difficulty arose. It had now developed into a 1-bladed screw, was unsymmetrical and consequently unbalanced. Centrifugal force and 1-sided thrust now jointly interposed with inimical results. It finally appeared that to produce a more efficient, compact, and symmetrical screw propeller, while employing only a fraction of a convolution, two or more *worms* were necessary—in other words, blades. Thus it gradually came to pass that the modern aerial true-screw propeller is but a very short length cut off a 2-threaded screw, in which the thread is relatively deep, with a pitch equal to about two-thirds its diameter. A marked later tendency was to err on the side of plurality of blades, and this was still in evidence when propellers first came to be used for aerial propulsion.

Thus the Ericsson marine propeller was formed of a short section of a 12-thread screw of very coarse pitch and naturally proved very inefficient. The aerial fan propeller of Moy had six broad vanes enclosed within a hoop, and was not a screw at all. It was little better. The same remarks apply to the propellers of Henson, Stringfellow, Linfield, du Temple, and many others. Even the first propeller fans used by Professor Langley were 6-bladed, though in his subsequent and highly successful aerodrome, the twin propellers were 2-bladed true screws, as were also those of the Maxim machine. The latter afforded striking evidence of the efficiency of large-diameter, slow-speed propellers.

Number. Theoretically, the number of blades need not be considered at all. The mass of air dealt with by the propeller is represented by a cylinder of indefinite length, the diameter of which is the same as that of the screw, and the rate at which this cylinder is projected to the rear, depends theoretically upon the pitch and the number of turns per minute of the propeller, and not upon the number of blades, one or an incomplete helix being sufficient, except for mechanical reasons. The minimum number which can be employed practically is, therefore, two—and experience has demonstrated that the same number represents the practical maximum for an aerial propeller. The function of the latter is to create *thrust,* and to do this, it must force the air to the rear with the least possible *internal disturbance, i. e.,* it should be thrust backward as a clean-cut cylinder, and not as a whirling, tumbling mass, which would tend to set up a dragging wake and interfere with the efficiency of the propeller and the speed of the machine. Any number of blades in excess of two could not operate in undisturbed air and would, in consequence, simply act to churn the mass already set in motion by the others. Except in case of very small propellers, three blades are ordinarily employed in marine practice so as to give better mechanical balance.

It may seem strange at first sight that a ventilating fan should operate most efficiently with a large number of blades set close together and with a fine pitch, while the opposite extreme is necessary for an aerial propeller. Stand in the blast of a big ventilating fan and it appears to set up a powerful current of air which should represent the equivalent of considerable thrust. It does, but it must be borne in mind that a ventilating fan and a propeller are two totally different things. Because many blades are found to be most efficient in the case of the former, it is wholly wrong to assume that the same conclusion holds good in the case of the latter. By increasing the number of blades, the skin friction due to the resistance that has to be overcome in rotating the propeller through the air is augmented. Moreover, a fan is stationary, while a propeller is constantly advancing as well as rotating through the air. The action of a fan blower is to move a small quantity of air at a high velocity, whereas the action of a propeller is, or should be, to move a large quantity of air at a low velocity, since the function of the screw is to create thrust. Operating on a yielding fluid medium this thrust will evidently be in proportion to the mass of fluid moved, and also to the velocity at which it is put in motion. But the power consumed in putting this mass of air in motion is proportional to the extent of the mass and to the square of the velocity at which it moves. From this, it follows that to obtain a given thrust with a certain amount of power, it is essential that as large a volume of air be handled as possible and that the velocity imparted to it be as little as possible. As explained in connection with the action of the propeller when the aeroplane is held and when in flight, the fan is designed to create static thrust while the propeller is designed to set up dynamic thrust. The maximum volume of air must be moved backward with the least possible acceleration. In fact, the multi-bladed propeller revolving at a high speed is apt to set up what is known in marine engineering parlance as "cavitation," in which the high speed of the screw causes it to carry round a certain amount of the medium with it, so that the blades strike no undisturbed or *solid* air at all with a proportionate decrease in thrust, or rather an almost entire absence of it. The propeller literally "digs a hole in the air" and revolves in it without pushing the aeroplane ahead.

It will also be evident that there is possible a number of blade arrangements. Not only may the blades differ in their number, in their outline, in their cross section, pitch, and angles of setting, but they may also differ in the angles they make with their plane of rotation, in their longitudinal placing on the propeller shaft, and in the use of longitudinal sections from hub to tip that are straight or curved. Propeller blades in line, or at right angles to the shaft, are almost universal. The advantage of this is that centrifugal force exerts a direct pull from the hub without any tendency to move the blades longitudinally, parallel with the axis of revolution. A supposed disadvantage is the escape of air from the propeller tips without aiding in propulsion. But as any such rapidly thrown air is more apparent when the propeller is held and is then working as a fan, than when working in flight, it has never been considered of sufficient seriousness to be taken into consideration.

Dihedrally-arranged propeller blades with the hub forward, either with straight or curved blades, would utilize the air that is apt to escape at the tips, but they would also increase the amount of the disturbance, subjecting the air behind the blades to direct centrifugal action. Moreover, this would require very stiff blades or guy wires, to prevent the blades from straightening out under centrifugal force, and such wires would interpose additional resistance to rotation with a corresponding disadvantage.

Area. This violent disturbance of the air is affected very markedly by the area of the blades. In marine engineering, narrow blades are usually employed on slow-speed propellers where cavitation is not a factor to be guarded against. But in high-speed marine propellers, where it is likely to occur, the projected area of the blades is sometimes as much as 0.6 of the total disk area. In the case of aerial propellers, cavitation is not likely to occur, particularly with a 2-bladed propeller, unless the speed is very high—1,500 r. p. m. or more, so that narrow blades are preferable. Experiments in marine propulsion also show that the thrust depends more upon the disk area than upon the width of the blades. Both in marine and aerial practice, multiplicity of blades, or increased blade area, tends to reduce the efficiency, apart altogether from the questions of weight and constructional difficulties.

Contour. It must be borne in mind that a propeller is nothing more nor less than a form of aeroplane specially designed to travel a helical path, and that the same laws govern it as those pertaining to the action of the supporting surfaces in striking and passing through the air which forms their support. The blades should, therefore, be *concave* or *hollow-faced* and partake of the *stream line* formation, a condition that is not fulfilled where the face of the blade is flat, such a surface cutting into the air with considerable shock, and by no means creating as little undesirable motion in the surrounding medium as possible. A curved face blade has of necessity an increasing pitch from the cutting edge, or attacking face, to the trailing edge (considering, of course, any particular section). In such a case, the pitch of the propeller is its mean effective pitch. This question of increasing pitch with the width of the blade, has an important bearing on the subject of blade area, as to make a wide hollow-faced blade would soon result in reaching an excessive angle. In the case of the flat blade, the same thing is true, because by the contact of its molecules with the "initial minimum width" the air has already been accelerated up to its final velocity, and further area is not alone wasted, but is detrimental to efficiency. Requisite strength and stiffness, of course, set a limit on the final narrowness of the blades, apart from other considerations.

Flexible Type. Reference has been confined to propellers with rigid blades—preferably of wood. There is another type, known as the flexible-bladed propeller, which is so constructed as to give a self-feathering action to the blades, *i.e.*, a self-varying pitch, the air resistance to rotation causing the blades to twist, and to become of less and less pitch with increasing speed. This type has found some advocates, or at least it did three or four years ago. Experiments with it indicate a great loss of power, so that it is far from efficient. A flexible-bladed type of this kind measuring 19 inches in diameter and having three blades showed on test a thrust of only 3 ounces at 480 r. p. m. The power was estimated at about $\frac{1}{5}$-horse-power, which would give a result of 1 pound thrust per horse-power, so that it seems hardly worth while to experiment further with this type.

Fabric-Covered. Another form of propeller that has been used consists of a frame, over which canvas is stretched taut to form the blades, but the fabric does not remain taut when the propeller is revolving at a high speed. It is, moreover, difficult to make anything but a flat-bladed propeller in this form and have it sufficiently rigid. Such propellers were employed on some of the early French dirigibles, mainly on account of their lightness, but they did not prove practical.

Another disadvantage of these fabric propellers was the fact that the blades consisted of only comparatively small, isolated surfaces at the outer ends of the supporting arms, and this fault was repeated in some of the metal propellers employed abroad. This has been done on the ground that the part of the blade near the hub adds little or nothing to the effective thrust of the propeller. While this is undoubtedly true, every part of the blade, except where it actually loses its curvature to become part of the hub, exerts its proportionate amount of propulsive power, whereas in the other type, resembling a double canoe paddle, the cut away part merely adds to the air resistance of the machine as a whole, and the efficiency of the screw itself is reduced proportionately. Variable pitch propellers for aeroplanes have again been taken up in France notably by Brequet and Antoinette, but the blades have been of wood or metal, mounted so as to permit of partially revolving on their own axis, this movement being controlled by springs.

Speaking of efficiency, it will be noted that the best results obtained by some of the earlier experimenters were not very high. The thrust per brake horse-power obtained by Langley was 7 pounds, by Maxim 9 pounds, by Spencer, using a Maxim-type propeller, 6 pounds, by Farman and a number of other French experimenters, between 6 and 7 pounds. These figures have not been improved upon to any great extent, except in isolated cases, up to the present day, so that it will be apparent that the aerial propeller is lamentably inefficient, and that most of the recent successes have obtained in spite of its shortcomings, rather than otherwise. The cost of this is redundant power and weight, since the propellers waste a very substantial fraction of the energy supplied by the motor. This extravagant provision of excess power that is necessary likewise involves a larger, stronger, and heavier machine as a whole, for a given passenger-carrying capacity.

Propeller Construction. *Material.* In actual propeller construction various expedients have been tried by the French and while some of these propellers have been ingenious, the example thus set has not been generally followed. The Antoinette is one of the very few machines, if not the only one, that employs a metal propeller. Bleriot experimented with metal propellers in the early days but shortly abandoned them for wood, which he has since adhered to. The Antoinette propeller has a diameter of 7 feet 2 inches and a pitch of 4 feet 3 inches. It is composed of a stiff steel tube to which are attached two blades of sheet aluminum riveted to it. The blades themselves, however, are adjustable, thus permitting of varying the pitch. It is designed to run at 1,100 r. p. m. The Vendome is a hollow two-bladed propeller, 8 feet in diameter, which is built of hickory veneer, mounted on canvas, so that despite its size, it weighs only 4.4 pounds. While this represents exquisite workmanship and a beautiful finish, an extremely light weight is no advantage, particularly where the propeller is relied upon to act as a substitute for the flywheel of the motor, as is generally the case. The Tatin, another French example, is a two-bladed propeller built up of laminated wood, and represents one of the rare instances in which the design calls for a pitch exceeding the diameter. The latter is 7 feet 8 inches, while the pitch is 8 feet 2 inches, the propeller being designed to run at 700 r. p. m., being driven through a reducing gear. Its construction is peculiar in that instead of being built up by simply gluing one board over another, a number of thin superimposed sheets or laminations of wood are let into framing, the whole being covered tightly with Japanese silk and then varnished.

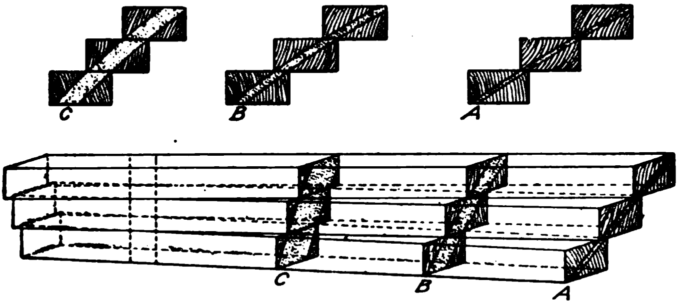

Fig. 6. Method of Fitting Blocks from Which Propeller is Shaped

Standard Construction. The standard method of propeller construction, in that it is now most generally followed, is that of gluing a number of boards together under heavy pressure and then practically whittling the propeller out of the block thus formed, Fig. 6. Wood is preferred to steel for a number of reasons, chief among which is the liability of a steel blade to snap suddenly and without warning under the influence of temperature changes or violent shocks. If sufficiently strong, a wood blade is less liable to snap, and gives warning of impending fracture by bending and splitting. Wood propellers are also much lighter than those of steel. The blade of an aerial propeller has sharp edges, particularly on what is termed the "attacking edge," but it is quite thick along its median line. It is made thick, not merely to strengthen it, but because thickness offers the same aerodynamic advantage in the propeller that it presents in the sustaining surfaces of the aeroplane. This thickness gives ample strength when the material is wood, while it would make a steel propeller unnecessarily strong and excessively heavy, though, for that matter, it would be possible to employ sheet-steel stampings or pressed steel, autogenously welded together. In this case, the expense for dies would be prohibitive unless propeller designs were standardized, so that wood has the advantage of being much easier to work than steel.

Chauviere Method. The Chauviere propellers, used on most French machines, are built up of several planks of well seasoned ash or walnut. These planks are cut to the shape of a number of sections transverse to the axis of a propeller designed in accordance with the special conditions proposed, such as the r. p. m. rate at which it is to turn, torque, tractive effect, and the speed for which the aeroplane itself is designed. Each plank forms part of both blades of the 2-bladed propeller, and therefore a hole is cut into the center to receive the hub. The planks are then glued together on their faces, after having been accurately centered and orientated, so that they represent the form of the finished propeller approximately and show some of its lines accurately. The next operation consists of removing the superfluous wood between these lines and working the entire surface to the required form. This is a delicate task requiring great skill and care, for the removal of too much material at any point would ruin the work. The surface is finished by polishing.

A still more delicate operation is necessary to balance the blades, as even a slight difference in length, weight, or shape might set up dangerous vibrations in a rapidly revolving propeller. The propeller is mounted on a mandrel, which is poised on very sensitive friction wheels in a specially-devised machine, and the blades are carefully retouched until the propeller remains in equilibrium in every position. It is then coated with special varnish to give it a smooth surface and to protect it from the weather. The finished propeller is firmly attached to the shaft by clamping its central portion between two steel disks, connected by bolts passing through the wood of the hub.

American Methods. Two methods are in vogue in this country at present. In one, the planks forming the propeller are offset upon one another in such a manner that when the superfluous wood represented by their protruding edges is removed, the surface thus obtained is the curvature desired in the finished propeller. The planks must, accordingly, be finished very accurately before gluing and must be put together very accurately to insure this result. The other method, which is that mentioned in the article on "Building a Curtiss biplane," and illustrated therein, Fig. 21, is merely to glue the planks together in such a manner that sufficient excess material is allowed, back and front, to whittle the resulting block down to the required dimensions and shape. Templates, representing the curvature of the back and front at sections 3 inches apart from the hub right out to the tip, are employed to note the accuracy of the work as it proceeds. The greatest care must naturally be employed not to cut too deep at any point. In either case, the finish is the same—rubbing smooth, polishing, and varnishing. Ever since the accident to the propeller of the Wright machine in which Lieutenant Selfridge was killed at the United States Army acceptance tests in 1908, it has become customary to protect the tips of wood propellers by covering them for a foot or more from their ends with cheese cloth, or other light fabric. This cloth is stretched on very tight, like a pocket covering the end of the tip, and is glued down and varnished, so that it practically becomes a part of the wood and there is no break in the surface. Some such protection is necessary to prevent splintering when accidentally striking objects, particularly when on the ground, as the propeller tips are very thin and correspondingly fragile.

The method of gluing the planks together in fan shape so that the points at which the planks overlap will practically mark the line of curvature of the finished blade, is that followed in the making of the Wright propellers. Contrary to the custom of employing ash, maple, walnut, and other hard woods, or alternate laminations of these with spruce, the Wright Brothers pin their faith to spruce alone, as is the case in the construction of the entire framing of their machine, with the exception of the bed for the motor. The Wright propeller is built up of three planks glued together as shown in Fig. 6, so that they overlap like the sticks of a fan to an extent which diminishes as the distance from the axis increases. The superfluous parts of the wood represented by the dark and triangular areas of the upper diagrams in the figure, are then cut away, the curvature being tested at every point with the aid of templates as the work proceeds. In contrast with this, Chauviere propellers are made from six or seven overlapping planks. The finished propeller contains only about 8½ per cent of the wood of the original planks. A study of the sections, *A*, *B*, and *C* in Fig. 6 will make clear both the progressive variation in slope and the curvature from the axis to the periphery, and the corresponding variation in the thickness of the blade. The general direction of these sections will be more or less inclined to the axis of the propeller according to their distance from it. In the making of metal propellers, the blades are usually riveted to the arms, composed of steel tubes brazed into the hub. The blades themselves are then given the proper curvature by hammering upon a form. Casting in the form desired and twisting into shape have both been tried, but without much success, very few metal propellers of any kind being in use today.

Hollands. A recent British patent on an all-steel propeller is of interest. It is known as the Hollands propeller and is formed of thin steel plates, brazed together at their edges. In cross section the blades are of shell-like form concave on the driving side and convex on the leading surface, the concavity being less than the convexity. The greatest depth of concavity equals one-eighteenth of the width of the blade, and is situated at one-third of the breadth from the leading edge throughout the length of the blade. The blades taper from root to tip and are set at a gradually decreasing pitch angle, being 15 degrees at the tip and 30 degrees midway the length of the blade. An efficiency of 85 per cent is claimed for it on the ground that it has a minimum radius of centers of pressure and mass, resulting in minimum torque in relation to thrust, or greatest thrust for a given turning moment, least centrifugal stress for a given angular velocity and diameter, and the least bending moment on the blades.

Propeller Design. *True-Screw Type.* There are two forms of propellers extant, the true-screw and the variable pitch, the former being very largely in the majority, in fact, used almost altogether, although the variable-pitch type likewise has its advocates. The effect of revolving an aerial propeller, as already explained, is to create a column or shaft of air out of the body of air in which it is run, of a diameter nearly corresponding to the diameter of the propeller, the column being given, by the pitch and rotation of the blades, a backward motion proportionate to the power delivered to the propeller, the movement of the latter being similar to that of a nut when being moved along a bolt in the operation of loosening. The underlying principle of the screw thus being necessary, it is essential that the propeller, which is the column-forming instrument, should be true to work with the greatest efficiency; it should run through the column within the main body in the same way that a well-made nut worms its course along a well-made bolt. Each part of the bolt-engaging surface of the nut must engage with the surface of the "fluid-bolt" it creates, with equal pressure throughout the whole of its convolutions. Any distortion or lack of trueness in the thread of an ordinary nut will effectually spoil its bolt by stripping the thread to some degree, in other words, ruining its engaging surface while coincidently taking a uselessly large amount of power to force it along the bolt. The same principle applies in the case of the propeller, and if the blades are distorted, rough, or untrue, they will act in the same manner as the badly-made nut and waste a great deal of the power exerted in driving.

On the true-screw principle, the effect of the propeller in the air must start from the point where the blade springs from the hub and continue right through its entire length and surface. Each blade must accurately match its counterpart and be fixed in relation to it so that at no point will one part of the propeller try to climb through more air, or worm through any more or less of its true course, than it should. If not properly and accurately made, instead of thrusting backward a clean-cut column of air, it will simply churn and worry it with a great loss of power. But a propeller which is true screw in shape, may be very untrue in its action on the air. To be efficient, it must act as a whole upon the air, as a true screw nut does upon its bolt. In other words, the best propeller for any particular case may have greater or less angularity of its blade at various places, than would be called for if the propeller were designed to be a true-screw shape for the particular pitch speed required. In any case, it must be a true screw in its operation. As mentioned in connection with the details of building a Curtiss biplane, the number of aeroplane designers competent to build a properly-made variable-pitch propeller is very small indeed, which probably accounts for the small number in use. Moreover, the advantages claimed for it appear to be so largely based upon theory as to provide small incentive for its adoption.

Some idea of the dynamics of the action of the aerial propeller may be gained by citing a very simple illustration. Take the case of a smoker "blowing rings." It will be noted that a cylinder of air is propelled from the mouth into the still air of the room. At the edge of this cylinder of air is the smoke ring, and it will be evident that it revolves within itself, the inside traveling forward and the outside of the ring to the rear. This is obviously due to the friction between the moving cylinder of air and the still air through which it travels. This action is more markedly apparent in the smoke rings that issue from saluting guns and from locomotive stacks under favorable atmospheric conditions, but equally effective results may be obtained with a "smoke ring box," made from an ordinary stationery box with a circular hole cut out of the center of the cover. Fill this with smoke and tap lightly, to compress the air within, and a ring will be emitted. A hard tap will cause a clear, sharp ring to shoot rapidly upward, but by raising the box cover slightly and gently lowering it, a series of rings will emerge and float slowly up, affording sufficient opportunity to study their evolutions closely. In any case, when a smoke ring is produced, its center is very small and grows larger as the ring expands. It is with the first stage of the ring that we will deal.

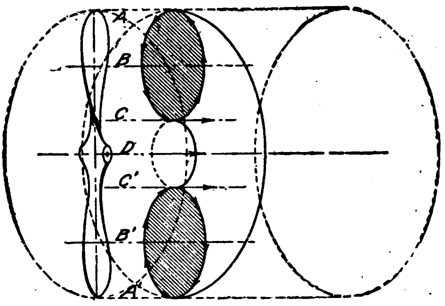

Fig. 7. Diagram Showing Action of Propeller Blades

Assume the two cross-hatched ellipses of Fig. 7 to show the section of a smoke ring, cut through its center. The ring, acted upon *by a* force in the direction of *D*, revolves within itself as shown by the arrows. Friction with the outside air mass causes this rotation and reduces the velocity of the extreme edge of the ring to zero, as shown at *A* and *A'*. This ring then apparently rolls inside a tube of air, and as its maximum velocity is at *C* and *C'*, the points *B* and *B'* must attain a velocity equal to one-half that at *C* and *C'*. The portion between *C* and *C'* forms the shank and hub in most propellers and does not assist materially in propulsion, if at all. The above may be taken as the relative velocities of various portions of the disk of the air column sheared loose by the slip of a screw-pitch propeller while traveling through the air at its normal speed.

Variable-Pitch Type. Taking a screw-pitch propeller, blade incidence angles (blade angles not corrected for slip) are found at the different radii corresponding to Fig. 7, to be as follows: At *C* and *C'*, 14 degrees; at *B* and *B'*, 7 degrees; and at *A* and *A'*, 3½ degrees. Now the velocity at *C* and *C'* is twice as great as at *B* and *B'*. In order, therefore, to raise the velocity at *B* and *B'* to that at *C* and *C'*, we must increase the blade angle of the propeller as much again, or from 7 to 14 degrees. The velocity at *A* and *A'* being practically zero, it will be necessary to increase the blade angle considerably at this radius. Doubling the blade angle at *B* and *B'* has doubled the velocity at this point; hence, increasing the blade angle at *A* and *A'* (3½ degrees) to the former angle of *B* and *B'* (7 degrees), should give this radius the former *B* and *B'* velocity, or one-half that of *C* and *C'*. By doubling this angle, *i. e.*, increasing it to 14 degrees, we again reach the velocity of *C* and *C'*.

These angles may then be assumed to give a *slip column* of air of uniform velocity, and as such a column of air is what the propeller pushes against, the *slip column* would give a more efficient background for *propeller purchase*, so to speak, than the *varied velocity column* delivered by the screw-pitch propeller. This constitutes an argument for the uniform pitch propeller, it being noticeable that the products of increasing and doubling the various angles result in each case in the same angle, namely, 14 degrees. Correcting this angle throughout its length in order that the theoretical and practical foot pitch may agree, add, say, 2½ degrees, and the result will be a uniform or straight-pitch propeller, with a blade angle of 16½ degrees.

From what has been said thus far, it will be apparent that there is considerable diversity of opinion regarding the design of the propeller, and likewise a lamentable lack of definite knowledge regarding propeller efficiencies. Since errors in the design may necessitate a motor of 30 to 100 per cent more power to attain the desired result, the importance of working along well-settled lines will be manifest.

Problems in Design. The salient points of design already dwelt upon, putting them in the form of questions which must be answered by the designer when planning his propeller, are as follows:

1. At what speed should the propeller be revolved to give a certain thrust?
2. What combination of pitch and number of turns per minute would produce the maximum thrust with the minimum power?
3. Is it better to use a fine pitch and revolve the screw fast?
4. Or is it better to use a coarse pitch and turn the screw slowly?
5. Are wide or narrow blades preferable?
6. Should the blades have a uniform or an increasing (variable) pitch?
7. Which is preferable to use, two, three, four, or more blades?
8. Given two screws exactly alike, but one with two or three times the diameter of the other, how much more thrust should the larger one give than the smaller when revolved at the same speed?
9. How much more power is required to obtain a given number of pounds thrust while traveling at 20, 30, or 40 miles an hour, than to give the same thrust when standing still?
10. What percentage of the power used is due to skin friction?

Propeller Tests. *Herring.* To obtain propeller data, Herring, long associated with Curtiss, devised the apparatus shown in Fig. 8. On this a great many propellers have been tested, both in still air and in a powerful blast of definitely known velocity, to simulate the condition of traveling through the air. M represents a variable-speed electric motor of 5 horse-power. This is rigidly mounted on a table, and by means of resistances and a controller, may be kept running steadily at any speed desired between 700 and 1,500 r. p. m. The propeller to be tested, V is mounted on a shaft T on which is mounted a pulley P. This shaft runs in ball bearings W and U, and is held in place in the room by six wires H', H'', etc. These suspended wires have turnbuckles inserted in them for the purpose of adjustment, and very stiff springs for taking up the vibration at high speeds. An endless belt connects the motor pulley

R with the pulley *P* on the propeller shaft. This belt passes under the ball-bearing, mounted pulleys *N* and *O*, which have suspended from them the equal weights *C* and *D*, for the purpose of keeping the belt taut. In testing, the speed at which the propeller is turning is measured at *W* where the shaft projects through the bearing.

The amount of power in foot pounds per minute used in driving the screw, is the pull on the belt multiplied by its speed. Or, to be more exact, it is the pull on the belt multiplied by the number of turns of the pulley *P* per minute, multiplied by the circumference of this pulley in feet. The circumference of *P* can be directly measured, while the pull on the belt is always exactly half the reading of the scale *B*. The thrust of the screw is measured direct by means of the scale *A*, which is connected by a wire with the bearing *U*. A stop *S* prevents the shaft *T* from moving back beyond a certain point. An electric contact *E* and the lamp *L* show when the propeller pulls enough to move the bearing away from *S*.

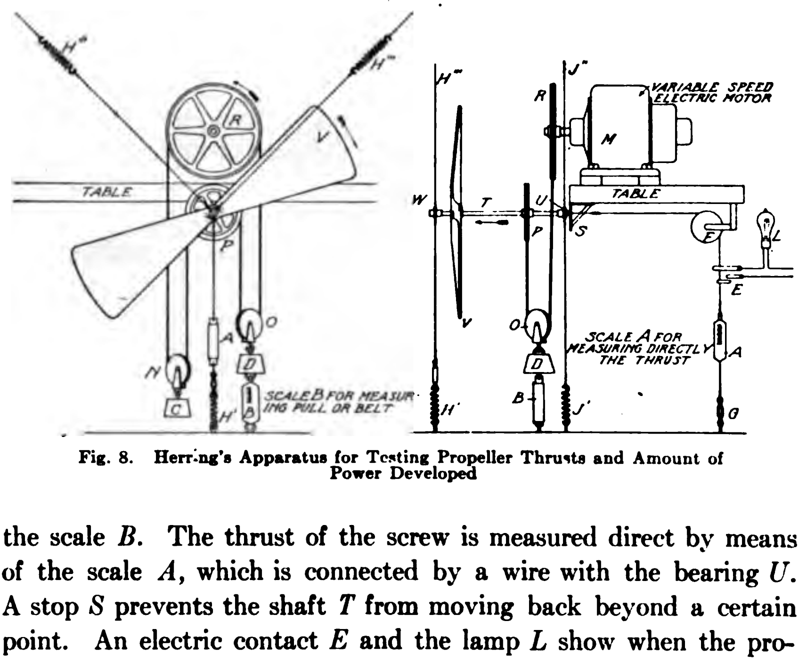

Fig. 8. Herring's Apparatus for Testing Propeller Thrusts and Amount of Power Developed

The turnbuckle *G* is used for adjusting the force with which the propeller axle is held against the stop *S*, which force must be overcome before the lamp *L* glows. This force—the actual thrust of the screw—is measured direct on the scale *A*.

Screws ranging from 7 inches to 4 feet in diameter were tested at some 15 to 20 ranges of speed each, and screws with wide and also narrow blades, but of the same diameter and pitch, were tried. Also screws of the same number and width of blades, differing only in pitch, were tried. A screw of 40-inches diameter and having no pitch was also tested at many speeds to determine the power absorbed in skin friction. As the apparatus was built with extreme care and fine ball bearings were used throughout, its friction was found to be surprisingly small—so small in fact, that even in the experiment on skin friction, the forces could be measured with accuracy. Incidentally, the reduction of the thrusts of the various screws caused by wind pressure against the pulley *P* was arrived at with considerable accuracy by substituting pulleys of different diameters, and noting the change in the thrust of the screws when running at the same speed.

To obtain an idea of the relative values of different designs of screws under conditions of actual practice, a second motor which does not appear in the drawing, was mounted in front of *W*. A propeller was mounted direct on the shaft of this second motor, and made to furnish a blast in which the screw being tested worked. As the second motor also could be driven at any desired speed, and the blast from it accurately measured, the screws were tested under conditions which closely approached those to be expected in practice, when the aeroplane is moving through the air in flight.

The results embraced some 900 or more readings and showed in a striking manner that comparatively slight differences in design may easily mean great saving or waste of power. By placing an obstruction in front of the propeller when it was revolving in still air, more thrust was obtained than was theoretically possible. Blocking the flow of air at the side of the propeller had a tendency to diminish the thrust.

While this testing apparatus more or less approximates conditions of practice, it is evident that a uniform blast of wind is far from representing the actual condition under which a propeller has to work, so it would seem that the only conclusive test of a propeller is to try out the screw itself under practical flight conditions. But this may be a risky undertaking, either in a dirigible or an aeroplane, and more particularly the latter, as through some error in design, it may fall so far short of calculations as to be a menace to the safety of the aviator.

British Tests. The English firm, Vickers Sons & Maxim, who were responsible for the construction of the huge British naval dirigible, have gone to great expense to build a testing apparatus for this purpose. It consists of a great whirling table. From a high tower of steel erected on a hill at an open place, is hung a big cantilever. The arm on which the propeller is mounted is 110 feet long, and is balanced by an arm 56 feet long and carrying a water-ballast tank at its outer end. Both arms are built up of steel angles and are tied by steel rods to a bracket at the top of the tubular tower. At the head is a large ball bearing which supports the entire weight of the moving part of the structure, while a guide for the bottom end is supplied with four horizontal rollers carried on cast-iron brackets bolted to the lower end of the steel tube and rolling on a turned track on the collar.

For the motive power, there is a 100-horse-power engine situated in a cabin built round the tower on the revolving arms. A line of shafting carries the power to the extremity of the propeller testing arm and drives the propeller through bevel gearing. The propeller is mounted on a sliding shaft which works against a spring thrust abutment. To reproduce actual working conditions more thoroughly, a car is rigged up, and resistance can be put upon the arm to vary the speed at which it rotates. This motion of the arm is due entirely to the propeller thrust, and this thrust can be measured accurately to within 1 per cent, a special device being introduced to compensate for the circular flight path. Although one of the reasons for the erection of this monster propeller testing plant has been to promote the trials of the new screws for the naval dirigible, it is also employed for other tests and is open to British military and various experimenters.

Number of Propellers. The number of propellers and their location on the aeroplane are also considerations of importance which form part of the problem of propulsion. The chief reason for urging the use of plural propellers is to overcome the unbalancing brought about by the gyroscopic effects and those of reaction, it being evident that they can be readily neutralized by the use of two or more propellers of the same size, symmetrically placed and revolving in opposite directions. That such effects exist can not be denied, but the prevailing opinion is that their magnitude with propellers ranging from 5 to 10 feet in diameter and weighing from 3 to 20 pounds, with a large proportion of this weight in the hub, is too trifling to be seriously regarded—a view that is apparently upheld by the fact that the Wright and Cody biplanes are the only successful twin-screw machines of large size, *i.e.*, not flying models. This system was first seriously applied by Maxim to his huge multiple-plane machine and was subsequently employed by Langley on his flying models. It certainly appears logical that a narrow propeller blade from 2 to 5 feet long, moving at high speed on one side of an aeroplane, can not produce any considerable reaction per unit of area against a broad wing surface on the opposite side, from 10 to 25 feet long.

For instance, take Bleriot's cross-channel machine. In this the propeller blades are $3\frac{3}{8}$ feet long and the wing span 25 feet. The most effective speed of this propeller is about 1,200 r. p. m. at which about 25 horse-power is required. This amount of power is equivalent to 825,000 foot pounds a minute, or 688 foot pounds a propeller revolution, meaning that the two propeller blades encounter a maximum possible resistance to their rotation of 688 divided by 21, the approximate surface in square feet of the propeller circle or disk. This gives an approximate resistance of 33 pounds, figured at the propeller tips, which, extended to the wing tips, is the equivalent of a trifle over 8 pounds load on the one wing end, raising the weight supported per square foot of area an average of one and two-thirds ounces higher on one wing than on the other. Assuming a normal load of 75 ounces to the square foot, which is very close to the actual, the addition of this amount unbalances the machine to the extent that the weight is only 2 per cent more on one side than on the other.

Wilbur Wright asserts that the Wright machine can be flown with 50 pounds of unbalanced weight, and Santos-Dumont has flown with 40 pounds on one side of the body of his monoplane, nothing more than a slightly increased warping of the wings on one side being necessary to correct the balance, from which it will be apparent that the unbalanced reaction from a single propeller is not as serious in practice as it is in theory.

The gyroscopic action of the single propeller is more dependent upon the factors of mass and speed. With heavy propellers, it might undoubtedly become serious, but with the light wood propellers so generally employed, it is quite as negligible a quantity as the reaction effect.

Location of Propellers. The most important single question of design still unsettled is the position of the propeller. There is a distinct advantage in placing the propeller at the rear in marine practice, utilizing a pushing or propulsive action, on account of the frictional wake created behind the ship, and which causes the water to flow after the vessel, but at a lesser velocity. In placing the propeller behind, it is put in such a position as to act upon and take advantage of this phenomenon, the effect of the propeller being to bring this wake to rest.

Theoretically, a boat can be propelled with less power than is necessary to tow it, but with respect to aeroplanes, apart altogether from the difference of mediums, there is at present a very considerable difference of form, an aeroplane bearing but little resemblance to the hull of a boat. Undoubtedly there is a frictional wake in the case of the aeroplane, perhaps quite as much as in the case of a boat, allowing for the difference in medium. Admitting then that this wake does exist, it follows that a propulsive screw is better than a tractor. In a matter of this kind, constructional considerations, as well as ease of launching and ability to land without damage, must be given due weight. In the case of monoplanes, constructional details have had most to do with the use of the tractor or forward position of the screw, but monoplanes are now being built with propulsive screws. Good results have been obtained in a small flying model equipped with two screws, placed fore and aft in line with one another, the forward screw being a tractor and the latter a propulsive screw, but so far as the writer is aware this arrangement has never been tried in actual practice.

Experience has shown that no improvement whatever is obtained where efficiency is concerned, either by the use of a ring connecting the propeller blade tips, or by the employment of any form of shrouding. It has frequently been considered that locating the propeller in a cylindrical or conical chamber, or employing some form of guide through which the air is led to the propeller is necessary, and quite a number of machines—few of which have ever flown, by the way—have incorporated this feature. That nothing of this kind is an improvement, either when placed before or behind the propeller, is now self-evident. The air does not fly off from the tips of the blades under the influence of centrifugal force, as has been commonly supposed, but is powerfully drawn inward in a well-designed propeller, so that the maximum efficiency is obtained by allowing it to revolve in a free air space.

Propeller Efficiency. The efficiency of a propeller depends upon two fundamental laws—the law of kinetic energy and the law of momentum. A propeller rotating upon a standing machine discharges a certain number of pounds of air backward every second. The law of kinetic energy is expressed by the equation

$$W=\frac{64\ K}{V^2}$$

where K is the number of foot pounds of energy which, when applied to a body, or volume of air, of W pounds weight, will give it a velocity of V feet per second.

The law of momentum is expressed by the equation

$$F=\frac{W\ V}{32\ T}$$

where F is the force in pounds, which, applied to a body, or volume of air, of W pounds weight for a time T seconds, gives it a velocity of V feet per second.

But there are two meanings of the term "propeller efficiency." One, the *true efficiency*, is the useful work of the propeller, divided by the power absorbed by it. The useful work is the speed of the aeroplane, multiplied by the thrust of the propeller while driving the machine at that speed, and, of course, the power absorbed is the brake horse-power (in foot pounds) of the engine at the number of revolutions made under those conditions, less the power lost in transmission.

The other meaning of propeller efficiency is simply the *thrust exerted by the propeller* when revolving at a fixed point, multiplied by the pitch velocity, and divided by the foot pounds delivered to it by the engine.

The pitch velocity is the pitch times the number of revolutions per minute.

It is efficiency in the latter sense that is considered here, and a comparison of two propellers of different diameters will show, in a striking manner, the increase in efficiency with increase in diameter. Take, for example, two propellers rotating on standing machines using the same horse-power, but of different diameters. The given horse-power acting on the smaller amount of air in the smaller propeller gives the discharged air a higher velocity than with the larger propeller. This velocity corresponds somewhat to the slip in a propeller on a moving machine and should not be mistaken for the velocity of the machine.

Let the two propellers be of such sizes that, for one horse-power applied to each, the velocity given to the discharged air by the small one would be 40 feet per second, and by the larger one 20 feet per second. One horse-power is equivalent to 550 foot pounds of energy expended per second. Consider the law of kinetic energy as applied to the volume of air discharged in one second by the two different propellers. We have for each propeller, $K = 550$ foot pounds; $V =$ 40 and 20 feet per second, respectively. Then the weight W of air discharged by the small propeller in one second is

$$W = \frac{64\ K}{V^2} = \frac{64 \times 550}{40^2} = 22 \text{ pounds of air}$$

Again, for the larger propeller

$$W = \frac{64 \times 550}{20^2} = 88 \text{ pounds of air}$$

Now that we have the values of W, or the weights of the air discharged in each case, we can apply them in the equation of momentum and ascertain the force applied to the air, or the thrust of the propellers.

For the smaller propeller we have

$$F = \frac{W\,V}{32\ T} = \frac{22 \times 40}{32 \times 1} = 27.5 \text{ pounds thrust}$$

Again, for the larger propeller

$$F = \frac{88 \times 20}{32 \times 1} = 55 \text{ pounds thrust}$$

Of course, in these calculations, the losses due to skin friction and to the churning of the air, are neglected, but the figures show a striking comparison in favor of the larger propeller, both in having smaller slip and in giving a higher thrust than the smaller one for the same amount of energy in each case expended in producing slip.

EXAMINATION PAPER

AERIAL PROPELLER

Read Carefully: Place your name and full address at the head of the paper. Any cheap, light paper like the sample previously sent you may be used. Do not crowd your work, but arrange it neatly and legibly. *Do not copy the answers from the Instruction Paper; use your own words, so that we may be sure you understand the subject.*

1. Define the *pitch* of a propeller.
2. What is the *slip* of a propeller?
3. Why is it not desirable to eliminate the slip entirely?
4. Define *dynamic thrust* and *static thrust.*
5. What are the factors affecting the thrust of a propeller?
6. What is meant by *pitch ratio?*
7. Assuming properly designed concave propellers, which will be more efficient, that of large size and slow speed or that of smaller size and higher speed, all other things being equal?
8. How does the peripheral speed affect the propeller design?
9. What is the theoretical formula for the diameter of a propeller in relation to thrust and speed?
10. What is meant by *cavitation?*
11. Why is the number of necessary propeller blades limited to two?
12. What is a true-screw propeller?
13. Describe the contour of a true-screw propeller blade.
14. Give a brief description of the standard construction of a propeller.
15. Do American propeller construction methods differ from standard methods? If so, in what particulars?
16. State the problems which confront the designer of aerial propellers.
17. Why is the gyroscopic action of a single propeller not serious?