The Rotor Ship and Aeronautics.

By Prof. L. BAIRSTOW, F.R.S.

THE conversion by Herr Anton Flettner of the sailing ship *Buckau* into a rotor ship was referred to in NATURE of November 22, p. 758, and brief reference was then made to the principles underlying the new proposal for ship propulsion. Since then, details of experiments in wind channels have appeared from which estimates may be made of the forces on rotating cylinders and the power needed to drive them.

Experiments at Göttingen, and the underlying theory, are described by Prof. L. Prandtl in *Die Naturwissenschaften* for February 6, whilst the same material is the basis of a small booklet, "Das Rotorschiff und seine physikalischen Grundlagen," by J. Ackeret.¹ Both these publications contain a bibliography, the earliest reference being to a paper by B. Robins in 1842 (London). Owing to the importance of his investigations, the effect on which the rotor ship depends is spoken of as the "Magnus effect," and is described in a paper published in 1852 in connexion with artillery investigations. Lord Rayleigh's paper of 1877 "on the irregular flight of a tennis ball" deals with the same mathematical theory. Tests for the American National Advisory Committee for Aeronautics have been made and the results published in Technical Note No. 209, a very full abstract of which appears in the issue of *Flight* for January 8, 1925.

The analysis underlying the use of rotating cylinders for rotor ships is the classical hydrodynamical theory to be found in standard treatises.² In the application, certain approximations are made and there is some lack of agreement between calculation and observation corresponding with them. The most important assumption is that which supposes the effects of viscosity in a real fluid to be confined to a thin layer on the surface of the cylinder and that, outside this boundary layer, air behaves as an inviscid fluid. The general theory of the boundary layer as given by Prandtl shows it to be thinner and thinner as the speed and size increase and as the viscosity decreases. The exact criterion is a "Reynold's number." For a non-rotating cylinder this "Reynold's" number is Vr/ν , where V is the forward speed of the cylinder, r its radius, and ν the kinematic coefficient of viscosity. When the cylinder is rotating with a circumferential velocity U there will be a separate "Reynold's number" for each value of the ratio U/V .

Any one acquainted with the flow of air or water past bluff obstacles will be aware of the fact that eddies form in their wake and that there is a region of stagnant fluid which does not conform to the hypothesis that the boundary layer is thin, and in fact the classical hydrodynamics is wholly inapplicable to a non-rotary cylinder. The streamlines as calculated are shown in Fig. 1, and give a motion for which there is no force on the cylinder in any direction. The flow round a cylinder in a real fluid differs very greatly from that shown behind the section BB.

Rotation of a cylinder in stationary fluid produces

circulation. Viscosity is called into play to ensure the transmission of the motion of the cylinder to the fluid in contact with it, but in all other respects viscosity is ignored. The resulting streamlines are circles concentric with the cylinder, the velocity in them being inversely proportional to the distance from the centre of the circle.

By superposition on the well-known lines of Clerk

FIG. 1.—Theoretical streamlines round a stationary cylinder. Reproduced by courtesy of *Die Naturwissenschaften*.

Maxwell and others, it is easy to combine the flow shown in Fig. 1 with a circulation of any amount, and the result is shown in Fig. 2. The circulation has produced lack of symmetry above and below a horizontal line through the centre of the cylinder, but has not disturbed symmetry about the line BB'. By an application of Bernoulli's theorem it may be deduced that there is a force along BB' but none at right angles

FIG. 2.—Theoretical streamlines round a rotating cylinder. Reproduced by courtesy of *Die Naturwissenschaften*.

to it. Bernoulli's theorem as applied to an inviscid fluid gives a relation between pressure, velocity, and density, which shows that high velocity is associated with low pressure, and vice versa. Above the cylinder, at B, the streamlines are close together, and since the same amount of fluid passes between any two consecutive lines, the velocity is high and the pressure low. Similarly the pressure at B' is high.

The general theory of inviscid flow with circulation leads to the formula

Lift = Force across the direction of motion = $\rho V U 2\pi r l$, where ρ is the density of the fluid, V , U , and r have

¹ "Das Rotorschiff und seine physikalischen Grundlagen." Von J. Ackeret. Pp. 48+7 Tafeln. (Göttingen: Vandenhoeck und Ruprecht, 1925.) 1.80 gold marks.
² "Hydrodynamics," Lamb, Articles 68 and 69.

already been defined, and l is the length of the cylinder. Strictly speaking, l should be the length of that part of an infinite cylinder on which the force is measured, but it appears from experiment that a cylinder of moderate ratio of length to diameter can be used if discs of double diameter are attached to the ends; a circulation is then obtained which is equivalent to that on a cylinder of indefinite length.

As the speed of rotation increases, the streamlines change their character progressively up to a limit. When the circumferential velocity is twice the velocity, a limit is reached to the value of the lift divided by ρUV , and in aeronautical language this leads to a limiting value of the lift coefficient defined as

$$\text{Lift coeff., i.e. } k_L = \frac{\text{Lift}}{\rho V^2 \times \text{projected area of cylinder}}$$

This limit, or maximum lift coefficient, is 2π . The quantity is important, because the loading of an aeroplane per unit area of surface at a given speed is proportional to k_L or, conversely, for a given loading the landing speed is inversely proportional to the square root of k_L (max.).

The more efficient aeroplane wings of the day have a maximum lift coefficient of about 0.6 and may reach 0.85; by introducing a number of slots Mr. Handley Page has obtained the highest values known, about 2.0. From figures at Göttingen given by Ackeret, it appears that the maximum lift coefficient for a sail is about 0.4. All these values are much below the theoretical value of 2π , i.e. 6.28. Making allowance for partial failure of the theory, it still remains true that the loading per unit area of a rotor cylinder may be ten times as great as that on a sail and several times as great as that on any aeroplane wing in use.

It may be of interest to point out the existence of a conformal transformation by Joukowski by means of which the circle of Fig. 2 can be transformed into a section very like that of an aeroplane wing. Experiments at the National Physical Laboratory have shown that such a transformation gives a passable representation of facts but that the lift is overestimated by 25-30 per cent. A circulation has been shown to exist of exactly the right amount to explain the measured—as distinct from the calculated—lift. An aeroplane wing, therefore, is able to produce circulation without any movement of its surface corresponding with the rotation of the cylinder. The transformation is important in its aeronautical aspects, but the numerous points of interest which arise cannot be further discussed here.

It is interesting to see how far the predictions of this partial theory are borne out in practice. In some respects there is a considerable divergence between German and American results, and a suspicion that the experiments in the wind channels have not yet been carried out on a scale large enough to reach limiting conditions. The doubts chiefly affect the resistance.

In the American tests, smoke jets were used to indicate the flow of air, and Fig. 3 shows how rotation of the cylinder (clockwise) deflects the air. The symmetry about a vertical line through the centre of the cylinder is not perfect, and the streamlines suggest resistance as well as lift. The extent to which air

is carried to the back of the cylinder at the higher speeds of rotation is a notable feature shown by the photographs.

Measurements of lift showed a maximum lift coefficient of 4.5 (theoretical value 6.28) when the peripheral speed was about four times the forward speed. Instead of the maximum value of 6.28 when the peripheral speed was twice the forward speed, observation gave a value of 2.0. These comparisons show to what extent the neglect of viscosity in the theory has vitiated the conclusions.

It will be noticed that high speeds are required at the surface of the cylinder to give the maximum effect:

FIG. 3.—Deflexion of air stream by rotating cylinders: top, 600 rev. per min.; middle, 1200 rev. per min.; bottom, 2400 rev. per min.
Reproduced by courtesy of *Flight*.

Regarded as an aeroplane wing, such high speed would be required at the moment of landing, and if an alighting speed of 30 m.p.h. is aimed at, the surface of the cylinders would need to move at 120 m.p.h. For transport efficiency when once in the air, the factor of greatest importance is the ratio of lift to drag, and on a rotating cylinder this is obtained when the peripheral speed is about two and a half times as great as the forward speed. Whilst the Göttingen results give a maximum ratio of 3.5, the American figures give 7.5-8, and the discrepancy is very great. The figures are subject to a deduction for the power required to rotate the cylinders, a deduction of rather uncertain amount but of the order of a quarter to a third of the

values stated. The modern aeroplane has a ratio of lift to drag of 9, and some of the light aeroplanes indicate a figure as high as 12 or 14, so that the best of the results on rotating cylinders compare very unfavourably with the aeroplane for efficiency.

Whatever may be the final utility of the rotating cylinder and the commercial fate of the *Buckau*, it

may be expected that many attempts will be made to utilise the aspect of fluid motion brought into new prominence by the rotor ship. Whilst it is difficult to see immediate uses in aeronautics, there are certain directions in which speculation suggests the possibility of early benefit by a modified application of the principles involved in the propulsion of the rotor ship.

The Mountain Structure and Geographical Relations of South-Eastern Asia.¹

By Prof. J. W. GREGORY, F.R.S.

THE greatest mountain system in the world is the Alpine-Himalayan, which forms the backbone of Europe and Asia. Its continuity has been proved from western Europe to eastern India. Its further eastward continuation has long been subject of controversy. According to one view it passed north-eastward across central China to Bering Straits; according to another it was bent round against the mass of Chinese Tibet, and passed through western Burma to Sumatra and thence along the southern islands of the Eastern Archipelago. The interpretation of the mountain structure of Chinese Tibet is complicated by being due to movements at two different dates. The later mountains are of the same age as the Alps and Himalaya and are geologically modern. The other group is much older, and its fragments remain as highlands, which are the worn down stumps of the mountain foundations. The older system is represented in Europe by the Hercynian Mountains, and in Asia by the Altaids, members of which cross Chinese Tibet on lines approximately north and south, and continue southward as the Indo-Malayan Mountains. The Himalayan and Alaid Mountains meet in Chinese Tibet, and the mountain lines due to these two systems have to be carefully distinguished. The Himalayan movements have disturbed the grain due to the older Alaid folding and they admit of simplest proof where the rocks were not in existence when the Alaid Mountains were made. For example, the folds and overfolds in the salt-bearing red sandstones of Yunnan must be post-Alaid, as those rocks were not in existence until after the Alaid movements. In other places the evidence is more complex. Some of the folds are too shallow to be Alaid, and the arrangement of the outcrop of the older rocks indicates upfolds on lines with the Himalayan trend.

The further extension of the Himalayan line eastward of Chinese Tibet is indicated by the claim of the French geologists in Tonkin that at the date of the Himalayan movements a band of country in southern China was pushed southward smashing the country in front of it. The existence of a rich mercury field in south-western China is also in favour of the country having been disturbed by intense mountain movements of the Himalayan period. The continuation of the main Alpine-Himalayan axis therefore appears to pass across southern China, and the Burmese-Malayan Arcs must belong to a loop to the south corresponding to the Atlas-Apennine loop around the western Mediterranean and the Syrian Arc beside the eastern Mediterranean.

The traditional cause assigned to such folding as that of the Alps and Himalaya is the contraction of the crust owing to the shrinkage of the earth. That theory has been repeatedly criticised in recent years owing to the contraction having been attributed to cooling; but there are more effective and more probable causes of contraction than cooling. That contraction has taken place is proved by the geological evidence. The restriction of the Alpine-Himalayan compression to a long narrow band, varying in latitude from 40° to 48° in Europe, and from 25° to 38° in Asia, is the natural result of that sinking of the northern dome of the world which is shown by the polar flattening. The junction of the northern dome with the tropical belt is naturally one of crumpling and crustal disturbance. This process would produce uplifts in the same zone of the crust around the northern hemisphere, and traces of this continuous upheaval are found. The West Indies and Central America include fragments of mountain chains formed at the same time as the Alps and with a similar trend.

The abrupt ending of the mountain grain of the continents on both sides of the Atlantic indicates the former extension of the land into the ocean. That the land once crossed the whole width of the Atlantic is supported by the biological evidence. Similar animals are found on opposite sides of the Atlantic in corresponding latitudes, and the resemblances of the South American and African faunas are not likely to be due to passage via Scotland and Greenland if there are no representatives of those groups in Europe or North America. The distribution of the ridges and deeps on the North Atlantic floor indicates uplifts in North America and western Europe at the time of the Alpine movements. There is similar evidence of former land extensions across the northern and southern Pacific, such as the occurrence of the alligator in the Yangtze Kiang, the resemblance of the flora of southern China to that of the south-eastern United States, and the occurrence on both sides of the South Pacific of various groups which are unrepresented in the lands on either side of the North Pacific. The biological evidence is supported by the ridges on the Pacific floor and the distribution of the coral islands. The former trans-Atlantic and trans-Pacific connexions must have endured until the time of the Alpine-Himalayan uplifts, for they were broken before the spread of the more specialised mammals and birds, and were available to some living groups of reptiles, amphibians, and specialised invertebrates.

The Indian Ocean was also once occupied by land, the disruption of which has affected the mountain structure of south-eastern Asia. At the end of the

¹ From a discourse delivered at the Royal Institution on Friday, January 30.