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TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 310

THE "MAGNUS EFFECT," THE PRINCIPLE OF THE FLETTNER ROTOR.

By A. Betz.

From "Zeitschrift des Vereines deutscher Ingenieure,"
January 3, 1925.

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THE "MAGNUS EFFECT," THE PRINCIPLE OF THE FLETTNER ROTOR.*

By A. Betz.

It is indeed possible, by means of the theory of the "ideal fluid" to make a fairly thorough investigation of the action of currents producing a lifting force. The question of the origin of such currents and the cause of the resistance or drag can, however, be satisfactorily answered only by means of Prandtl's "theory of marginal layers." The latter theory is also able to explain the "Magnus effect," the nature of which was so thoroughly investigated at the Göttingen Aerodynamic Experimental Institute, that Flettner was straightaway able to utilize the results obtained at Göttingen for the propulsion of ships.

Theoretical Section.

Thanks to the successful trial runs of the Flettner Rotor ship "Buckau," a hydrodynamic phenomenon, which, under the name of "Magnus effect," has been known for a long time, has suddenly acquired practical importance. Since this phenomenon has not been much discussed in scientific literature and has sometimes been incorrectly presented, it may not be amiss to state the facts clearly in the present article.

A short but very able description, of recent date, is con-

* From "Zeitschrift des Vereines deutscher Ingenieure," January 3, 1925, pp. 9-14.

tained in Fottinger's lecture, "New Basic Principles for the Treatment of the Propeller Problem" in "Jahrbuch der Schiffbautechnischen Gesellschaft," 1910, p. 335. Lanchester gives another good description in "Aerodynamics," p. 36. Leipzig, 1909, B. G. Teubner. An essay by Prandtl will appear shortly in "Naturwissenschaften" and a popular description by Ackeret will be issued by Vandenhoek and Ruprecht of Göttingen.

I would like to mention at the outset, that the "Magnus effect" is not by any means easy to understand, since the necessary basis, Prandtl's "theory of marginal layers," is very little known, although it has been twenty years in existence.

The phenomenon of the Magnus effect consists in the fact that a revolving body moving relatively to the surrounding fluid (air) is subjected not only to drag (i.e., a force acting in a direction opposite to that of the direction of motion), but also to a lift, that is to say, a force acting at right angles to the direction of motion. The lift is directed toward the side where the relative velocity between the fluid and the surface of the revolving body is smallest, that is, the side where the peripheral motion, due to rotation, is in the direction of flow of the fluid (i.e., the air), as illustrated in Fig. 1, in which ω indicates the angular velocity, v the forward velocity of the revolving body, w the drag, and A the lift.

Apart from the experiments of Magnus, the effect was constantly noticed in the form of the deviation of artillery projectiles from their true trajectory. In fact, it was this phenomenon which led Magnus to investigate the problem. It was also noticed in the strangely curved trajectory of tennis and other balls used in games (Fig. 2). (See Lord Rayleigh's paper: "On the Irregular Flight of a Tennis Ball," - "Scientific papers," Vol. I, p. 344.)

Before we endeavor to explain how the Magnus effect is produced, it will be well to look a little more closely into the terms "lift" and "drag" and the causes producing these forces. If we move a body (Fig. 1) with a velocity of v, we must, in order to overcome the drag W, produce, every second, a power equal to Wv. The lift A, on the other hand, calls for no expenditure of energy, since it is at right angles to v. In an "ideal fluid," in which there is no loss of energy, a body moving at a uniform rate would meet with no resistance, but there would probably be a lifting force. In investigating the process connected with this lifting force in general, we can, therefore, base our inquiries on the processes in an ideal fluid (i.e., a fluid which, in flowing, loses none of its power). In this way, we learn a great deal about the connection between the flow and the lift, but the question as to how and why, in a given case, this particular flow should be connected with the lift produced, still remains unanswered.

In the case of an airplane having normal wings with a sharp trailing edge, knowing, as we do, that the fluid does not flow around sharp edges, we can say something about the lift to be expected. But, since the reason why the liquid does not flow around sharp edges is as yet not clearly known, this method of reasoning fails, when the edge is not sharp, but more or less rounded.

To enable us to follow the discussion in the present essay more clearly, let us briefly examine the processes going on in ideal fluids, the so-called "potential flow," and then inquire into the more complex causes of drag and lift, as explained by Prandtl's theory.

For a body to be subjected to a lift, it is necessary that there should be, on an average, a higher pressure on the lower side than on the upper. Inasmuch, however, as the pressure p and the velocity v are connected with each other by the relation $p + \frac{\rho}{2} v^2 = \text{constant}$ (known as Bernoulli's equation, in which ρ denotes the density of the fluid), if there is a lift at all, then the velocity must be, on an average, greater above than below. Following up this line of reasoning, we find, that the best plan is to take the circulation Γ as the standard for this difference in velocity, which we arrive at as follows:

After drawing the line s (Fig. 3), around the moving body, we assume that the velocity at a certain point of s is v and that the component of v, touching this point in the direction of the tangent to s, is v'. Then the circulation is

$$\Gamma = \int_{o} v' \, d\, s,$$

whereby the integral $_{o}\int$ is to be continued clear around the s line. For the lift A, we then get the simple equation (Kutta-

Schukowsky formula) $A = \rho v \Gamma l$. Here again ρ is the density of the fluid; v, the velocity at a great distance from the body; and l, the length of the body at right angles to the plane of the drawing. The circulation is assumed as constant throughout the whole length.

We can imagine a current with a lift, as being composed of two motions without lift. In one of them the circulation Γ is 0, but there is the velocity v relative to the body at a great distance from it (Fig. 4). In the other, however, there is only a circulation current Γ, but no forward velocity ε (Fig. 5). Both currents are possible as potential motions. Now, if we superpose the two currents, i.e. if, at every point, we combine the two velocities vectorially (like forces in a parallelogram of forces), we then once more get a potential motion, composed of the circulation Γ of one motion and the forward velocity v of the other, resulting in a lift (Fig. 6).

The introduction of the term "circulation" is very useful, as an aid to the understanding of the connection between the course of the flow and the lift, but it does not answer the question as to how this lift is produced. Ultimately it reduces to the question as to how the "circulation" is produced. Nevertheless this method can advance us a little. If the fluid (i.e., in this case, the air) and the body are both at rest, it is clear that the circulation must be 0, since, of course, the velocity throughout the entire length of s is 0. Then, if we set the body in motion, the state of the circulation can, according to a law of hydrodynamics, undergo a change only when vortices or eddies stray out of or into the zone enclosed within the s line (Fig. 3). In this event, the increase or decrease in the circulation is exactly equal to the sum of the circulation round about the vortices or eddies coming in or going out respectively, (one direction of rotation to be reckoned as positive, the opposite as negative). We see, therefore, that the production of a circulation around a body surrounded by a fluid which hitherto has been at rest, is possible only when vortices or eddies are formed simultaneously in the fluid. In an ideal fluid this, as the very definition implies, is an impossibility, since, of course, the formation of vortices or eddies is inseparably connected with loss of energy. We must therefore now turn to those processes which cause the formation of vortices or eddies in <u>actual</u> fluids.

If a fluid is set in motion by a difference in pressure alone, a potential motion is produced, as in an ideal fluid. In actual fluids, however, owing to their viscosity, there are added, to the forces of pressure P (Fig. 7), shearing forces T, which impart a rotary motion to the particles of the fluid and thus produce eddies or vortices. Shearing forces of this kind appear when the velocity increases at right angles to the direction of the flow. Inside the fluid the effect of these shearing forces is generally of no consequence, since the velocity variations are not very abrupt. Moreover, as we can prove, so long as the current is of a potential nature, the various shearing forces exerted on a particle of fluid (T_1 to T_4 in Fig. 7) counterbalance one another. On the other hand, the effect of these forces is of supreme importance, when the current flows past a firm wall or surface. Then, within a thin layer, there is a transition from the normal current velocity to zero velocity on the wall (Fig. 8). It is, therefore, in this, the so-called "marginal layer," that the viscosity, which distinguishes actual from ideal fluids, plays an important part. In this layer nearly all those disturbances have their origin, which distinguish the flow of actual fluids from a potential flow. As far back as twenty years ago, Prandtl called attention to the importance of the processes going on within this marginal layer and demonstrated their effect by means of convincing experiments. The following remarks follow closely the original arguments adduced by Prandtl. In our inquiries let us consider the flow around a cylindrical body, which interests us in particular. Most of the arguments, however, apply also to bodies of other shapes.

On the sides of the cylinder (above and below in Fig. 4) the lines of flow are more closely crowded together than elsewhere. Here the velocity is the greatest and the pressure the smallest. In a potential flow the velocity is reduced and the pressure increases again. The kinetic energy of the fluid particles enables them to penetrate into the region of higher pressure. In this process, their velocity, under the influence increasing pressure, is retarded in precisely the same measure as expressed in Bernoulli's equation. Let us now consider a particle of the marginal layer. Its velocity is lower than that of the normal flow outside this layer. Its kinetic energy is therefore insufficient to enable it to penetrate into the zone of higher pressure. It stops, before it gets there, and reverses the direction of its motion. However, since new marginal layers are constantly flowing out of the zone of lower pressure, more and more marginal-layer material gradually accumulates in the region where the pressure is increasing. This marginal-layer material has two important properties:

1. Its total energy $(p + \frac{\rho}{2} v^2)$ is less than that of the rest of the current.
2. Its individual particles are rotating.

The subsequent stages in the development of the marginal layer accumulations are illustrated by Figs. 9 to 11 (according to experiments and pictures made by Prandtl in 1904, and by Rubach, at Prandtl's institute in 1913-14). The marginal layer material is indicated by the stippled portions. When the marginal layer material has become fairly thick, it is carried along by the current and finally passes away in the form of vortices; whereupon the whole process is repeated. The symmetry of the departing pairs of vortices is not stable and, consequently, one vortex gets ahead of its companion. Hence the subsequent formation of vortices is not symmetrical, but takes place alternately on the two sides. This, however, does not affect the following investigations.

The vortices or eddies constantly being formed are the cause of resistance or drag. We can understand this fact by regarding it from two different angles:

1) In a system where the fluid is at rest and the cylinder is moving, in potential motion the fluid behind the cylinder returns to its condition of perfect rest. Owing to the formation of vortices, however, the fluid behind the cylinder is in motion and therefore possesses kinetic energy, which increases with each new vortex. This kinetic energy must be created by the work done in moving the cylinder, which is only possible by overcoming resistance.

2) In front of and behind the cylinder the potential flow is exactly symmetrical and consequently the pressures on the front side are exactly the same as those on the corresponding points on the rear side. The various pressures, therefore, counterbalance one another. On account of the formation of vortices, however, the pressure increase on the rear side cannot attain its full strength. The pressure on the front side therefore exceeds that on the rear side. The difference between these two is the resistance or drag (to which must be added the surface friction, which, however, in the case of a cylinder, is usually a negligible quantity).

Having now seen how the formation of vortices becomes intelligible with the aid of Prandtl's theory of marginal layers, we can return to the question of the origin of the lift, which we left a little while ago, just after arriving at the conclusion that lift is possible only when vortices of corresponding circulation stray through the s line around the cylinder (Fig. 3). If we apply this manner of reasoning to the process illustrated in Figs. 9 to 11, we find that the same number of vortices flow from each side of the cylinder, since the same prerequisite conditions for the formation of vortices exist on both sides of the cylinder, excepting that the two sets of vortices rotate in opposite directions. If, therefore, a vortex flowing from one side passes through the s line at a given rate of circulation, it is counterbalanced by a corresponding vortex emanating from the opposite side, at the same rate of circulation, but opposed to it in value (one being positive and the other negative). In this way, therefore, no circulation is produced around the cylinder, which is not surprising, since, for reasons of symmetry, no unsymmetrical force, such as lift, can be expected.

Conditions undergo a radical change, however, as soon as we change the prerequisites for vortex formation on both sides. Such a change is produced, for example, when the obstacle is unsymmetrical. Typical examples are the well-known profiles of airplane wings. We can also produce this effect by causing the cylinder to revolve around its axis. On the side where the peripheral motion of the cylinder is in the direction of the flow, no marginal layer at all, or only a very much thinner one, is formed. This requires much more time to accumulate to such an extent, that it can flow off in the form of a vortex. On the opposite side the conditions are reversed. Here the marginal layer is thicker and more vortices are formed. We now have an instance of more vortices flowing off the cylinder on one side than on the other, in other words, an increase in circulation around the cylinder, thus producing a lifting force.

So long as this process continues, the circulation and, consequently, the lifting force would go on increasing; but this process is soon terminated. Owing to the flowing off of the vortices only on one side, the entire flow around the cylinder is changed. A circulation is started, which affects the flow as illustrated in Fig. 6. The velocity on the upper side has increased, while that on the lower side has decreased. The higher velocity, however, means the formation of more vortices and vice versa. The circulation, therefore, increases until this influence counterbalances the effect of the rotation of the cylinder on the formation of vortices and until an equal number of equally strong vortices flow off the cylinder on both sides, although now in an unsymmetrical arrangement (Compare with Fig. 12, drawn from a picture taken by Prandtl, about 1910). If we increase the velocity of rotation, both the circulation and the lifting force are increased by the one-sided formation of vortices, until the balance is restored.

We can also picture the process as follows. The thinner marginal layer on one side causes the flow to adhere to the cylinder longer on this side than on the other. When it does flow off, it has already acquired, on its upper side, a velocity which causes a strong downward pressure. On the lower side, the upward deviation of the current is much less pronounced, because it parts company with the cylinder sooner. On the whole, there is consequently a downward deflection, which produces an upward reaction or lift.

There is still a third viewpoint, from which we can regard the problem. As the fluid (i.e., the air) flows past the cylinder, its cross-section first contracted and then expanded, much like a tube with a constricted section in it. The process at the point, where the cross-section expands and where velocity is converted into pressure, is always attended by considerable losses, due to the formation of vortices, especially when the expansion takes place rapidly, which is the case on the rear portion of the cylinder. On one side the beneficial effect of the expansion is greatly increased by the rotation of the cylinder, since fewer vortices are formed, and consequently there is less loss of energy. Let us imagine that in a wind tunnel there are two constrictions side by side, the narrowest part of the constriction being exactly of the same diameter in both cases, the widening of one being a gentle slope (a in Fig. 13) with correspondingly high efficiency; the other (b in Fig. 13), abrupt, with poor efficiency. The quantity of fluid (air) flowing through the opening a with high efficiency will be greater than the quantity flowing through the other, since it meets with less resistance. On account of the consequent greater velocity at the narrowest point of the constriction, the negative pressure will also be greater (Bernoulli's equation. Observe also the similarity of the middle partition to the cross-section of an airplane wing). In a similar manner, in the case of our cylinder, the fluid (air) will flow with greater velocity on the side where the rotation reduces the loss of energy and where the negative pressure is greater. This difference in pressure, however, generates a lifting force.

The process has recently been represented as follows. Owing to the rotation, the friction is reduced on one side and, consequently, the fluid flows faster on that side. This explanation, however, is somewhat misleading, inasmuch as the surface friction does not affect the flow directly, but only in an indirect way, by the formation of vortices. The forces produced by surface friction would be far too small to exercise such a far-reaching influence on the flow. The surface friction promotes the formation of vortices, which, in their turn, thoroughly transform the nature of the flow diagram.

All three ways of explaining the problem lead to the same ultimate conclusion, that the flow is greatly influenced by the marginal layer. This influence is, however, diminished on one side and increased on the other by the rotation of the cylinder. As to the magnitude of the lift to be expected from a given number of revolutions, it is thus far impossible to say anything definite on the basis of this theory, since the mathematical calculation of the forces produced by the separation phenomena, described qualitatively in Prandtl's theory of marginal layers, is extremely difficult. In this connection, I would like to point out that, in the technical press, the circulation is sometimes stated, on the basis of incorrect conceptions, to be equal to the peripheral velocity multiplied by the circumference of the cylinder, the lift being then calculated from this product according to Schukowsky's formula. There is, however, no justification for this purely arbitrary method. Moreover, the figures obtained in this way do not agree with the experimental results.

Experiments

The first experiments, as already mentioned, were made by the Berlin physicist Magnus, in 1853. They proved the existence of the effect beyond all doubt, without, however, determining its magnitude. The first actual quantitative measurements were probably made by the Frenchman Lafay, in 1912. These experiments appear to be practically unknown in Germany. Engineer Ackeret was not aware of their existence until some time after the conclusion of his own experiments. Owing to circumstances to which I shall refer later on, he was, however, only able to produce lifting forces with a maximum value barely double that of a good airplane wing having a chord equal to the diameter of the cylinder. In aviation technics it is customary to denote the properties of a wing by the respective lift and drag coefficients c_a and c_w, the lift being

$$A = c_a F \frac{\rho}{2} v^2,$$

and the drag

$$W = c_w F \frac{\rho}{2} v^2.$$

The resultant force is

$$R = \sqrt{A^2 + W^2} = \cancel{v_r F \frac{\rho}{2} c^2}. \quad C_r F \frac{\rho}{2} V^2$$

In the above equations F denotes the greatest projection of the wing surface, ρ the density of the fluid (air) and v the velocity. For a good wing the highest attainable c_a is about 1,2 to 1.4. Unusual forms (slotted wings and very highly cambered wings) give values of c_a up to about 2. Lafay obtained a maximum $c_a = 1.8$ or $c_r = 2.4$.

Dr. Wieselsberger, at the Aerodynamic Experimental Institute in Göttingen, belonging to the Kaiser Wilhelm Society, attempted, during the first years after the war, to fathom the Magnus effect by taking exact measurements. These experiments came to nothing, owing to technical difficulties, and were then dropped, because Dr. Wieselsberger left the Institute. In 1923, an opportunity was afforded to carry out the experiments with much improved means. Several small high-speed motors of comparatively high efficiency had been built at the Göttingen Experimental Institute, to drive small propellers on airplane models suspended in the wind tunnel for the purpose of taking measurements, which propellers had to be driven under conditions approximating actual conditions as closely as possible. These motors were highly suitable for driving a cylinder at high speed in the investigation of the Magnus effect. The diameter of these motors, in their present form, is 42 mm; length, about 180 mm; maximum number of revolutions, 30,000 R.P.M.; about 1 HP. These motors are now being built by the "Elektroschaltwerke A.G." in Göttingen. For theoretical reasons, already set forth, it was to be expected that, in order to obtain a powerful effect, peripheral velocities would be required amounting to several times the velocity of the wind. Now if the diameter of the cylinder and the wind velocity were to be kept within the limits desirable for technical reasons, it was obvious that the revolution numbers would have to be high. These new motors were, however, quite capable of supplying them. Engineer Ackeret made use of this favorable opportunity to determine finally the magnitude of the Magnus effect. The first experimental apparatus was very simple. There was a nozzle or funnel 200 x 200 mm² in cross-section (Figs. 14 and 15) with two wooden walls as extensions of the side walls of the funnel. Between these two walls he fitted a cylinder 40 mm in diameter, revolving on ball bearings and driven from outside the walls by one of the aforesaid high-speed motors. When the air was blown out of the funnel against the cylinder at rest, it flowed away behind the cylinder in a practically horizontal direction. If, however, the cylinder was rotated (direction of rotation as indicated in Fig. 14, with the lifting force directed downward), the air current was diverted upward (arrows in Fig. 14). Now, since the deflection of the current required a force, which can be easily calculated by the law of impulse and since this force can only have its origin in the cylinder, conclusions could be drawn, as to the magnitude of this force, from the angle of deflection (which was nearly 90°). Even this first crude experiment resulted in an unusually large lift, about three times that of a good airplane wing ($c_a = 4$). There is no object in giving the exact results of these preliminary experiments, as they were subsequently repeated with improved apparatus, the results being given in Figs. 20 and 21.

In order, however, to make quite sure that the determination of the lift from the deflection did not lead to wrong conclusions, the whole apparatus (walls, cylinder and motor) were installed on a platform balance in the big wind tunnel of 4 m² cross-section, at the Aerodynamic Experimental Institute, so that the lift could be measured. Here also the same large lift values were obtained.

These really remarkable results were still unsatisfactory, since the theory indicated the possibility of obtaining far greater lifting forces ($c_r = 4\,\pi = 12.6$). Although it was to be expected, on account of disturbing influences connected with the formation of vortices and other reasons, that the maximum could not be attained, yet the discrepancy was too great to be explained in this way. Prandtl therefore asked himself what causes might stand in the way of obtaining a greater lift. A careful investigation of the course of the current, by suspending silk threads in it, showed that the lifting force was confined chiefly to the middle portion of the cylinder. Prandtl explained this as follows: On the suction side of the cylinder there is an exceptionally large negative pressure due to the unusually great lifting force (with $c_r = 4\pi$, p_{min} would be $-15 \frac{\rho}{2} v^2$; with $c_a = 0$, p_{min} would be $3 \frac{\rho}{2} v^2$). At the ends of the cylinder, however, there is air at ordinary pressure, which is drawn into the negative pressure zone (Fig. 16) and interferes with the production of the Magnus effect, by having the same effect as a thick marginal layer (Compare the foregoing explanation of the production of the Magnus effect).

The wooden walls, used in the experiments, cannot prevent the flowing in of outside air, since the marginal layer on the surface of these walls is partly drawn inward toward the central portion of the cylinder and is partly separated from the walls by the great differences in pressure, thus enabling the outside air to penetrate to the cylinder (Fig. 17).

Having, to this extent, obtained an insight into the conditions governing the process, it became possible to devise means for effectually preventing the inflow of outside air. Prandtl suggested putting disks on the ends of the cylinder, larger in diameter than the latter and revolving with it (Fig. 18). Owing to the rotary motion, the marginal layer of these disks is subject to approximately the same conditions as the marginal layer on the surface of the cylinder. Therefore, like the latter, it is not forced to separate on the suction side, but is actually driven outward by the centrifugal force.

The subsequent experiments, carried out with a cylinder fitted with terminal disks, fully confirmed Prandtl's views. The lift increased to $c_a = 9$ ($c_r = 11$). This figure so closely approximates the theoretical maximum, that the difference is no longer strange.

The disturbance of the Magnus effect, caused by the lateral inflow of air in the absence of terminal disks, becomes all the more pronounced, the shorter the cylinder is for a given diameter. With very long cylinders, the disturbance is relatively small and the terminal disks are not of such great importance. This also explains why, at Göttingen, we were able to get far better results than Lafay, even without disks, since the cylinder used by Lafay was shorter than ours. A subsequent test, made with a cylinder such as used by Lafay, confirmed his results.

As the result of these experiments, the question of the Magnus effect had been practically solved, both by experiment and calculation. It only remained to repeat the experiments with more perfect apparatus, in order to bring the results up to the high standard of accuracy required by the Göttingen Institute. At this stage, Director Flettner learned of these results. At that time he was working on the idea of replacing the sails of a ship by rigid wing-shaped devices and was having experiments made for this purpose at the Göttingen Aerodynamic Experimental Institute. With his remarkable insight he immediately recognized the special significance of these new results for his purpose of replacing the sails of ships by more suitable devices. In the great majority of cases, in which lifting forces are used technically, their production by means of the Magnus effect would require a very high revolution speed, involving, in its turn, such great technical difficulties, that the advantage sought would be entirely wiped out.

In the case of a sailing ship, the conditions are especially favorable. The wind velocities required to produce the maximum efficiency are not high (5 to 10 m/sec.) and consequently, the peripheral velocities also remain within moderate bounds (up to about 30 m/sec.). The cylinders are always several meters in diameter, so that, even the greatest peripheral velocity requires only moderate revolution speeds, which occasion no fear of disagreeable resonance phenomena. On the other hand, the advantages are very great. Owing to the fact that the maximum lifting force with revolving cylinders is about thirty times as great as the resistance or drag produced by non-revolving cylinders in a wind of equal velocity, even the most violent gale blowing against non-revolving Flettner rotors has no more effect than a moderate wind revolving cylinder driven at a suitable number of revolutions. Whereas, on an ordinary sailing ship, the forces must be adapted to the velocity of the wind by setting or reefing the sails, all that is necessary on a rotor ship is to adjust the revolution speed by means of a hand-wheel or two.

The exceptionally powerful lifting forces obtained by Ackeret were particularly valuable in this connection. They enabled the designer to keep the dimensions of the revolving towers (rotors) within such moderate limits, that they do not endanger the stability of the ship in a gale. If, for instance, we had been compelled to calculate the dimensions of the rotors on the basis of Lafay's measurements, they would have had to be five times as large, which would probably have made the whole thing impossible. The ready adaptability to the force of the wind renders it possible to utilize stronger winds to a far greater extent than is feasible with ordinary sails. With the latter, one is always afraid that it may not be possible to furl the sails quickly enough, in the event of a gale brewing, and consequently does not always dare to set all the sail the ship might be able to carry at the time. With a rotor ship we can come much closer to utilizing the maximum power. Another advantage is, that the effect of squalls on the rotors is much less pronounced than on sails. With the latter the force increases as the square of the velocity. In the case of the rotor with increasing wind velocity and unchanged revolution speed, the ratio of the peripheral velocity to the wind velocity decreases and the force diminishes with it, so that it does not increase according to the square of the velocity but approximately as the velocity.

The revolving upright cylinders also present advantages from a navigation point of view. With careful calculation we can run closer to the wind than with an ordinary sailing ship and moreover, in turning, we can assist the maneuvering of the ship very easily and effectively by means of the rotors. For this purpose the direction of rotation of either rotor can be reversed.

The great advantages of revolving cylinders led Flettner to pursue energetically his resolve to exploit the Magnus effect for the propulsion of sailing ships, notwithstanding the technical difficulties of construction. Further experiments were carried out at Göttingen with the assistance of the Flettner Company. By these experiments the peculiar properties of revolving cylinders were explored and determined with still greater accuracy than before. In these experiments the motor was fitted into the cylinder itself. The arrangement is shown in Fig. 19. The ends of the shaft projecting from the cylinder, or rather their ball-bearings, were connected by wires to the regular wind-tunnel balances. In this way it was possible to measure not only the lifting force, but also the resistance or drag of the cylinder and the power required to drive it. To enable the measurements of the moments to be made, the motor itself was also fitted so as to be able to revolve on the bearing at the extreme right in Fig. 19, and could be prevented from revolving only by means of a lever adjoining the balance. Some of the results obtained are shown in Figs. 20 and 21. Other experiments had to do with the action of the rotors on the ship. For this purpose, a model of the ship was made. The rotors on the model could be operated by high-speed motors installed in the model. The whole ship with its revolving rotors was suspended by wires from the balance beams.

In addition to this experimental work, the first working drawings were made at Göttingen for the rotors to be fitted on board the ship, these drawings being ultimately followed with but trifling alterations. In this work we were supported by the energetic cooperation of engineer Croseck, whom the Flettner Company sent to Göttingen. The work thus planned was then executed at the Germania Ship Yards at Kiel, which admirably solved the many difficult problems presented. One especially remarkable achievement deserves special mention; namely, that the rotation of the towers (which are 2.8 m in diameter and 15 m high and revolve at the rate of 120 R.P.M.) produces practically no noise nor vibration.

I hope the foregoing remarks may not only contribute toward a fuller understanding of the Magnus effect, so mysterious to the average layman, but may also show that such revolutionary advances in technical science can only grow, as it were, on soil which has been carefully prepared by long, scientific and practical preliminary work. Now that we are enjoying the harvest, let us not forget the seedtime, nor neglect to provide the means for facilitating to the utmost the beneficent work of our scientific institutions.

Translated in Office of
Naval Attache, Berlin.
Revised by D. M. Miner,
N. A. C. A.

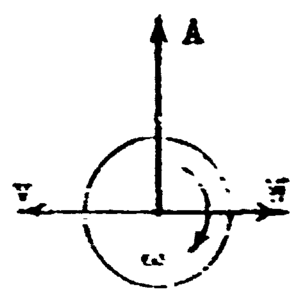


Fig. 1 Diagram of Magnus effect.

Fig. 2 Path of tennis ball

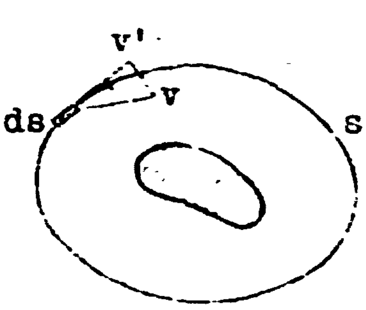


Fig. 3 Diagram of circulation

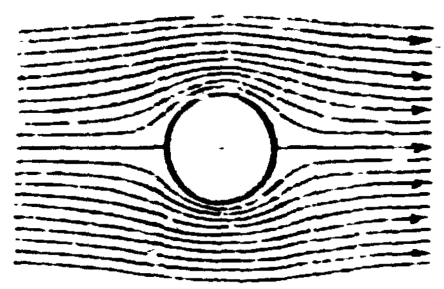


Fig. 4 Cylinder in parallel flowing non-viscous fluid.

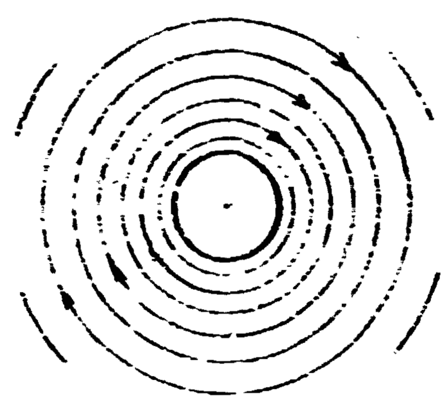


Fig. 5 Circulation flow around a cylinder

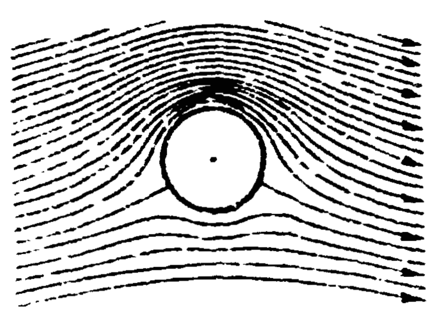


Fig. 6 The flows in Figs. 4 & 5 vectorialy combined. The resultant flow produces a lift.

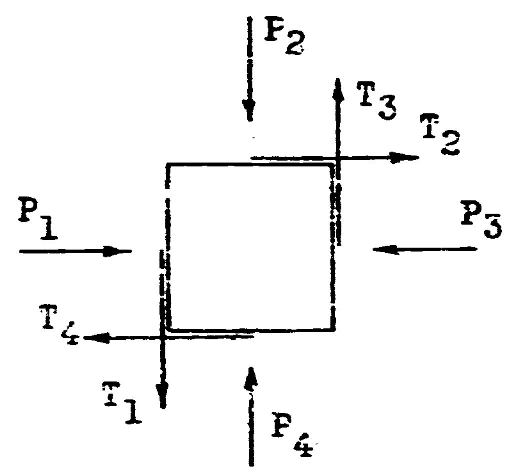


Fig. 7 Pressure and shearing forces in a viscous fluid.

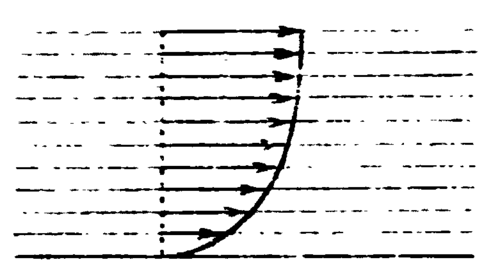
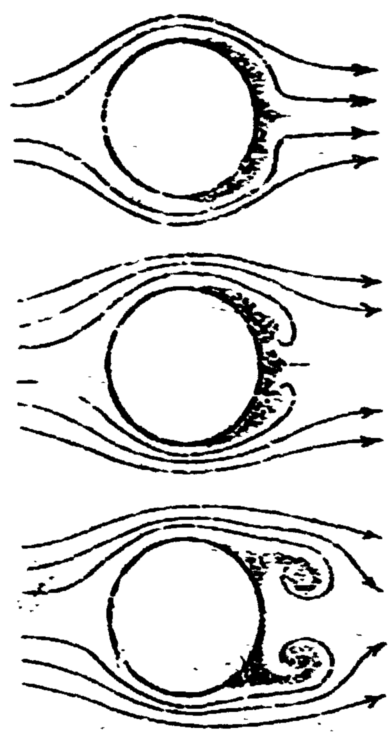


Fig. 8 Velocity distribution (or variation) near a wall (marginal layer).



Figs. 9 to 11 Development of vortices (or eddies) from the marginal layer.

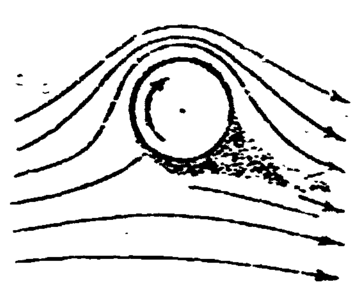


Fig. 12 Stream lines and marginal layer in the case of a rotating cylinder, from a photo by Prandtl.

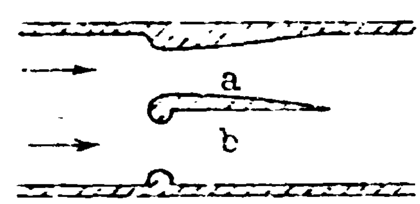
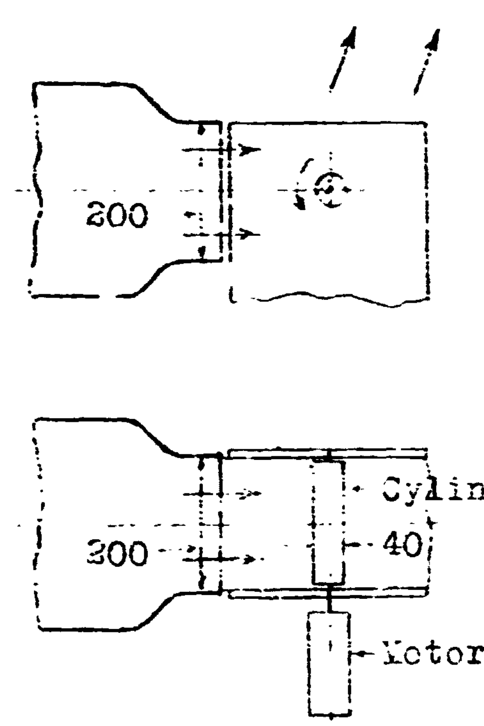


Fig. 13 Flow through two constrictions



Figs. 14 & 15 Experimental arrangement for determining the magnitude of the Magnus effect.

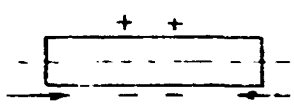


Fig. 16 Effect of a high negative pressure on the air next to the cylinder.

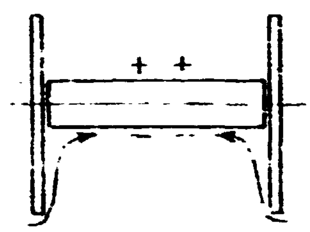


Fig. 17 Inflow of neighboring air, in spite of fixed disks.

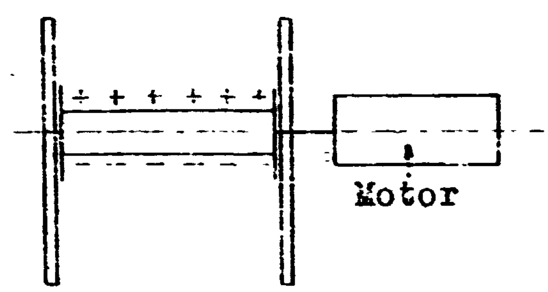


Fig. 18 Inflow of neighboring air prevented by rotating disks on ends of cylinder.

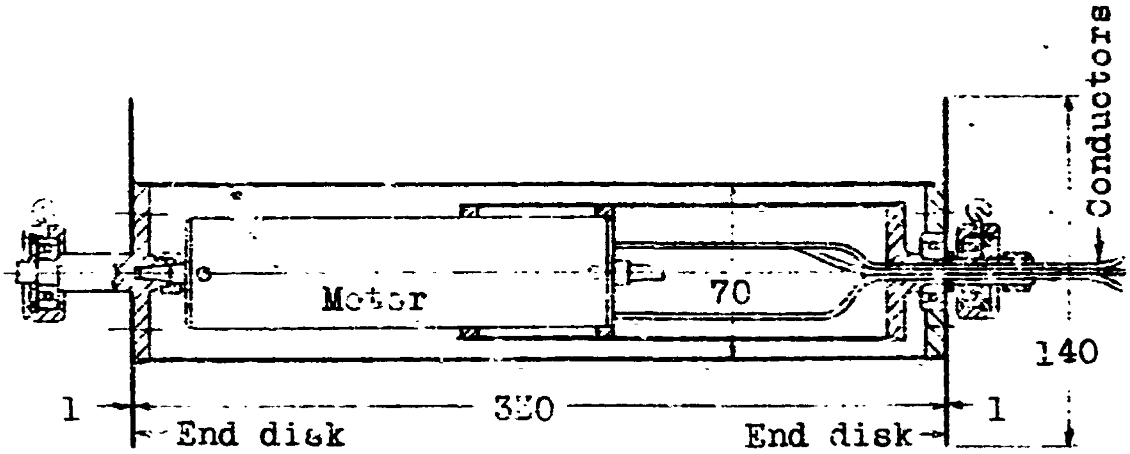


Fig. 19 Rotating cylinder with built-in motor for the more accurate wind tunnel tests.

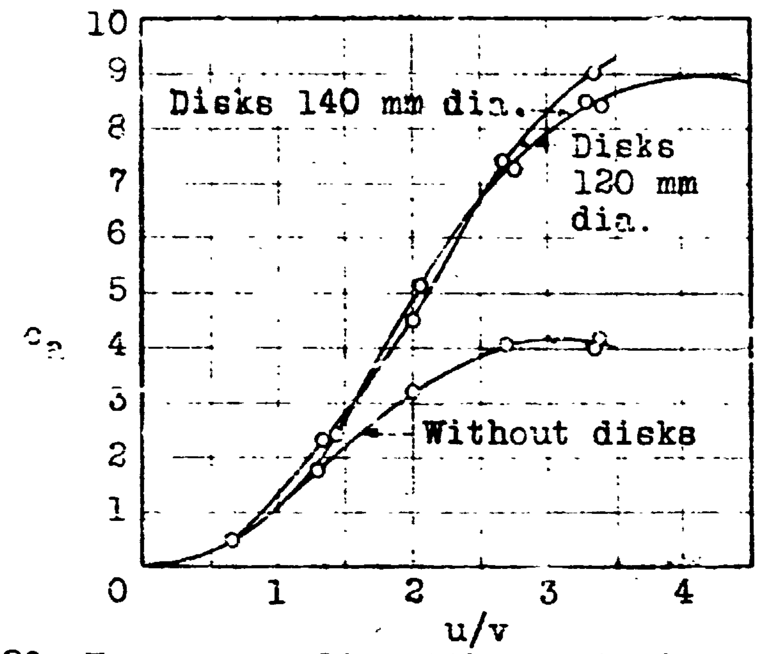


Fig. 20 Exper. results with a rotating cylinder, diameter 70 mm, length 330 mm. Wind velocity v = 11 m/sec.

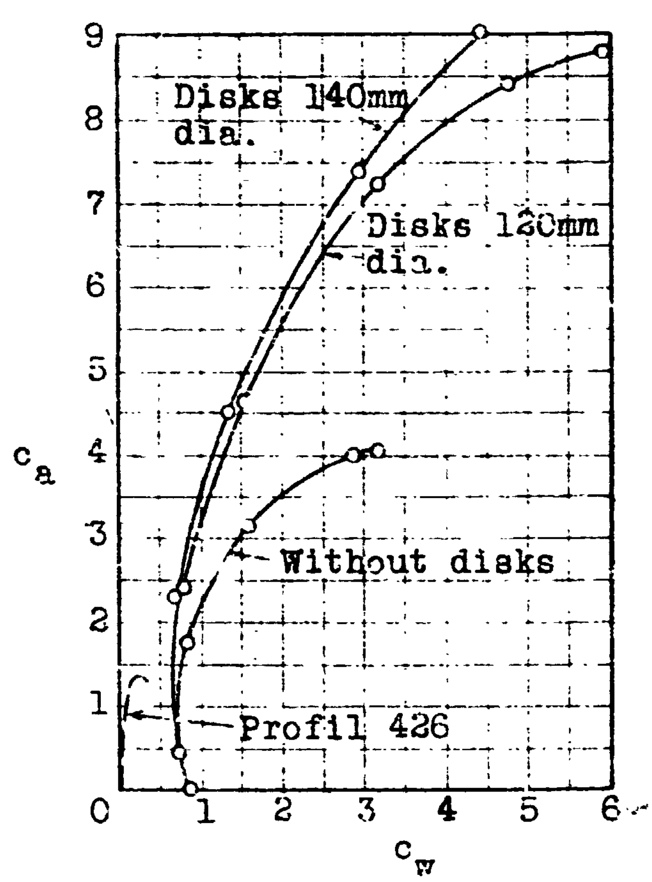


Fig. 21 Lift coefficients of a rotating cylinder of 70 mm diameter and 330 mm length, without end disks and with end disks of 120 and 40 mm diameter.