TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 491

PROPELLER PROBLEMS

By A. Betz

Washington
December, 1928

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL MEMORANDUM NO. 491.

PROPELLER PROBLEMS.*

By A. Betz.

The propeller, especially the screw propeller, has been the subject of many researches, both experimental and theoretical. The phenomena of the screw propeller are not especially difficult to understand. It is comparatively easy to make propellers with very high efficiencies of over 90%. The fact that the propeller problem is constantly being made the subject of new researches is due to the difficulties arising from unfavorable conditions. I will make a brief survey of the most important problems arising in this connection and simultaneously endeavor to show the present status of our knowledge. A propeller generally works in conjunction with a vehicle. Just this joint action of vehicle and propeller develops very great difficulties. In order to make further progress, we must first obtain a sufficiently clear idea of the phenomena with the vehicle alone and with the propeller alone. We must therefore first consider the propeller without the vehicle, the so-called "detached" propeller.

* "Propellerfragen," a reprint from Zeitschrift für angewandte Mathematik und Mechanik," Vol. VII (1927), pp. 431-436.

The Detached Propeller

The essential principles of our present propeller theories were discovered half a century ago by the Englishmen Rankine and Froude.* There are two viewpoints. The so-called "propeller-slipstream theory" considers the momentum and energy of the fluid before and behind the propeller. In its simplest form, whereby only forces and velocities in the axial direction are considered, it leads to two important conclusions:

1. For a given propeller diameter, an unavoidable loss of energy is necessitated by the operating conditions, namely, the required thrust, speed of translation and fluid density. This loss is due to the fact that, for producing the thrust, the fluid must be driven backward and its kinetic energy is thus uselessly expended. The essential result of this viewpoint is the well-known maximum theoretical propeller efficiency.

2. The velocity, at which the fluid passes through the propeller, is the arithmetical mean of the velocities before and behind the propeller.

The other viewpoint, the so-called propeller-blade theory considers the phenomena on the propeller blade. In particular,

---

*Rankine, "On the Mechanical Principle of the Action of Propellers," Transactions of the Institution of Naval Architects, Vol. VI (1865), p.13;
Froude, "On the Elementary Relation between Pitch, Slip and Propulsive Efficiency," Tr. of the Inst. of N.A., Vol. XIX (1878), p. 47; Froude, "On the Part Played in Propulsion by Differences of Fluid Pressure," Tr. of the Inst. of N.A., Vol. XXX (1889), p. 390.

it establishes the fact that the resistance of the blade to its direction of motion causes a loss of energy which can likewise be expressed in terms of efficiency. We will call this the blade efficiency. Moreover, this viewpoint gives the blade width and angle of attack required to produce a certain thrust. It was long discussed as to the relation of these two theories, both of which give the propeller efficiency, though they are based on entirely different considerations. We now know that these two theories, when properly formulated, cover two sources of loss which are essentially independent of each other. The losses obtained by the two methods are therefore to be added. These two sources of loss cannot be sharply separated because, on the one hand, the blade resistance also affects the induced velocities in the slip stream and, on the other hand, the mutual effect of the blades on one another can best be expressed by the propeller slip-stream theory. Fortunately, the blade resistance of a good propeller is so small in comparison with the other forces (especially the propeller thrust), that its effect on the induced velocities can generally be disregarded. This makes the slip-stream theory independent of the special properties of the blade, which means a considerable simplification. The special blade characteristics can then be completely separated by the propeller-blade theory.* On the contrary, the results of the slip-stream theory are generally required for the perfect application of the propeller-blade theory. In order to judge the phenomena on the blade, we must know the velocity of the blade with reference to the fluid. This is not exactly identical, however, with the absolute velocity of the propeller in space, since motion is imparted to the fluid by the propeller, so that the fluid has a velocity of its own in the plane of the propeller. The magnitude of this induced velocity is given by the slip-stream theory.

However, if we wish to use the slip-stream theory for the purpose of determining the induced velocities in the propeller plane, in order to obtain an idea of the phenomena on the blade and especially of the requisite size and position of the blades for the desired action, the above-mentioned simple form of the slip-stream theory no longer suffices. The propeller accelerates the fluid not only in the axial direction, but also exerts

*In principle it would naturally be better to use one general theory covering the phenomena on the blades and their mutual reactions. In this case, however, we would have to dispense with the considerable simplification afforded by the separation into the propeller-blade theory and the slip-stream theory. An example of such a general theory is given by H. Reissner, in his work "Studien zur Berechnung und planmässigen Prüfung der Luftschrauben," Zeitschrift für Flugtechnik und Motorluftschiffahrt, Vols. I-III. Such general viewpoints are chiefly important in dealing with propellers under unfavorable operating conditions when the losses on the propeller blade are no longer relatively small, so that the above-mentioned separation of these losses from the other phenomena is hardly admissible. In a general treatise, however, so many simplifying assumptions must usually be made, that it is questionable whether the results are any more reliable than in the separation of the propeller-blade phenomena.

a rotary moment on the fluid, which imparts a rotary motion to the slip stream. This rotary motion means a further loss of energy and a consequent lessening of the efficiency. In very many instances, however, the magnitude of this lost energy is of subordinate importance. The knowledge of the rotary motion of the slip stream is of special importance for judging the phenomena on the propeller blade.

If the rotation of the slip stream be disregarded, all points of the propeller-disk area will be equivalent in their effectiveness. In the simple slip-stream theory, the thrust is therefore assumed to be distributed uniformly over the propeller disk. This is the simplest way for the calculation and, moreover, yields the minimum loss. If, however, the rotation of the slip stream be taken into account, then the parts situated near the axis will yield a considerably poorer efficiency than the other portions, since the torsional energy is there relatively large. The question must, therefore, be given special consideration, as to how the thrust must be distributed over the propeller-disk area, in order that the loss may be as small as possible for a given thrust and air speed. I must here emphasize the fact, however, that the purpose of this quest for the best thrust distribution is not so much to obtain the absolutely best efficiency, as to find the flow relations for the conditions chiefly occurring in practice, since it is desirable, of course, to work with the best possible efficiency.

Moreover, it has been found that the relations are very simple under these most favorable conditions.

Several years ago in an article in the Göttinger Nachrichten,* I was able to show that this quest for the minimum loss of energy led to a relatively simple statement of the nature of the flow in the propeller slip stream. The flow is as if the paths traversed by the blades were congealed and moved backward like rigid helical surfaces. For lightly loaded propellers, i.e., propellers for which the induced velocities are small in comparison with the motion of the propeller itself, the flow in the propeller plane can be quite easily determined on the basis of this theory regarding the phenomena in the slip stream. This conclusion is especially favored by the law that the induced velocities in the propeller plane are half as large as in the slip stream, already discovered in connection with the simple slip-stream theory, which still holds good, even with inclusion of the rotational effect.

Serious difficulties are encountered, however, in the transition to heavily loaded propellers for which the induced velocities are no longer small in comparison with the motion of the propeller itself. The above-mentioned statement concerning the

*A. Betz, "Schraubenpropeller mit geringstem Energieverlust" (Screw Propellers with Minimum Loss of Energy) in Nachr. d. Ges. d. Wissenschaft zu Göttingen, Math.-Phys. Kl. 1919, p. 193. Subsequently republished in book "Vier Abhandlungen zur Hydrodynamik und Aerodynamik," by J. Springer, 1927. The latter publication contains a bibliography on the subject.

nature of the flow in the slip stream still holds good, but the calculation of the velocities in the slip stream on the basis of said statement encounters difficulties in that, through the rotation of the slip stream, a negative pressure is produced within it, which affects the velocity distribution. In particular, the transition from the phenomena in the slip stream to those in the plane of the propeller develops difficulties because, for heavily loaded propellers, the induced velocities in the propeller plane are no longer half as large as in the slip stream. I have recently investigated these questions, with the assistance of Mr. Helmbold, and think we have found practical solutions, which I hope we will soon be able to report.

Consequently, the problem of the detached propeller might be handled quite broadly. It is not possible, however, to foresee to what extent new problems will arise from new operating conditions. The following are the principal aggravating conditions:

1. The available space for the propeller is limited, e.g., by the nearness of the ground in the taking off and landing of airplanes and by the draft in the case of ships. Consequently, propellers must often be more heavily loaded than is desirable.

2. The propeller speed must be adapted to the engine speed. For the sake of saving weight, the engine speed is generally too

great for the propeller. The result is either an unfavorably small pitch, which impairs the blade efficiency, or a too small propeller diameter and consequent excessive loading. In recent times this condition has often been helped by the use of a reducing gear between the engine and propeller.

3. The peripheral velocity of a propeller is absolutely limited in air by the velocity of sound; in water, by cavitation. When the peripheral velocity approaches the velocity of sound, the operation of the blades is disturbed and their efficiency is greatly impaired. In water, negative pressures can be developed only to the vicinity of an absolute vacuum, since the water then vaporizes and essentially alters the nature of the flow. These phenomena develop difficulties, especially for very swift airplanes.

4. A propeller must be able to function under greatly varying conditions. The proposed theories generally undertake the task of finding, for a given condition, the thrust, revolution speed and air speed of the most favorable propeller, and its behavior under this given condition. The same propeller, however, must often work under other conditions, especially in taking off, when at first the air speed is zero. Of course, the same propeller cannot be expected to be equally good for all conditions. There must be a certainty, however, that it will not entirely fail under any conditions occurring in practice. It will hardly

happen that a propeller, which is well suited to an airplane in normal flight, will absolutely fail in the take-off. It may very well happen, however, that, due to too small a thrust at low speeds, the take-off run will be excessively prolonged. The method usually followed is to design the propeller for the most important working condition and then investigate as to how it meets other important conditions. Special care must be exercised to avoid an excessive angle of attack in starting, which would cause the air flow to separate from the blades and thus interfere with their normal functioning. If necessary, we must deviate somewhat from the most favorable form, e.g., make the blades wider . For swift airplanes it will hardly be possible however, to avoid such unfavorable conditions (separation of air flow) in starting. Care must at least be taken to shorten this unfavorable period as much as possible. One means for diminishing these difficulties is the variable-pitch propeller. This introduces a disagreeable complication, however, and does not completely solve the problem.

The Propeller on the Vehicle

When the propeller functions on the vehicle, the latter, on the one hand, disturbs the action of the propeller and, on the other hand, the propeller alters the flow past the vehicle and the forces exerted on the latter. Consequently, the apparently simple conception of thrust becomes complicated. In order to illustrate these relations, I will take a very extreme case (Figure 1). The fluid does not flow through the propeller and consequently, aside from the lost energy, no energy is required to run it. Nevertheless, considerable negative pressure can be developed in the space shut off by the propeller, and the propeller then works like a pump piston. Hence, quite a large thrust can be measured on the propeller shaft. This only indicates the magnitude of an internal force of the system, since an equivalent force acts on the ship in the opposite direction. This thrust has nothing to do with the transformation of energy. Of course such extreme conditions never occur, but this phenomenon always exists in some degree.

Several years ago Fresenius explained these phenomena with great clearness ("Das grundsätzliche Wesen der Wechselwirkung zwischen Schiffskörper und Propeller." Schiffbau, 1921-1922, p. 257). Two cases must be clearly distinguished. The disturbance caused by the motion of the ship's hull is partly potential motion without loss, which disappears after the ship has passed by. It is partly due to the ship's resistance, hence to phenomena involving loss of energy, in that momentum is transferred to the liquid and does not disappear. If the propeller is in a simple potential flow (Fig. 2), we can follow the slip stream until we come to a disturbed region. Since the thrust on the whole system, as well as the propeller efficiency, can be determined from the slip stream, it follows that we can obtain the same thrust and the same propeller efficiency with the propeller in another location, if it only produces the same slip stream at a long distance from the vehicle. The only difference is that we need a larger propeller at points of low velocity than at points of high velocity. Hence in this case the propeller should be located as nearly as possible to the region of maximum velocity.

It is quite another case when the disturbance is caused by the ship's resistance. The energy developed by the motion of the ship is partially transformed into heat, or vortices whose energy is soon transformed into heat. In part, however, it also generates visible fluid motions, whose energy might be recovered by suitable devices. In particular, the dead water behind the ship has a motion, relatively to the surrounding water, in the direction of the ship's motion (Fig. 3). This relative motion can generally be used directly for recovering energy. If a propeller works in the following dead water, it regains a portion of the energy by propelling the water in the opposite direction or by at least reducing its velocity and thus diminishing its kinetic energy. This takes effect as follows. The effective output of the propeller is the thrust times the velocity of the ship. The power requirement is not determined, however, by the ship's velocity, but by the relative velocity of the propeller and water. The latter is smaller, however, in the following dead water and hence the power requirement is also smaller.* Therefore in this case, where the disturbance is due to loss of energy, the propeller is best located at the point of least velocity. On account of this opposite behavior, it is important to separate the wake into its two parts; the part due to potential flow and the part due to loss of energy. An experiment of this kind was described by Helmbold in an address before the "Schiffbautechnische Gesellschaft" (Society of Naval Engineers) in the autumn of 1926 (Horn, "Versuche mit Tragflugel-schiffschrauben," Jahrbuch der schiffbautechnischen Gesellschaft, Vol. 28, 1927).

The correct shape to give the propeller is not determined, however, in this manner. Since the wake differs from point to point, the propeller pitch must be adapted as well as possible to the different conditions. Mr. Kempf undertook this with good success ("Dem Nachstrom angepasste Propeller" in Werft, Reederei und Hafen, 1924, p. 93). In this connection, however, only the radial variations of the flow can be considered. Aside from this, one and the same particle of water varies in velocity during a single revolution of the propeller (Fig. 4). This variation cannot be remedied by any adaptation of the propeller. With regard to such conditions, we must use blade sections which are adapted to a large angular range. The task greatly resem-

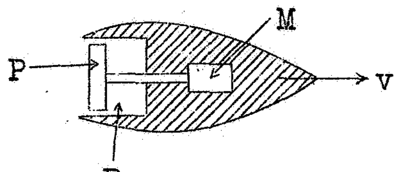
*This is also the case in a potential flow, but there the gain through the after-flow velocity is again offset by a corresponding increase in the ship's resistance through the so-called "suction vortex."

bles the problem of the detached propeller with respect to its starting.

Another mutual reaction between the propeller and vehicle is due to the fact that the pressure distribution on the vehicle, as affected by the propeller, affects the phenomena of the boundary-layer separation and consequently the resistance of the vehicle. Unfortunately, we yet know very little on this point. Experiments are being instituted at Göttingen for the solution of these problems.

I have endeavored, in so far as permitted by the short time at my disposal, to give you a comprehensive survey of the most important propeller problems. As regards the detached propeller, the status of our knowledge is fairly satisfactory. The most important and the most backward problems are afforded by the joint operation of propeller and vehicle. But even here there are some encouraging results and we hope gradually to penetrate the remaining region of darkness.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.



P, propeller.
M, motor.
R, inclosed space.

Fig.1

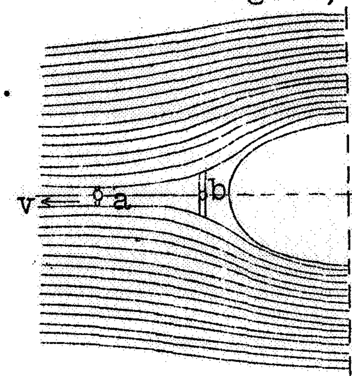
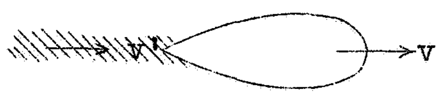


Fig.2 Potential flow behind a body. The small propeller at "a" can generate the same slipstream as the larger one at "b".



v, velocity of body.
v', velocity of dead water.

Fig.3 The following dead water behind a moving body.

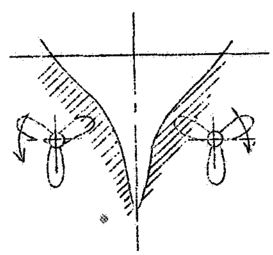


Fig.4 Dead water (hatched) at stern of twin-screw ship and location of propellers with respect to it. Propeller blades work alternately in regions of higher velocity (undisturbed flow) and lower velocity (dead water).