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No. 819

EXPERIMENTAL APPARATUS FOR THE STUDY OF PROPELLERS

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the Royal Engineering Institute of Turin

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A special financial contribution of 60,000 lire granted by the Ministry of National Economy and supplemented by personal gifts of Arturo Bocciardi, Pietro Fenoglio, and of the firms of Ilva, Terni, and S. Giorgio of Borzoli, directed by them, totaling 27,500 lire has permitted the Aeronautical Laboratory of the Royal Institute of Engineering at Turin to create an experimental station for model propellers.

The apparatus consists of a universal balance with transmission at variable speeds from 300 to 5,000 revolutions per minute and a group directly coupled to the model for speeds of 5 to 30,000 revolutions. The balance was designed by the director of the laboratory according to the plan of a similar apparatus at the Experimental Laboratory of the Ministry of Aeronautics at Rome except that the new apparatus was provided with a torsion meter for measuring the torque (fig. 2).

The balance consists of a yoke suspended on knife edges and in the yoke is inserted a vertical arm d supporting the propeller nacelle O, on which in turn is mounted the propeller, fore or aft. Two horizontal arms at right angles to each other (fig. 3) $B_1 B_3$, $B_2 B_4$ are arranged so that one is parallel and the other normal to the wind-tunnel axis, the first arm being used for measuring the thrust T and the second for measuring the torque C of the propeller. Figure 3 shows the plan view of the balance. The height h of the propeller axis above the center G of the suspension is 1,300 millimeters and the length a of each lever arm of the pans p and weights P from the center is 650 millimeters. Denoting by p_l and p_t the weights on the longitudinal and transverse

*"Impianto Sperimentale per lo Studio delle Eliche." Experimental Reports by the Aeronautical Laboratory of the Royal Engineering Institute of Turin, Series 1, pp. 12 to 23, and 76 and 77.

arms, respectively, required for balancing, we have:

$$T = p_l \frac{a}{h} \qquad C = p_t\ a$$

By varying the velocity V of the wind and the rotational velocity $n = \frac{60}{2\pi}\omega$ of the propeller of radius R, a very large range of the velocity ratio* $\frac{V}{\omega R} = \gamma$ may be obtained, not excluding very large values of γ for which the propeller thrust and the torque required to maintain it become negative, transforming the propeller into a windmill.

Tests on propeller models extended over the above range have been carried out on this balance by Faraboschi (reference 1) and published in L'Aerotecnica. The distinctive character of the apparatus of the Turin laboratory is the torsion meter connected to the two-component balance for measuring the torque transmitted by the model propeller.

If the angle between the wind direction and the propeller axis is zero the torque can thus be measured by two methods, one of which could be used as a check against the other. It is likewise possible to obtain the <u>efficiency of the transmission</u> as the ratio of the moment recorded by the transverse balance arm to that simultaneously indicated by the torsion meter. This calibration is effected by testing the propeller without setting the tunnel air in motion so as to avoid any possible yawing of the propeller axis with respect to the wind direction.

The value of the efficiency thus obtained, which is a function of the speed of rotation, is then applied to the tests with the air in motion, so as to deduce from the reading of the torsion meter the torque acting on the rotating propeller. This torque obtained with the air in motion does not come out equal to that indicated by the transverse arm of the balance due to the phenomenon of side flow which is very difficult to eliminate entirely.

By recording the setting of the propeller axis by means of a graduated circle rotated by worm F, such deviations may be eliminated or at least reduced to small

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*Translator's note: Author uses ratio $\gamma = V/\omega R$ instead of the more familiar V/nD.

values and the position thus found assumed for the purposes of the test. Finally, by measuring the angles of the side wind deviation and repeating the weighings for two positions inclined at the same angle but at opposite sides ("conjugate" positions), the aerodynamic effect of the side deviation of the flow could be obtained.

The rotational motion of the propeller is controlled by a motor with axis vertical - that is, placed at the base of the balance and has a variable and reversible speed. The speed could be varied from 300 to 5,000 by a Léonard converter by which the motor is fed. At its maximum speed, the motor develops a torque of 2,700 kilogram meters corresponding to 18 horsepower.

The transmission from the motor to the model is by means of a shaft, likewise vertical, and running along the height of the measuring apparatus. The shaft is divided into two branches, the one below the suspension containing the torsion meter and the upper one running inside the arm supporting the propeller nacelle mounted at the height of the wind-tunnel axis.

Inside the nacelle, by means of toothed wheels of angle N, the motion may be transmitted to either a tractor propeller placed at the bow A or a pusher propeller at the stern H, or both propellers may be mounted and turned in opposite directions for the purpose of investigating the behavior of propellers mounted in tandem.

By changing the toothed wheels the transmission ratio may be varied up to a value where the speed of the model is twice that of the motor, the model speed thus being raised to 10,000 r.p.m.

The joining of the two branches of the shaft is also by means of a universal joint G, whose center coincides with the center of the balance suspension. In this way there is no decrease in the freedom of motion of the vertical arm, required for making the weighings, by the continuity of the internal transmission shaft. The lower branch of the transmission shaft is hollowed out so as to permit the torsion-meter rod to be enclosed in it and is divided into two parts, one of which turns together with one end of the rod, the second part turning with the other rod end. The two parts end in disks, one of which D_3 is of one piece with the lower shaft branch and carries a transparent celluloid disk graduated in divisions, each of which corresponds to 2°. The disk D_2 which is of one piece with the upper branch and is opaque, carries a window through which the scale can be viewed (fig. 4). A third opaque disk D_1 likewise of one piece with the upper branch, is connected at a convenient distance from the second disk and also carries a window and an indicator.

A light ray directed vertically upward passes through the disks when the latter pass in front of the eye of the observer and a 45° mirror reflects the light ray, permitting the reading of the angle of twist of the rod.

The torsion rods with which the balance is furnished, are separated at the top by 560 millimeters and the respective diameters are 11, 8, 5, and 4 millimeters. There are two stiffening branches of 10 millimeters to bring the constant near the desired value and avoid too sharp a discontinuity at the section.

The engine torque C in kilogram meters is obtained from the reading of the angle of torsion α in degrees by means of straight-line formulas deduced experimentally, as the following for the 8-millimeter rod:

$$C = 100\ [\alpha^\circ - 0.4^\circ]$$

The balance is likewise provided with an epicycloidal gear train by means of which there is communicated to the lower disk a twist relative to the two upper disks ten times greater than the torsion under which the rod is subjected. The gear-wheel support is fixed to the upper branch of the hollow shaft and carries two coaxial gear wheels, the one r_1 having 16 teeth meshing with a wheel R_1 having 80 teeth and connected to the lower branch, the other R_2 of 64 teeth meshing with a pinion r_2 of 32 teeth connected by a sleeve to the upper branch and supporting the transparent disk D_3. Naturally another set of gear wheels is situated at the diametrically opposite position so as to balance the first set and reduce the forces acting on the teeth. (See fig. 5.)

The rotation α of the hollow lower shaft with respect to the upper is equal to the twist of the bar and since the transmission ratio as deduced from the number of teeth is $\frac{80}{16} \times \frac{64}{32} = 10$, the rotation of the last wheel r_2 with respect to the first R_1 is equal to $10\ \alpha$ as indicated on the sketch (fig. 5).

The gear wheels are made of elektron and balanced so that the resultant centrifugal force passes through the center of the ball bearing. In spite of this the friction affects the sensitivity of the torsion meter when the rotational speed is very high.

MEASUREMENT OF THE EFFECT OF THE ANGLE BETWEEN THE PROPELLER AXIS AND THE WIND DIRECTION

The effect of the angle of yaw is to introduce:

1. A side force H lying in the plane of the propeller disk in the same direction as the projection U on this plane of the velocity V of the wind;

2. A torque M normal to the force H.

The existence of these actions is made clearer by considering two diametrically opposite blades and two sections of equal radius r shown superposed in figure 6, S (upper blade) and J (lower blade). As a result of the angle of yaw the section S is acted upon by a greater resultant relative wind W_s at an angle of attack α_s and hence develops a lift R_s much greater than R_i. The difference between the projections of R_s and R_i on the propeller disk gives the side thrust H. Taking the moments of R_s and R_i with respect to the diameter parallel to U their difference gives the moment M. It is easy to see that the above explanation agrees with the general rule given when the conventions for representing the vectors ω and M are identical.

Other effects of less importance result from the yaw due to the action of the propeller rake but since the rake is not generally reproduced on the model and the effects are of negligible magnitude, we have not taken them into account in the present investigation.

For measuring the effect of the yawed propeller the balance is provided with a turret (fig. 2) rotating with the vertical arm d that carries the nacelle O and hence the axis of the propeller. The angles of side deviation are read upon a graduated circle on the turret.

The foot of the balance is fixed for the present and hence also the longitudinal direction about which the torque is measured and the transverse direction with respect to which the thrust is measured, but it is planned to modify the apparatus so that the directions may be varied with respect to the wind direction.

With the wind parallel to the fixed longitudinal axis, the above measurement of the torque and thrust are made and the reading of the torsion meter should agree with that of the balance about its longitudinal axis provided, of course, the torsion-meter formula takes into account the mechanical losses in the transmission.

After the above check, two tests may be carried out in conjugate positions; that is, with the propeller axis deviating to the right and left of the wind direction by an equal angle δ so as to obtain identical values but opposite in sign for the force H and the moment M, and thrust T and torque C of equal magnitude and sign.

From the sketch shown on figures 7 and 8, the following equations are deduced: For the yaw δ to the right (fig. 7) on the assumption of a right-hand propeller:

$$\begin{aligned} (T \cos \delta - H \sin \delta)\, h + C \sin \delta - M \cos \delta &= a\, p_t' \\ (T \sin \delta + H \cos \delta)\, h - (C \cos \delta + M \sin \delta) &= a\, p_l' \end{aligned} \qquad (9)$$

where p_t' and p_l' are the weights about the transverse and longitudinal axes, respectively, on the pans indicated in the figure, and $a = 0.650$; $h = 1.300$ are the lever arms of the balance as indicated in figure 1.

For the same yaw δ to the left

$$\begin{aligned} (T \cos \delta - H \sin \delta)\, h - C \sin \delta + M \cos \delta &= a\, p_t'' \\ -(T \sin \delta + H \cos \delta)\, h - (C \cos \delta + M \sin \delta) &= a\, p_l'' \end{aligned} \qquad (10)$$

Naturally since T, C, H, and M for a given propeller are all functions of the velocity ratio γ and proportional to $\rho\, \omega^2$, it is necessary to divide the above equations by the latter quantity and we shall assume that this has been done without changing the notation of the equations.

Since it is necessary to substitute values of

p_t' p_t'' p_l' p_l'' corresponding to the same value of γ, the curves of these must first be drawn as functions of γ and then sets of values of p assumed for each value of γ for which it is desired to know the values of T, C, H, and M.

Introducing the following brief notation:

$$s = \sin \delta \qquad c = \cos \delta$$

$$D_t = (p_t' - p_t'') \frac{1}{\rho\omega^2}; \quad S_t = (p_t' + p_t'') \frac{1}{\rho\omega^2}$$
$$D_t = (p_l' - p_l'') \frac{1}{\rho\omega^2}; \quad S_l = (p_l' + p_l'') \frac{1}{\rho\omega^2} \qquad (11)$$

and noting that $h = 2a$, there are easily deduced from the equations above.

$$\tau R^4 = \frac{1}{4} (S_t c + D_l s); \quad h R^4 = \frac{1}{4} (D_l c - S_t s)$$
$$\kappa R^5 = 0.325 (D_l s - S_l c); \quad m R^5 = 0.325 (D_t c + S_l s) \qquad (12)$$

In the above formulas τ and κ are the well-known coefficients of thrust and torque in the expressions of Rénard for a propeller of radius R; h and m are the analogous coefficients for the side force and moment. The measurement that is simultaneously made with the torsion meter permits a very good check on the value of the torque κR^5 obtained from the above formulas.

If there is a small angle ϵ between the longitudinal axis of the balance and the direction of the wind, there are deduced by observations in conjugate positions with respect to the wind, the following relations (fig. 9):

$$[T_1 \cos(\delta+\epsilon) - H_1 \sin(\delta+\epsilon)] h + C_1 \sin(\delta+\epsilon) - M_1 \cos(\delta+\epsilon) = ap_t'$$
$$[T_1 \sin(\delta+\epsilon) + H_1 \cos(\delta+\epsilon)] h - C_1 \cos(\delta+\epsilon) - M_1 \sin(\delta+\epsilon) = ap_l'$$
$$[T_2 \cos(\delta-\epsilon) - H_2 \sin(\delta-\epsilon)] h - C_2 \sin(\delta-\epsilon) + M_2 \cos(\delta-\epsilon) = ap_t'' \qquad (13)$$
$$-[T_2 \sin(\delta-\epsilon) + H_2 \cos(\delta-\epsilon)] h - [C_2 \cos(\delta-\epsilon) + M_2 \sin(\delta-\epsilon)] = ap_l''$$

Naturally, $T_1 = T_2 \quad H_1 = H_2 \quad C_1 = C_2 \quad M_1 = M_2$

On the assumption that ϵ is very small and with the notation already introduced

$$\cos(\delta + \epsilon) = c - \epsilon s \qquad \sin(\delta + \epsilon) = s + \epsilon c$$

$$\cos(\delta - \epsilon) = c + \epsilon s \qquad \sin(\delta - \epsilon) = s - \epsilon c$$

Proceeding as in the previous case, there are deduced for the four unknowns the following values:

$$\tau R^4 = \frac{1}{4(1+\epsilon^2)} [(D_l - \epsilon D_t) s + (S_t + \epsilon S_l) c]$$

$$h R^4 = \frac{1}{4(1+\epsilon^2)} [(D_l - \epsilon D_t) c - (S_t + \epsilon S_l) s] \tag{14}$$

$$\kappa R^5 = \frac{0.325}{1 + \epsilon^2} [(D_t + \epsilon D_l) s - (S_l - \epsilon S_t) c]$$

$$m R^5 = \frac{0.325}{1 + \epsilon^2} [(S_l - \epsilon S_t) s + (D_t + \epsilon D_l) c]$$

In this case too, the torsion meter reading gives a check for the moment coefficient. If the absolute values of p are sufficiently near each other S_l is the difference between two rather large values of approximately the same magnitude so that the effects of instrument and observation errors are appreciable.

In obtaining the torque coefficient κ it is therefore advisable to rely on the readings of the torsion meter and compare the values obtained from the conjugate weighings as a check on the exact value of the angle ϵ which the wind direction makes with the normal to the longitudinal fulcrum of the balance.

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Torino E 2 (figs. 10 and 11).- We again consider a propeller having two controllable blades, the sections of which are shown in figure 10. The propeller characteristics are given only for the maximum value of the pitch ratio $p/D = 1.91$ for an angle of 20° between the propeller thrust line and the wind velocity V (fig. 11). The pitch was measured at 70 percent of the radius where the blade angle of the section was 40° 47' whose tangent is 0.863. Thus

$$\frac{p}{2\pi} = 0.863 \times 0.7 \times \frac{D}{2}$$

Figure 11 shows the coefficients τ and κ (thrust and torque coefficients, respectively) plotted against γ ($\gamma = V/nD/\pi = V/\omega R$ where R is the propeller radius) for the two cases where the angle δ between the propeller thrust line and the direction of the wind velocity V is 0° and 20°, the corresponding curves being indicated by dotted and full lines, respectively. Both coefficients are increased for large values of γ as a result of the angular deviation δ. For $\delta = 0°$ there is no divergence. The side force H and its torque M are represented by their coefficients

$$h = \frac{H}{\rho\ R^4\ \omega^2} \quad \text{and} \quad m = \frac{M}{\rho\ R^5\ \omega^2}$$

The first coefficient h increases with γ at a greater than proportional rate whereas the second increases at first, reaches a maximum for $\gamma = 0.5$, then becomes zero again for a value of γ somewhat greater than those at which κ vanishes. The coefficient h includes the action on the torpedo-shaped nacelle (100 mm in diameter, 430 mm long (figs. 2 and 3)). The latter effect was separately determined and subtracted from the total H thus deriving the coefficient h_e which corresponds to the propeller alone.

The method of testing the propeller is that described in a previous section of this report.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

REFERENCE

1. Faraboschi, A.: Esperimenti su eliche per tutti gli stadi di funzionamento e per diversi valori del rapporte passo-diametro. L'Aerotecnica, April 1931.

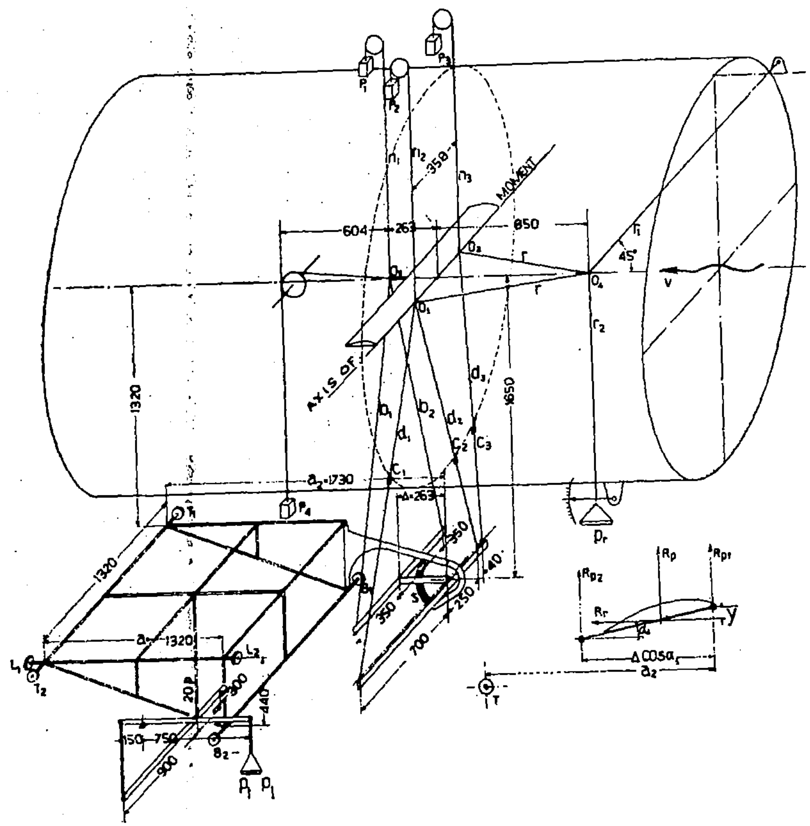

Figure 1.

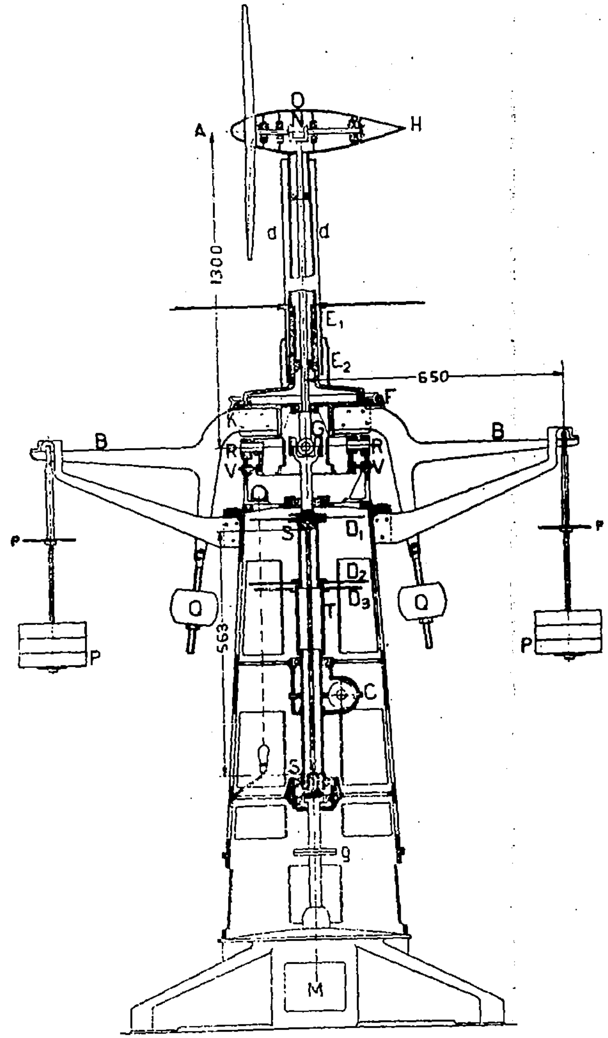

Figure 2.

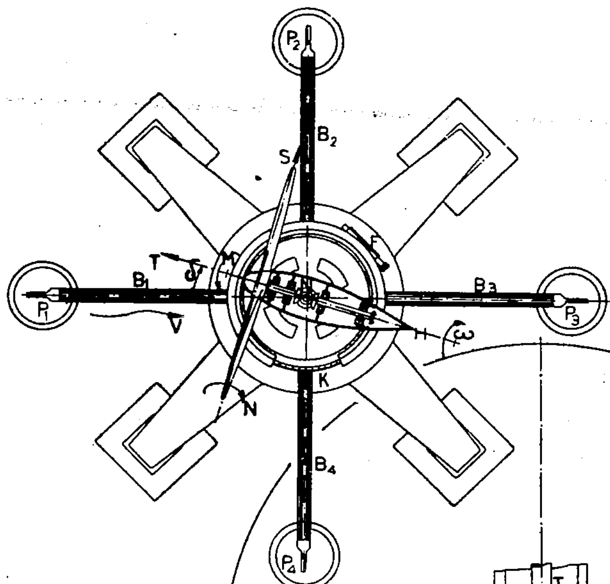

Figure 3.

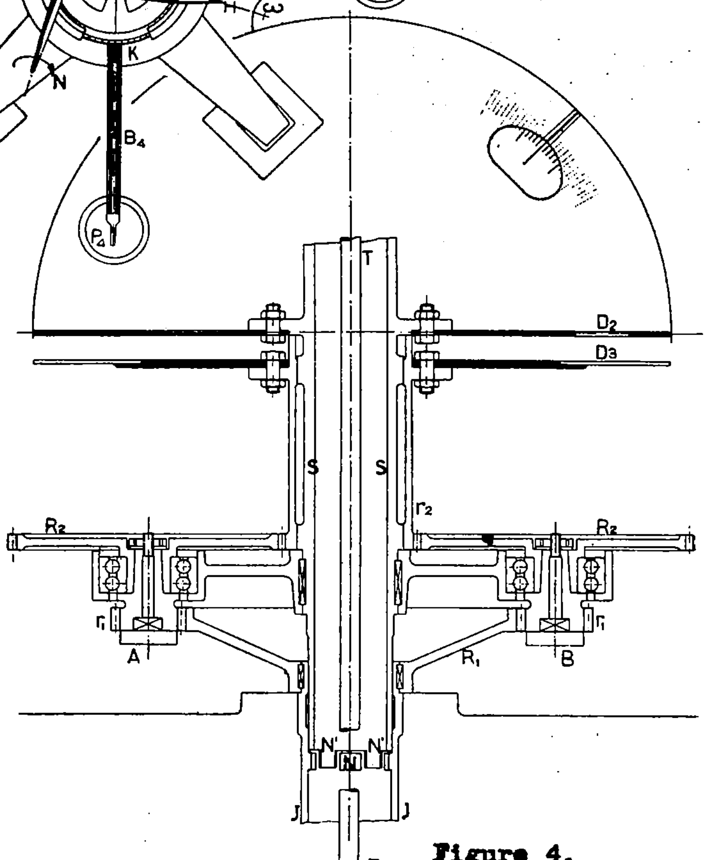

Figure 4.

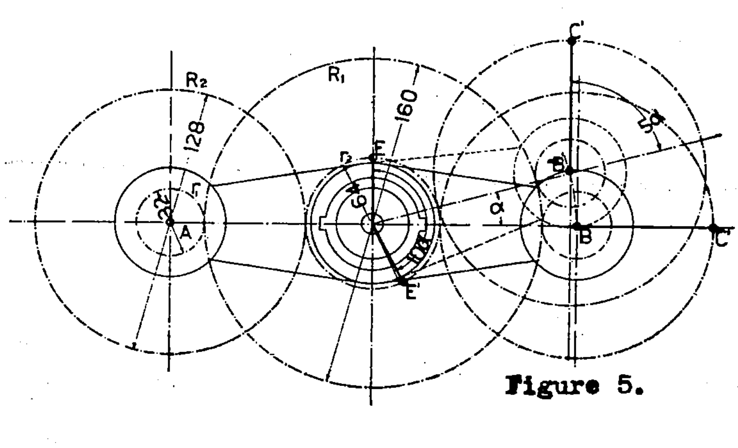

Figure 5.

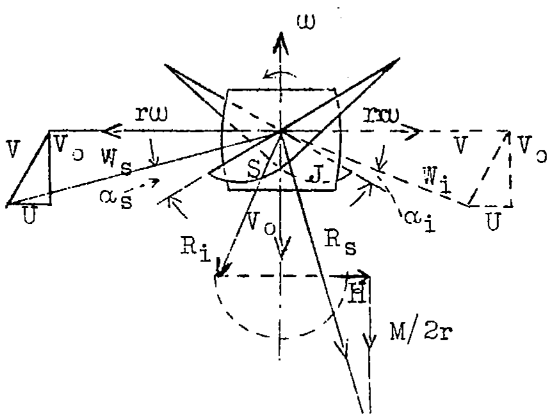

Figure 6.

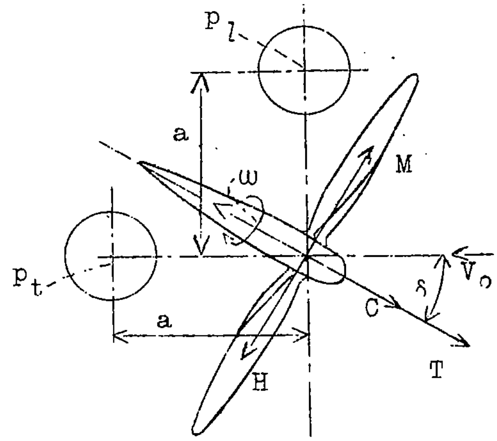

Figure 7.

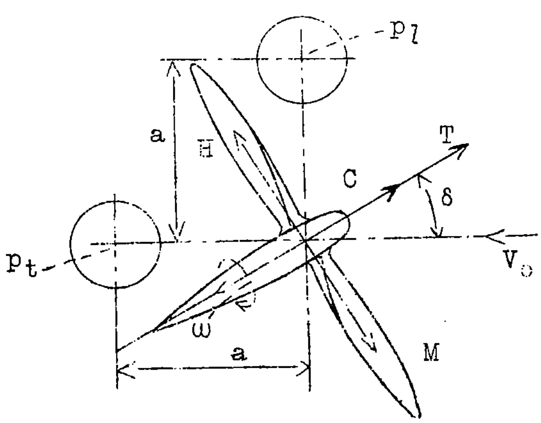

Figure 8.

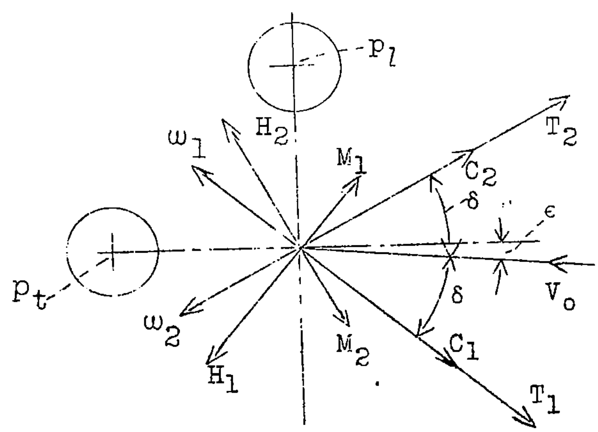

Figure 9.

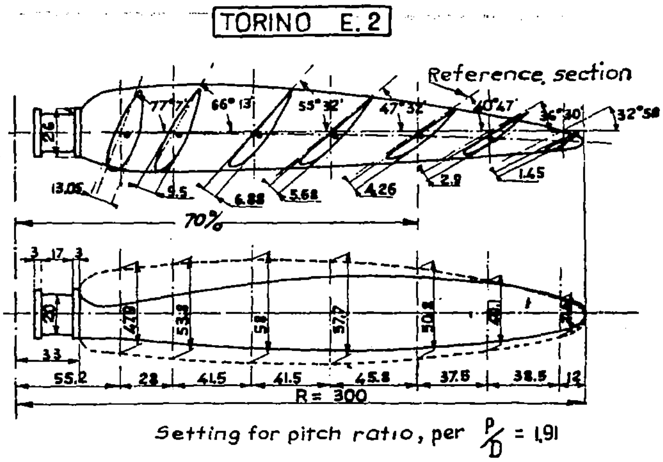

Figure 10.

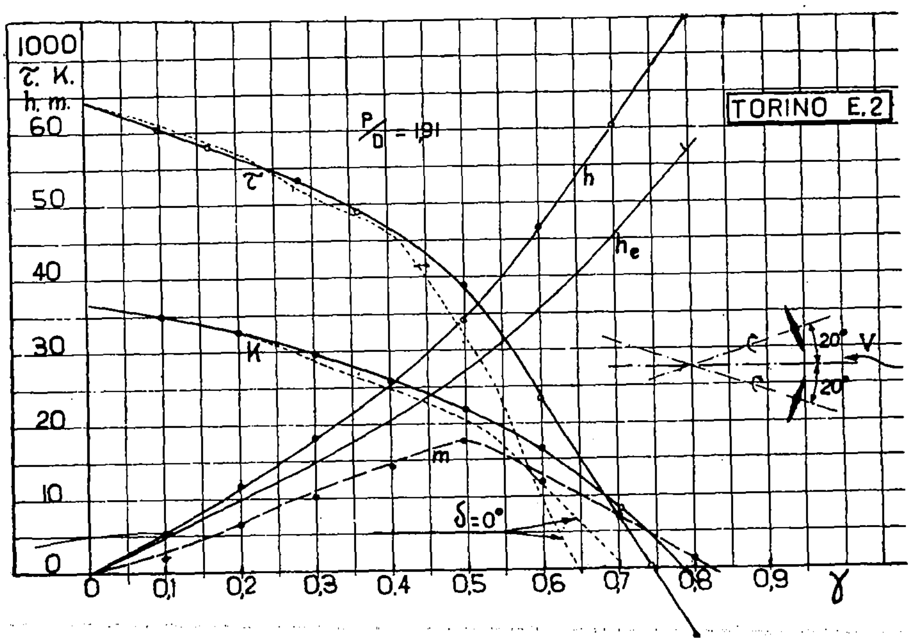

Figure 11.