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Wind Tunnel Tests of High Pitch Airscrews

(PART I)

By **C. N. H. LOCK**, M.A., **H. BATEMAN**, B.Sc.
AND
H. L. NIXON

OCTOBER, 1934

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WIND TUNNEL TESTS OF HIGH PITCH AIRSCREWS

(PART I)

By C. N. H. Lock, M.A., H. Bateman, B.Sc., and H. L. Nixon
of the Aerodynamics Department, N.P.L.

Reports and Memoranda No. 1673

5th October, 1934

Summary.—The main series of tests of the original family of airscrews described in R. & M. 829 consisted of measurements of overall thrust and torque on 5 two-bladed and four-bladed airscrews of pitch diameter ratios 0·3, 0·5, 0·7, 1·0 and 1·5. These tests have now been extended to much higher pitch values and the original tests repeated at a uniform Reynolds number. The additional tests were made with the blades of P/D 1·5 rotated to the equivalent pitch values 1·0, 1·25, 1·8, 2·2 and 2·5. Some of the tests on the low pitch screws were made in a closed 7 ft. tunnel, but the tests of the highest pitch screws were made in the new open jet tunnel No. 1 in order to use the higher maximum tunnel speed. Thus a comparison was obtained between observations in the closed and open jet tunnels for a number of airscrews and these support the standard methods of correction for tunnel interference. New apparatus was used including a new 15 H.P. induction motor of 9 in. diameter to drive the airscrew. The effect of the airscrew boss was eliminated by using a cylindrical guard body of 0·27 airscrew diameters with faired nose and tail of sufficient length to give a uniform flow in the absence of the screw. The thrust readings were corrected by pressure plotting the airscrew boss, so that the recorded thrust and torque coefficients refer to the exposed portions of the blades only. Instructions are given for correcting the performance data for the effect of interference when the screw is mounted on the fuselage of an actual aeroplane.

The results show that the maximum thrust coefficient for the higher pitches is limited by the stalling of the blades, so that after reaching a value of about 0·135 for the two-bladers and 0·26 for the four-bladers, the value of k_T remains very roughly constant and independent of pitch for all smaller values of J. These values are however subject to a scale effect on maximum thrust coefficient of 5 to 10 per cent. for an increase of Reynolds number from $1 \cdot 8 \times 10^5$ to 3×10^5 but there is some evidence to suggest that the full scale values will not differ greatly from those of the model. The torque coefficient increases with increase of pitch at all working conditions. The maximum efficiency for the two-bladers increases slightly from 88·4 per cent. at P/D 1·5 to an absolute maximum of 89·7 per cent. at a P/D rather less than 2·5. For the 4-bladers the corresponding figures are 84·8 and 86·8.

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Appendix

1. *Introduction.*—In the tests on the original family of airscrews of 3 ft. diameter (R. & M. 829)[1], the pitch diameter ratios (P/D) of the principal series of screws (two- and four-bladers) were 0·3, 0·5, 0·7, 1·0 and 1·5, this range being considered adequate to cover all practical requirements. After a lapse of 12 years, however, the pitch diameter ratios of full scale airscrews have increased almost to the limit of these tests and extreme values of 2·2 have been used. It was decided, therefore, that a further series of airscrews should be tested to extend the range of pitch values to 2·5.

It was realised at the outset that in order to reach a reasonable Reynolds number on the highest pitch airscrew, a considerable increase of power to drive the screw would be required over the original electric motor of 1·5 H.P. used in the experiments of R. & M. 829 or even the 6 in. diameter induction motor of 2·5 H.P. used in later experiments. Accordingly a new 3-phase induction motor of 9 in. diameter was designed by Mr. Relf to run at 3,000 r.p.m. at 250 volts and fitted with reduction gears of 1 : 1, 1·5 : 1 and 1·96 : 1; this motor developed 15 H.P. during the tests. Again, the Reynolds number for high pitch airscrews depended upon the maximum tunnel speed available, which in the 7 ft. No. 3 tunnel was only 90 ft./sec. It was therefore decided to await the completion of the open jet tunnel No. 1 in order to utilise its maximum air speed of 200 ft./sec. for the high pitch tests.

The centre of the airscrew was shielded to a radius of 0·27R by means of a long cylindrical guard body having a streamline nose and tail (Fig. 1). By this means it was possible to determine the thrust and torque of the blades only; it was considered that the results obtained in this way would be more directly applicable to the calculation of the performance of an actual aeroplane (*see* §2 below), and would simplify the comparison of the results with strip theory calculations. This change in the method of test eliminated the boss drag, which was a feature of the earlier observations of thrust, and suggested the advisability of repeating the main series of the original experiments; as the open jet tunnel was not then completed, the low pitch range was tested in the 7 ft. No. 3 tunnel. The advantages of this proposal were that the whole series of screws from 0·3 to 2·5 P/D could be correlated at a much higher Reynolds number than that obtaining in the original tests, and the velocity correction necessary in the N.P.L. type tunnel could be checked with some degree of certainty by a comparison of the performance tests of the same screw in the 7 ft. No. 3 and open jet tunnels.

2. *Application of the Results to Full Scale Airscrews.*—The application of the results given in the tables to full scale differs somewhat from that of previous experiments in that the thrust and torque (or power) coefficients represent the forces on the blades only.

According to the principles of airscrew body interference set forth in R. & M. 1522[2] (neglecting scale and compressibility effects), the curve of torque coefficient against J for an airscrew mounted in front of an aeroplane fuselage can be obtained from the model results by increasing all values of J in the constant ratio K. The value of K depends on the shape of the nose of the fuselage. An average value is 1·05 for a water-cooled engine and 1·10 for an air-cooled engine.

The efficiency of the blades of the airscrew on the actual aeroplane should be taken as the same as that given for the model at the same value of torque (or power input) coefficient. Thus the *total* power wastage (which must equal the total torque power in level flight) is made up of airscrew blade losses, as given by the model experiments at the same torque power: plus the total drag of the machine without airscrew: plus the increase of drag of the parts of the aeroplane situated in the slipstream. This last item can be calculated from the theoretical formula (R. & M. 1522 p. 6 (10))

$$\frac{\text{Increase of drag}}{\text{normal drag}} = \frac{8}{\pi}\,\frac{T}{\rho V^2 D^2}.$$

The experiments on streamline bodies and airscrews described in R. & M. 1522[2] indicate a slight additional "spoiling drag" resulting from the suction of the rotating stream at the tail, but this effect is unlikely to be appreciable for an actual fuselage.

The evidence from the limited data available of wind tunnel tests on actual aeroplane models with screw running is analysed by Bryant in T.3659[3]. He has analysed tests on these models as follows:—

Aeroplane.	Value of K.	Notes.
Puss Moth	1·05	Air-cooled in line engine.
Bristol Fighter	1·07	Water-cooled engine with large radiator.
Bristol Bulldog	1·12	Radial engine.

For all three models he finds that the total power wastage is roughly equal to the sum of the airscrew blade losses and the drag of the machine, without any allowance for the increase of drag due to the slipstream. According to the notation of R. & M. 1522 these results require a negative "spoiling drag" almost equal to the "slipstream drag". It is suggested that the slipstream improves the flow over an imperfectly streamlined body, so that the spoiling drag may be expected to be more and more negative the more the shape of the body deviates from a good streamline form.* The effective slipstream velocity may also be smaller than that given by the theoretical formula.

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* *See* T.3659[3] (unpublished), p. 19 and R. & M. 1522[2], p. 10. § 3.4.4.

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3.1. *Details of Experiment. Range of Pitch Values.*—The original main series of the family of airscrews consisted of five sets of detachable blades designed for constant geometrical pitch values of 0·3, 0·5, 0·7, 1·0, 1·5 (Tables 1 and 2); each blade could also be rotated in the boss to any other angle of pitch. In deciding whether it was necessary to manufacture additional blades for the pitch values greater than 1·5, it was noted that the difference of the blade angles between a constant pitch airscrew of P/D 2·5, and one of P/D 1·5 twisted to P/D 2·5 was small. This is shown by Table 2 in which the blade angles at various radii are recorded, as well as the difference between screws of constant pitch and the corresponding screws obtained by rotating the blades of P/D 1·5. It was therefore decided to use the blades of P/D 1·5 for all high pitch tests, and the pitch of each screw was defined as corresponding to the section at radius 0·7. On this basis the P/D 1·5 blades were tested at the following pitch ratios:—1·0, 1·25, 1·8, 2·2, 2·5 (*see* Table 2). Each was tested both as a two- and four-blader, making 10 screws in addition to the 10 screws of the original series, or 20 in all.

3.2. *Details of the Blade Sections.*—The main series of screws which form the subject of the present report all have the same plan form, and the sections at any given radius are the same for all the pitch values. The shapes of five standard sections along the blade are given in Table 1 and it will be seen from Fig. 2, which shows the principal sections and the central area shielded by the guard body, that those sections at greater radii than 0·45R have flat undersurfaces and are based on the R.A.F.6 type of section with a slight rounding of the leading edge.

3.3. *Reynolds Number.*—It was found convenient to make the tests at an approximately constant Reynolds number corresponding to an effective velocity of 200 ft./sec. at a radius of 0·7R. This was defined by the condition:—

$$\{V^2 + (2\pi rn)^2\}^{\frac{1}{2}} = 200 \text{ ft./sec.}$$
$$= \text{standard effective velocity } W_0,$$

where V is the tunnel-velocity in feet per second, n is the rotational speed in revolutions per second, and $r = 0{\cdot}7R$, R being the maximum radius of 1·5 ft.

Since the chord length at this radius is $c = 0{\cdot}232$ ft., the standard Reynolds number (W_0c/ν) of the tests was $2{\cdot}9 \times 10^5$, ($W_0c = 46$). This standard velocity corresponds (*a*) to a rotational speed, at zero V, of 30 revs. per second which is near the limiting safe value of rotation; (*b*) to a maximum H.P. of 15 for the highest pitch airscrew which is almost the maximum available power; (*c*) to a value of V at zero thrust for P/D 2·5 of 165 ft./sec. (the maximum speed in the open jet tunnel being 210 ft./sec.). The variations from the standard velocity during the tests amounted to as much as 20 per cent. as it was found convenient to keep the rotational speed constant over a range of tunnel speeds. For example the rotational speed for the highest pitch airscrew ranged from 30 r.p.s. at zero V to 19 r.p.s. at 180 ft./sec. in five or six steps.

3.4. *Cylindrical Streamline Guard Body.*—The general arrangement of airscrew and guard body is shown in Fig. 1. The diameter of the guard body is 9·75 in. or 0·27 airscrew diameters. The portion in front of the airscrew is cylindrical for 25·5 in. and is finished with a spheroidal nose. This length was found to give a sufficiently constant distribution of velocity in magnitude and direction over the region which the screw would occupy (*see* Appendix A.4 on velocity calibration). The airscrew boss is bounded by parallel-sided gaps about ¼ in. wide. The plates A and B, separate from the airscrew, contained a sufficient number of pressure holes to determine the resultant force on the plates by integration of the pressures (*see* Appendix A.6). These holes were connected through tubing to an inclined multitube manometer. The resultant force on the boss in an axial direction was assumed to be equal to the difference of pressure on the two fixed plates and was subtracted from the thrust reading so that the corrected thrust represented the axial force on the exposed parts of the blades. The torque on the boss due to air friction in the gaps was shown to be negligible by rotating a cylindrical boss without blades.

4.1. *Details of Apparatus. Thrust and Torque Balances.*—The general arrangement is shown in Fig. 1. The principle employed in the original apparatus, of suspending the airscrew motor with its axis near the point of intersection of two pairs of vee-wires C so that the motor could swing in the thrust direction and oscillate about the torque axis, was retained, but the majority of the other features were altered. Instead of suspending the motor on points, freedom to swing and oscillate was secured by carrying the suspending wires C (stranded cables) under grooved quadrants DD rigidly attached to the motor and arranged so that the virtual axis of oscillation coincided with the torque axis.

The tendency of the motor to rotate about the torque axis was restricted by a stranded cable E attached to a torque arm F, the upper end of the cable being attached by a point shackle G to the torque balance H which was a simple weighbeam of the lift balance type.

The tendency to swing forward under the influence of the thrust was restricted by the tension of a horizontal rod I attached to the motor by a point and cup J and hinged to rods K and L. Rod K, inclined at 45° to the horizontal, is hinged to an anchorage M on the floor of the tunnel, while L is attached by a point shackle N to the thrust balance O which is exactly similar to the torque balance. The hinges at PP where the angular motion is very small consisted of short pieces of stranded cable. The thrust is therefore transmitted as a pure tension through rod I to rod L and so to the thrust balance.

This suspension proved very rigid against deflections under the thrust and torque loads. The axial deflection of the airscrew under thrust load amounted to 0·06 in. under the maximum load of 50 lb.; the deflection at the end of the torque arm amounted to 0·14 in. under the maximum torque load of 40 lb. ft. The initial tension in the thrust linkage was maintained by inclining the supporting wire about 4°; the initial tension of the torque wire was maintained by the weight Q suspended from the torque arm.

Constants of the thrust and torque balances were obtained by direct calibration. The position of the torque balance had to be accurately adjusted, as an increase in tension in the torque wire would affect the thrust reading unless the wire and the vee-wires supporting the motor were parallel. This adjustment is best affected by calibration of the balance. If the adjustment is accurate at zero thrust, there will be a slight effect at large thrusts owing to the extension of the thrust linkage under load. The effect actually amounted to less than 0·0005 of the thrust when the torque had its maximum value. The effect of the maximum thrust on the torque reading was too small to be measured.

The above description applies roughly to the arrangement in both wind tunnels but certain modifications were required on transferring to the open jet tunnel. In the closed tunnel the thrust linkage and the torque wire both lay in vertical planes parallel to the wind direction. In the open jet tunnel it was necessary to shift the balances sideways in order to leave sufficient vertical clearance between the jet and the underside of the return duct for an observer to sit and read the balances. This was accomplished by rotating the thrust linkage through an angle of 20° about the airscrew axis, and inclining the torque wire through 13° in the same direction. This necessitated the addition of a roller R resting on an adjustable plane surface to support the weight of the thrust linkage.

In the closed tunnel most of the anchorages for wires, etc., were on the roof or floor of the tunnel; in the open jet the stranded cables supporting the motor, the rods supporting the after guard body and the rafwires supporting the forward body were all anchored to the two longitudinal girders S; the lower wires were taken to the floor covering the return duct, or the floor of the nozzle and collector. The majority of wires had to be made roughly double the length required in the closed tunnel; this involved some trouble from vibration, which was largely cured by shielding parts of some of the wires, especially near the boundary of the jet.

The authors are indebted to Mr. P. H. Allwork for the detail design of the apparatus.

Further details of the apparatus and methods of measurement are given in the appendices.

4.2. *Ease and Accuracy of Observation.*—The method of continuously observing and controlling rotational speed described in Appendix A.1 greatly increased the ease and accuracy of observation in both wind tunnels. Except when the airscrew was stalled the rotational speed of the screw remained constant, almost to one part in a thousand, with hardly any control. The air speed in the open jet tunnel appeared to be appreciably steadier than that of the 7 ft. No. 3 and, in conjunction with a visible indication of speed (Appendix A.2), allowed a greater rapidity of observation and probably greater accuracy than the 7 ft. No. 3 tunnel.

5. *Discussion of Results.*—The Figures (3–8) and Tables (3–5) give values of thrust coefficient k_T, torque coefficient k_Q and efficiency η derived from smooth curves drawn through the observation points. Below the stall, the observation points lie very well on smooth curves and it has been verified by cross plotting that variations with pitch are also sensibly smooth.

5.1. *Comparison with Experiments of R. & M.* 829.—A systematic discrepancy on the thrust coefficient is to be expected on account of the presence of a boss drag in the old values, and differences of both thrust and torque will arise as a result of scale effect (*see* § 5.4 below) because the experiments of R. & M. 829 were generally at a lower speed. The readings in the tables of R. & M. 829 for $J = 0$ apply in reality to the condition in which the tunnel fan is at rest, for which J has a value varying between 0·05 and 0·18. In the present report (Table 5 footnote) the true value of J at tunnel static is recorded and the performance at true static ($J = 0$) can be determined with fair accuracy by extrapolation.

Apart from these effects the new and old results are in very fair agreement except for the two- and four-bladed airscrews of lowest pitch (P/D 0·3) where the discrepancy exceeds 10 per cent. on k_Q for the two-blader. The new results have been carefully checked and are believed to be accurate. The errors of the old results may be partly due to errors in setting the blade angles ; a small error will have a relatively large effect on a screw of low pitch. A further point is that the new results at the lowest pitch values agree better than the old with the vortex theory calculations of R. & M. 892.[4]

5.2. *Values of* J *at Zero Thrust ; (Experimental Pitch).*—In the absence of a boss correction it becomes possible to produce a definite analysis of the values (J_0) of J at zero thrust. It is possible to define a " blade angle of zero thrust " θ_0 for a particular radius xR by the equation

$$\pi x \tan \theta_0 = J_0. \qquad (1)$$

Then the (negative) angle

$$\theta - \theta_0 = \alpha, \qquad (2)$$

represents the corresponding " incidence of zero lift " referred to the chord line for the particular radius x. The (constant) pitch ratio of the airscrew is defined by the equation

$$P/D = \pi x \tan \theta. \qquad (3)$$

It has been found by trial that a is approximately constant at a radius of 0·6 and has the value

$$a = -4^\circ\, 34' . \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (4)$$

By substituting from equations (1), (2) and (3) it can be shown that (4) is equivalent to

$$J_o = \frac{P/D + 0{\cdot}151}{1 - 0{\cdot}042\,(P/D)} . \quad \ldots \quad \ldots \qquad (5)$$

For airscrews not of constant geometrical pitch, the pitch diameter ratio has been defined at radius 0·7 ; hence it is not logically correct to apply equation (3) at radius 0·6R to these screws. It has been found, however, that equation (5) still fits the observations, using the P/D at 0·7R. Values of J_o calculated by this formula are included in Table 3 and are in good agreement with observation over the whole range of pitch. A detailed strip theory analysis at zero thrust based on the aerofoil data of R. & M. 892 has shown sensibly exact agreement with experiment over the whole range of pitch.

5.3. *Maximum Efficiency.*—The curves of efficiency are shown in Figs. 7 and 8 together with an approximate envelope, the values of which are recorded in Table 4. The maximum efficiency increases with pitch up to a pitch-diameter ratio of 2·0 ; after this value it remains approximately constant but has a tendency to drop slightly. The absolute maximum value for the two-bladed airscrew is 89·7 per cent. and for the four-bladed airscrew is 86·8 per cent.

In considering the values of efficiency shown here, it must be emphasised that they are calculated from the thrust and torque on the blades only, so that the effect of boss drag has been completely eliminated.

5.4. *Scale Effect.*—A number of observations have been taken to investigate the effect of change of Reynolds number. In general for the high pitched screws a series of three working conditions has been chosen, of which one is at zero thrust, one near maximum thrust and one midway between. At each of these conditions a series of observations was taken ranging from the highest to the lowest Reynolds number available. The results were plotted as isolated values of thrust and torque coefficient on the original large scale thrust and torque coefficient (standard R) curves ; the scale effect was then estimated from the ratio of the radial distances of the observation point and the curve from the origin. The scale effect was in all cases largest at zero thrust and considerably smaller at both the other working conditions. For example on the two-blader of P/D 1·8 there is at zero thrust an increase with Reynolds number of 4 per cent. between $R = 1{\cdot}5 \times 10^5$ and $R = 3{\cdot}7 \times 10^5$ for both thrust and torque curves, while at a value of J of 0·75 of that of zero thrust, the corresponding increase is only 1 per cent. The scale effect at zero thrust is in fact surprisingly large on the screws of very high pitch and no satisfactory explanation of it has been obtained. There is, however, a definite tendency for the rate of increase to be smaller at the higher Reynolds numbers.

The scale effect on the high pitched screws above the stall is discussed in the next section.

5.5. *Stalled Range.*—The principal novelty revealed by the extension of the tests to higher pitch values is the range in which the blades are stalled. In both two- and four-bladers, the maximum thrust coefficients are definitely marked and may be taken loosely as defining the " stalling point " of the blades. The behaviour of the screw is similar to that of some aerofoils in that the stalling point is immediately followed by an unsteady region, after which the conditions become steadier again. There is also a resemblance between the general shape of the thrust coefficient curve and that of the lift coefficient of an aerofoil. The unsteady region beyond the stall is marked by : (*a*) small variations in the rotational speed which may correspond to relatively large variations of torque ; (*b*) slight unsteadiness in the thrust and torque readings ; (*c*) an appreciable scale effect on thrust coefficient and a smaller one on torque coefficient (Figs. 3–6). The curves show that the scale effect becomes smaller again with a further decrease of J. When the unsteady region occurs at a low tunnel speed (P/D about 1·5), a characteristic fluttering sound is also audible. The series of curves for different pitches is surprisingly consistent in the stalled region and confirms the definiteness of the readings. It is to be expected however that the performance in the stalled region will vary critically with the blade section, and this point is under investigation.

To a very rough approximation the thrust coefficient has the constant value 0·135 for the two-bladers and 0·26 for the four-bladers at all points beyond the stall, these values being independent of pitch.

It is also possible to calculate the approximate speed range before the stall takes place for a high pitch airscrew. Denote the condition of maximum efficiency by the suffix *m* and the stalling condition (maximum k_T) by *s*. Then assuming that the airscrew operates at full throttle at its maximum efficiency at maximum flying speed, the speed range of the airscrew up to the stall will be V_m/V_s and, assuming constant engine torque, we have

$$\frac{n_m}{n_s} = \left(\frac{k_{Qs}}{k_{Qm}}\right)^{\frac{1}{2}}$$

and

$$\frac{V_m}{V_s} = \frac{n_m}{n_s} \cdot \frac{J_m}{J_s} .$$

Values of V_m/V_s calculated by these formulae are given in the last column of Table 3, from which it appears that the speed range between maximum efficiency and the stalling point of the airscrew, which is infinite for pitch ratios less than 1·0, decreases from about

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5 for P/D 1·25 to 1·9 for P/D 2·5; also that the larger solidity of the four-blader gives a slight advantage in this respect assuming that the tip speed is fixed by the condition of avoiding the compressibility stall.

These conclusions are however subject to the scale effect on maximum thrust coefficient which amounts to 5 to 10 per cent. for an increase of Reynolds number from $1{\cdot}8 \times 10^5$ to 3×10^5 (standard) as shown by a comparison of the curves at standard Reynolds number and at 0·6 of standard Reynolds number in Figs. 3 and 4. An analysis of the results at maximum k_T shows that the corresponding value of k_L on a section at 0·7R is of the order 0·7. In view of the general experience on aerofoil tests in the compressed air tunnel, it is not expected that the k_L at full scale Reynolds number will be much in excess of this value. The maximum k_T full scale should not, therefore, differ greatly from that of the "standard" model results.

5.6. *Glauert's Relation between the Thrust and Torque of a Completely Stalled Airscrew.*—In R. & M. 1342[5] Glauert has given a simple theoretical relation between the thrust and torque of a completely stalled airscrew based on the assumption that the resultant force on a blade element is normal to the flat undersurface at all radii. In order to check this relation observed values of the ratio $Pk_T/2\pi Dk_Q$ at tunnel static are plotted against P/D in Fig. 9 and confirm the tendency of the value of this ratio to approximate to unity as the pitch increases, as shown by the observations on a more limited range plotted in Fig. 5 of R. & M. 1342[5].

5.7. *Accuracy of Performance data.*—It is somewhat difficult to assess the true percentage accuracy of the results on account of the large number of possible sources of error involved. If, however, the criterion of accuracy is based on the variation of the radial distance from the origin to any point on the curve of thrust or torque coefficient against J, it is unlikely that the results are in error by more than 1 per cent. except possibly in the stalled region.

The most satisfactory check on the observational accuracy is given by the agreement of independent tests of a particular screw taken at a considerable interval of time. The percentage error, assessed as above, has never exceeded 1 per cent.

The maximum efficiency should be correct to 1 or 2 per cent.

6. *Conclusions.*—A more detailed discussion of the results is held over till the issue of reports on the analysis of the observations by means of the improved vortex theory and on the effect of change of blade section on the performance beyond the stall. The object of the present report is merely to publish results which are believed to represent the performances of the standard two- and four-bladed airscrews of the family over a range of pitch diameter ratio from 0·3 to 2·5 with all desirable accuracy.

The principal novel result revealed by the extension of the range of pitch of the original tests from P/D 1·5 to P/D 2·5, is the tendency of the airscrew to stall at a roughly constant value of k_T of 0·13 to 0·15 for the two-blader and 0·26 to 0·29 for the four-blader. The torque coefficient increases continuously with increase of pitch at all working conditions; the maximum efficiency increases only slightly beyond P/D 1·5 from 88·4 to 89·7 per cent. for the two-bladers and 84·8 to 86·8 for the four-bladers and has apparently reached an absolute maximum at a P/D less than 2·5 in both cases.

TABLE 1

Details of the Five Standard Sections Common to all Blades.

Sections FF, EE, DD, CC have flat undersurfaces; BB has a convex undersurface.

x = distance along chord, expressed as a fraction of the chord length.
y = distance above chord, expressed as a fraction of the chord length.
r_L = radius at the leading edge.
r_T = radius at the trailing edge.

Section	FF	EE	DD	CC	BB		
Radial distance/tip radius	0·90	0·75	0·60	0·45	0·30		0·70
Camber of section (t/c)	0·086	0·103	0·129	0·168	0·278		0·110
Chord length/max. chord	0·620	0·880	1·000	0·990	0·825		0·939
x	y	y	y	y	y_1*	y_2*	
0·05	0·051	0·061	0·078	0·099	0·097	0·060	
0·10	0·069	0·081	0·103	0·129	0·144	0·069	
0·20	0·082	0·099	0·125	0·160	0·184	0·078	
0·30	0·086	0·103	0·129	0·168	0·195	0·081	
0·40	0·085	0·102	0·127	0·166	0·193	0·080	
0·50	0·081	0·099	0·122	0·158	0·179	0·076	
0·60	0·075	0·090	0·112	0·145	0·157	0·070	
0·70	0·065	0·077	0·096	0·124	0·129	0·064	
0·80	0·052	0·059	0·074	0·097	0·098	0·054	
0·90	0·036	0·038	0·047	0·065	0·063	0·044	
r_L	0·011	0·0115	0·0135	0·027	0·062		
r_T	0·011	0·0076	0·010	0·017	0·027		

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* y_1 = distance above chord; y_2 = distance below chord.

TABLE 2

Blade Angles and Chord Lengths of the Standard Sections; Maximum Blade Width/tip radius = 0·164

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TABLE 2

Blade Angles and Chord Lengths of the Standard Sections ; Maximum Blade Width/tip radius = 0·164

Section		FF		EE		DD		CC		BB		
Radial distance/tip radius		0·9		0·75		0·6		0·45		0·3		0·7
Chord length/tip radius		0·1016		0·1446		0·1640		0·1626		0·1350		0·155
Description.	Pitch diameter ratio at 0·7R.	Blade angle (geometrical).	Difference from constant geometrical pitch.	Blade angle.	Difference from constant geometrical pitch.	Blade angle.	Difference from constant geometrical pitch.	Blade angle.	Difference from constant geometrical pitch.	Blade angle.	Difference from constant geometrical pitch.	Blade angle.
Constant geometrical pitch ..	0·3	6° 0′	—	7° 15′	—	9° 0′	—	12° 0′	—	17° 36′	—	7° 46′
Constant geometrical pitch ..	0·5	10° 0′	—	12° 0′	—	14° 48′	—	19° 24′	—	27° 54′	—	12° 49′
Constant geometrical pitch ..	0·7	13° 54′	—	16° 30′	—	20° 24′	—	26° 18′	—	36° 36′	—	17° 40′
Constant geometrical pitch ..	1·0	19° 30′	—	23° 0′	—	27° 54′	—	35° 18′	—	46° 42′	—	24° 28′
P/D 1·5 rotated	1·0	18° 10′	—1° 20′	22° 40′	—0° 20′	28° 40′	+0° 46′	36° 52′	+1° 34′	47° 58′	+1° 16′	24° 28′
P/D 1·5 rotated	1·25	23° 20′	—0° 31′	27° 50′	—0° 7′	33° 50′	+0° 16′	42° 2′	+0° 32′	53° 8′	+0° 8′	29° 38′
Constant geometrical pitch ..	1·5	28° 0′	—	32° 30′	—	38° 30′	—	46° 42′	—	57° 48′	—	34° 19′
P/D 1·5 rotated	1·8	33° 1′	+0° 31′	37° 31′	+0° 9′	43° 31′	—0° 12′	51° 43′	—0° 9′	62° 49′	+0° 26′	39° 20′
P/D 1·5 rotated	2·2	38° 44′	+0° 50′	43° 14′	+0° 11′	49° 14′	—0° 12′	57° 26′	+0° 9′	68° 32′	+1° 42′	45° 2′
P/D 1·5 rotated	2·5	42° 22′	+0° 53′	46° 52′	+0° 9′	52° 52′	—0° 8′	61° 4′	+0° 32′	72° 10′	+2° 49′	48° 40′
P/D 1·0 rotated	0·5	7°51′	−2° 9′	11° 31′	−0° 39′	16° 15′	+1° 27′	23° 39′	+4° 15′	35° 3′	7° 9′	12° 49′
	1·8	34° 22′	+1° 52′	37° 52′	+0° 30′	42° 46′	−0° 57′	50° 10′	−1° 42′	61° 34′	−0° 41′	39° 20′
	2	40° 4′	+2° 10′	43° 34′	+0° 31′	48° 28′	−0° 58′	55° 52′	−1° 25′	67° 16′	+0° 26′	45° 2′

TABLE 3

Summary of Principal Performance Data

Description.		Pitch diameter ratio at 0·7R.	Maximum efficiency per cent.	J at maximum efficiency.	Efficiency at J 0·7 times that of maximum efficiency.	J at zero thrust.		$V_{(\text{max. eff.})} / V_{(\text{stalling})}$ §5.5.
						Observed.	Calculated §5.2.	
2-blader constant pitch	..	0·3	56·6	0·285	50·5	0·467	0·467	
2-blader constant pitch	..	0·5	70·3	0·460	62·8	0·674	0·665	
2-blader constant pitch	..	0·7	77·6	0·660	71·5	0·885	0·877	
2-blader constant pitch	..	1·0	84·1	0·905	74·4	1·209	1·201	
2-blader P/D 1·5 rotated	..	1·0	84·2	0·935	76·6	1·202		
2-blader P/D 1·5 rotated	..	1·25	87·6	1·16	78·5	1·486	1·479	3·9
2-blader constant pitch	..	1·5	88·4	1·33	78·5	1·760	1·763	2·3
2-blader P/D 1·5 rotated	..	1·8	89·7	1·65	80·7	2·112	2·110	$2 \cdot 2_5$
2-blader P/D 1·5 rotated	..	2·2	89·4	2·01	81·4	2·580	2·590	1·9
2-blader P/D 1·5 rotated	..	2·5	89·8	2·34	82·7	2·970	2·962	$1 \cdot 8_5$
4-blader constant pitch	..	0·3	47·7	0·280	40·0	0·463	0·467	
4-blader constant pitch	..	0·5	63·2	0·455	55·7	0·667	0·665	
4-blader constant pitch	..	0·7	73·6	0·660	65·7	0·881	0·877	
4-blader constant pitch	..	1·0	80·9	0·945	71·8	1·205	1·201	
4-blader P/D 1·5 rotated	..	1·0	79·1	0·955	71·6	1·204		
4-blader P/D 1·5 rotated	..	1·25	82·8	1·20	74·4	1·480	1·479	5·1
4-blader constant pitch	..	1·5	84·8	1·38	74·8	1·750	1·763	$3 \cdot 0_5$
4-blader P/D 1·5 rotated	..	1·8	86·4	1·64	76·8	2·095	2·110	2·5
4-blader P/D 1·5 rotated	..	2·2	86·5	2·06	79·0	2·585	2·590	2·2
4-blader P/D 1·5 rotated	..	2·5	85·8	2·32	78·7	2·940	2·962	2·0

TABLE 4

Envelope of Efficiency Curves

V/*n*D.	Efficiency per cent.	
	2-Bladed Airscrews.	4-Bladed Airscrews.
0·2	50·2	40·8
0·3	60·6	53·0
0·4	69·1	62·6
0·5	74·2	68·4
0·6	77·8	72·3
0·7	80·5	75·2
0·8	82·7	77·4
1·0	85·6	80·8
1·2	87·6	83·3
1·4	88·8	85·1
1·6	89·3	86·3
1·8	89·7	86·8
2·0	89·7	86·7
2·2	89·7	86·3
2·4	89·6	85·5

TABLE 5

Smoothed performance data at " standard " Reynolds number

(Effective velocity 200 ft./sec. at radius 0·7).
Maximum blade width = 0·164 times tip radius.
Blade angles and chord lengths given in Table 2.

2-Bladed Airscrew No. 1. (P/D 0·3)

V/*n*D = J	k_T	k_Q	η %
0·081*	0·0568	0·00289	25·3
0·20	0·0442	0·00281	50·1
0·24	0·0388	0·00272	54·4
0·28	0·0328	0·00258	56·6
0·32	0·0266	0·00243	55·8
0·36	0·0201	0·00223	51·6
0·40	0·0130	0·00200	41·4
0·44	0·0053	0·00172	21·6
0·46	0	0·00152	0
0·52	—0·0112	0·00105	—
0·56	—0·0204	0·00048	—

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* The first entry for each screw corresponds to the condition in which the tunnel fan is at rest (tunnel static).

TABLE 5—*continued*

2-Bladed Airscrew No. 2. (P/D 0·5)

V/*n*D = J	k_T	k_Q	η %
0·087	0·0850	0·00518	22·7
0·26	0·0688	0·00508	56·0
0·30	0·0634	0·00500	60·6
0·35	0·0563	0·00480	65·3
0·40	0·0487	0·00452	68·6
0·45	0·0407	0·00415	70·3
0·50	0·0327	0·00374	69·6
0·55	0·0244	0·00326	65·6
0·60	0·0151	0·00269	53·6
0·65	0·0050	0·00208	24·9
0·674	0	0·00174	0
0·70	—0·0058	0·00134	—
0·75	—0·0170	0·00052	—

2-Bladed Airscrew No. 3. (P/D 0·7)

0·124	0·1090	0·00780	27·6
0·25	0·0974	0·00791	49·0
0·30	0·0914	0·00788	55·4
0·35	0·0853	0·00778	61·1
0·40	0·0791	0·00761	66·2
0·45	0·0726	0·00737	70·6
0·50	0·0656	0·00708	73·8
0·55	0·0584	0·00674	76·0
0·60	0·0508	0·00630	77·1
0·65	0·0430	0·00573	77·6
0·70	0·0348	0·00501	77·4
0·75	0·0267	0·00425	75·0
0 80	0·0171	0·00344	63·2
0·85	0·0070	0·00251	37·8
0·885	0	0·00185	0
0·95	—0·0135	0·00045	—

TABLE 5—*continued*

2-Bladed Airscrew No. 4. (P/D 1·0)

V/nD	k_T	k_Q	η %
0·153	0·1295	0·01195	26·4
0·30	0·1215	0·01250	46·5
0·35	0·1185	0·01260	52·4
0·40	0·1155	0·01265	58·2
0·45	0·1110	0·01270	62·6
0·50	0·1060	0·01270	66·5
0·55	0·1010	0·01260	70·3
0·60	0·0950	0·01245	73·0
0·65	0·0890	0·01220	75·5
0·70	0·0830	0·01185	78·0
0·75	0·0770	0·01140	80·6
0·80	0·0700	0·01085	82·2
0·85	0·0630	0·01025	83·2
0·90	0·0555	0·00945	84·1
0·95	0·0475	0·00860	83·6
1·00	0·0390	0·00755	82·2
1·05	0·0305	0·00645	79·0
1·10	0·0210	0·00520	70·6
1·15	0·0115	0·00385	54·6
1·209	0	0·00230	0
1·25	—0·0080	0·00090	—

2-Bladed Airscrew No. 5 twisted to P/D 1·0

0·17	0·126	0·0122	33·1
0·30	0·1178	0·0124	45·4
0·35	0·1137	$0{\cdot}0124_5$	50·8
0·40	0·1110	$0{\cdot}0124_5$	56·8
0·45	0·1076	$0{\cdot}0124_5$	62·0
0·50	0·1034	0·0124	66·3
0·55	0·0990	$0{\cdot}0123_5$	70·2
0·60	0·0936	0·0122	73·4
0·65	0·0877	$0{\cdot}0119_5$	76·0
0·70	0·0816	$0{\cdot}0115_5$	78·7
0·75	0·0752	$0{\cdot}0111_5$	80·5
0·80	0·0686	0·0107	81·7
0·85	0·0616	$0{\cdot}0100_5$	82·9
0·90	0·0544	$0{\cdot}0092_5$	84·4
0·95	0·0465	$0{\cdot}0083_5$	84·2
1·00	0·0383	$0{\cdot}0075_5$	80·8
1·05	0·0298	0·0063	79·0
1·10	0·0203	$0{\cdot}0050_5$	70·4
1·15	0·0105	$0{\cdot}0037_5$	51·2
1·202	0	0·0023	0

TABLE 5—*continued*

2-Bladed Airscrew No. 5 twisted to P/D 1·25

V/nD	k_T	k_Q	η %
0·17	0·1321	0·0172	24·4
0·30	0·1326	0·0166	38·2
0·35	0·1323	$0{\cdot}0164_5$	44·8
0·40	0·1302	0·0166	50·0
0·50	0·1236	0·0169	58·3
0·60	0·1181	0·0170	66·4
0·70	0·1110	0·0170	72·8
0·75	0·1068	0·0168	75·9
0·80	0·1012	$0{\cdot}0165_5$	77·9
0·85	0·0956	$0{\cdot}0161_5$	80·1
0·90	0·0900	$0{\cdot}0156_5$	82·4
0·95	0·0838	$0{\cdot}0151_5$	83·6
1·00	0·0774	0·0145	85·0
1·05	0·0712	0·0138	86·2
1·10	0·0643	$0{\cdot}0129_5$	87·0
1·15	0·0575	0·0120	87·6
1·20	0·0500	$0{\cdot}0109_5$	87·2
1·25	0·0421	0·0098	85·4
1·30	0·0338	$0{\cdot}0084_5$	82·8
1·35	0·0251	$0{\cdot}0070_5$	76·5
1·40	0·0165	0·0055	56·6
1·486	0	0·0026	0

2-Bladed Airscrew No. 5 (P/D 1·5)

0·19	0·1310	0·0244	17·1
0·30	0·1330	0·0227	28·1
0·40	0·1340	0·0218	39·3
0·50	0·1330	0·0215	49·3
0·60	0·1330	0·0214	59·4
0·70	0·1310	0·0217	67·3
0·80	0·1265	0·0220	73·2
0·90	0·1185	0·0220	77·2
1·00	0·1085	$0{\cdot}0213_5$	81·0
1·10	0·0975	$0{\cdot}0203_5$	83·9
1·20	0·0855	$0{\cdot}0189_5$	86·2
1·30	0·0730	0·0171	88·4
1·40	0·0590	$0{\cdot}0149_5$	87·9
1·50	0·0445	0·0123	86·4
1·60	0·0285	$0{\cdot}0091_5$	79·4
1·70	0·0110	0·0054	55·1
1·76	0	0·0030	0

TABLE 5—*continued*

2-Bladed Airscrew No. 5 twisted to P/D 1·8

V/*n*D	k_T	k_Q	η %
0·19	0·131	0·0314	13·3
0·30	$0{\cdot}131_5$	0·0305	20·7
0·40	0·132	0·0296	28·5
0·50	0·134	0·0282	38·0
0·60	0·133	0·0273	46·7
0·70	0·133	0·0271	55·0
0·80	0·136	0·0273	63·5
0·90	0·139	0·0277	71·7
1·00	0·1349	0·0283	75·9
1·10	0·1276	0·0282	79·2
1·20	0·1186	0·0276	82·1
1·30	0·1086	0·0267	84·2
1·40	0·0985	0·0254	86·5
1·50	0·0875	0·0237	88·2
1·60	0·0763	0·0217	89·6
1·70	0·0639	0·0193	89·6
1·80	0·0506	0·0164	88·4
1·90	0·0356	0·0129	83·4
2·00	0·0195	0·0090	69·0
2·112	0	0·0041	0

2-Bladed Airscrew No. 5 twisted to P/D 2·2

0·19	0·124	0·0395	10·0
0·30	0·127	0·0393	15·4
0·40	0·128	0·0386	21·2
0·50	0·129	0·0377	27·3
0·60	0·128	0·0367	33·4
0·70	0·126	0·0358	39·4
0·80	0·126	0·0350	46·1
0·90	0·130	0·0344	54·5
1·00	0·134	0·0346	62·0
1·10	0·140	0·0356	69·2
1·15	0·146	0·0366	74·1
1·20	$0{\cdot}148_5$	0·0368	77·2
1·30	0·142	0·0371	79·2
1·40	0·135	0·0370	81·4
1·50	0·127	0·0365	83·1
1·60	0·119	0·0356	85·2
1·70	0·110	0·0346	86·1
1·80	0·1005	0·0328	87·8
1·90	0·0905	0·0308	88·8
2·00	0·0800	0·0285	89·4
2·10	0·0689	0·0259	89·0
2·20	0·0567	0·0227	87·4
2·30	0·0436	0·0190	84·0
2·40	0·0303	0·0150	77·2
2·50	0·0155	0·0102	60·4
2·58	0	0·0062	0
2·60	—0·0010	0·0051	—

TABLE 5—*continued*

2-Bladed Airscrew No. 5 twisted to P/D 2·5

V/nD	k_T	k_Q	η %
0·19	0·120	0·0447	8·1
0·30	0·121	0·0445	13·0
0·40	0·122	0·0443	17·6
0·50	0·123	0·0434	22·7
0·60	0·124	0·0426	27·9
0·70	0·124	0·0420	33·0
0·80	0·124	0·0413	38·4
0·90	0·127	0·0407	44·9
1·00	0·130	0·0397	52·3
1·10	0·132	0·0397	58·5
1·20	0·137	0·0407	64·6
1·30	0·144	0·0422	70·9
1·40	0·150	0·0434	77·4
1·45	0·1518	0·0439	79·8
1·50	$0{\cdot}149_5$	0·0444	80·3
1·60	0·143	0·0445	81·8
1·70	0·136	0·0440	83·6
1·80	$0{\cdot}128_5$	0·0433	85·0
1·90	$0{\cdot}120_5$	0·0422	86·4
2·00	0·1118	0·0407	87·4
2·10	0·1031	0·0390	88·2
2·20	0·0942	0·0369	89·5
2·30	0·0847	0·0346	89·6
2·40	0·0748	0·0319	89·6
2·50	0·0641	0·0288	88·6
2·60	0·0522	0·0252	85·7
2·70	0·0398	0·0210	81·5
2·80	0·0256	0·0166	68·7
2·90	0·0117	0·0116	46·3
2·97	0	0·0080	0

4-Bladed Airscrew No. 1. (P/D 0·3)

0·108	0·0840	0·00546	26·4
0·23	0·0613	0·00504	44·5
0·26	0·0549	0·00485	46·9
0·30	0·0457	0·00457	47·7
0·34	0·0354	0·00424	45·2
0·38	0·0245	0·00388	38·2
0·42	0·0130	0·00349	24·9
0·463	0	0·00300	0
0·50	—0·0118	0·00253	—
0·54	—0·0248	0·00197	—
0·58	—0·0385	0·00138	—

TABLE 5—*continued*

4-Bladed Airscrew No. 2. (P/D 0·5)

V/*n*D	k_T	k_Q	η %
0·134	0·1328	0·00977	29·0
0·26	0·1103	0·00935	48·8
0·30	0·1015	0·00903	53·7
0·35	0·0898	0·00856	58·4
0·40	0·0778	0·00801	61·9
0·45	0·0651	0·00737	63·2
0·50	0·0521	0·00663	62·5
0·55	0·0378	0·00578	57·4
0·60	0·0226	0·00481	44·9
0·65	0·0056	0·00377	15·4
0·667	0	0·00335	0
0·70	—0·0122	0·00252	—
0·75	—0·0315	0·00120	—

4-Bladed Airscrew No. 3. (P/D 0·7)

0·169	0·1752	0·01527	30·9
0·25	0·1615	0·01502	42·8
0·30	0·1525	0·01477	49·4
0·35	0·1431	0·01444	55·1
0·40	0·1329	0·01401	60·4
0·45	0·1217	0·01348	64·8
0·50	0·1102	0·01284	68·3
0·55	0·0982	0·01212	71·0
0·60	0·0855	0·01122	72·9
0·65	0·0723	0·01015	73·6
0·70	0·0587	0·00894	73·2
0·75	0·0440	0·00767	69·1
0·80	0·0278	0·00622	56·9
0·85	0·0109	0·00457	32·3
0·881	0	0·00354	0
0·95	—0·0250	0·00105	—

TABLE 5—*continued*

4-Bladed Airscrew No. 4. (P/D 1·0)

V/*n*D	k_T	k_Q	η %
0·20	0·233	$0\cdot0240_5$	30·8
0·30	$0\cdot218_5$	0·0244	42·8
0·35	$0\cdot210_5$	0·0245	47·8
0·40	$0\cdot201_5$	0·0244	52·6
0·45	$0\cdot192_5$	0·0242	56·9
0·50	0·183	0·0239	60·9
0·55	0·173	0·0235	64·5
0·60	0·163	$0\cdot0229_5$	67·8
0·65	$0\cdot152_5$	0·0223	70·9
0·70	$0\cdot142_5$	0·0215	73·8
0·75	$0\cdot131_5$	0·0206	76·2
0·80	0·120	0·0195	78·5
0·85	$0\cdot107_5$	0·0183	79·4
0·90	$0\cdot094_5$	$0\cdot0168_5$	80·4
0·95	$0\cdot081_5$	$0\cdot0152_5$	80·9
1·00	$0\cdot067_5$	$0\cdot0134_5$	79·9
1·05	0·052	0·0114	76·2
1·10	$0\cdot036_5$	0·0091	70·1
1·15	0·020	$0\cdot0068_5$	53·4
1·205	0	0·0040	0
1·30	—0·035	—0·0014	—

4-Bladed Airscrew No. 5 twisted to P/D 1·0

0·22	$0\cdot227_5$	$0\cdot0240_5$	33·1
0·30	0·217	0·0243	42·7
0·35	0·209	0·0243	47·9
0·40	$0\cdot199_5$	0·0242	52·6
0·45	$0\cdot190_5$	0·0240	56·9
0·50	0·181	0·0237	60·8
0·55	0·171	$0\cdot0233_5$	64·2
0·60	0·161	$0\cdot0227_5$	67·6
0·65	$0\cdot150_5$	$0\cdot0220_5$	70·7
0·70	0·140	0·0213	73·2
0·75	0·129	0·0204	75·6
0·80	$0\cdot117_5$	$0\cdot0193_5$	77·3
0·85	0·105	0·0182	78·0
0·90	0·092	0·0168	78·5
0·95	$0\cdot079_5$	0·0152	79·1
1·00	0·066	$0\cdot0134_5$	78·2
1·05	$0\cdot050_5$	0·0116	72·8
1·10	0·035	0·0095	64·5
1·15	0·018	$0\cdot0072_5$	45·5
1·204	0	0·0045	0
1·25	—$0\cdot017_5$	$0\cdot0020_5$	—

TABLE 5—*continued*

4-Bladed Airscrew No. 5 twisted to P/D 1·25

V/*n*D	k_T	k_Q	η %
0·252	$0{\cdot}251_5$	0·0322	31·4
0·40	0·244	0·0328	47·4
0·50	0·231	$0{\cdot}0329_5$	55·8
0·60	$0{\cdot}214_5$	0·0328	62·5
0·70	0·196	0·0320	68·2
0·80	0·176	0·0308	72·8
0·90	$0{\cdot}155_5$	0·0290	77·0
1·00	$0{\cdot}134_5$	0·0266	80·5
1·10	$0{\cdot}111_5$	0·0238	82·0
1·20	0·086	$0{\cdot}0198_5$	82·8
1·25	0·073	$0{\cdot}0177_5$	82·0
1·30	0·059	0·0155	79·0
1·35	$0{\cdot}044_5$	$0{\cdot}0130_5$	73·1
1·40	$0{\cdot}027_5$	0·0103	59·9
1·45	$0{\cdot}010_5$	0·0073	33·5
1·48	0	0·0054	0
1·55	—0·035	0·0006	—

4-Bladed Airscrew No. 5. (P/D 1·5)

0·25	$0{\cdot}240_5$	0·0428	22·4
0·40	$0{\cdot}251_5$	0·0420	38·1
0·50	0·261	0·0418	49·7
0·55	0·262	0·0419	54·8
0·60	$0{\cdot}255_5$	0·0422	57·8
0·70	$0{\cdot}241_5$	0·0425	63·4
0·80	0·226	0·0423	68·1
0·90	0·209	0·0414	72·3
1·00	$0{\cdot}190_5$	0·0399	76·0
1·10	0·171	0·0377	79·4
1·20	$0{\cdot}150_5$	0·0350	82·1
1·30	0·129	0·0317	84·2
1·40	$0{\cdot}105_5$	0·0277	84·8
1·50	0·080	0·0228	83·8
1·60	$0{\cdot}050_5$	0·0170	75·6
1·70	0·017	0·0108	42·5
1·75	0	0·0073	0
1·85	—0·035	—0·0002	—

TABLE 5—*continued*

4-Bladed Airscrew No. 5 twisted to P/D 1·8

V/*n*D	k_T	k_Q	η %
0·25	0·247	0·0560	17·6
0·40	0·246	0·0544	28·8
0·50	0·246	0·0527	37·2
0·60	0·251	0·0527	45·5
0·70	$0\cdot263_5$	0·0534	55·0
0·75	$0\cdot271_5$	0·0538	60·2
0·80	$0\cdot272_5$	0·0540	64·3
0·85	0·268	0·0541	67·0
0·90	0·260	0·0542	68·7
1·00	0·244	0·0539	72·1
1·10	0·229	0·0532	75·3
1·20	$0\cdot213_5$	0·0520	78·4
1·30	$0\cdot196_5$	0·0499	81·5
1·40	$0\cdot177_5$	0·0473	83·6
1·50	$0\cdot157_5$	0·0441	85·2
1·60	$0\cdot136_5$	0·0403	86·3
1·70	$0\cdot113_5$	0·0356	86·3
1·80	0·089	0·0301	84·7
1·90	0·062	0·0235	79·8
2·00	0·032	0·0163	62·5
$2\cdot09_5$	0	0·0085	0
2·20	—0·037	—0·0010	—

4-Bladed Airscrew No. 5 twisted to P/D 2·2

0·26	$0\cdot240_5$	0·0706	14·0
0·40	0·241	0·0706	21·8
0·60	0·237	0·0682	33·2
0·80	$0\cdot241_5$	0·0662	46·5
0·90	0·257	0·0666	55·3
1·00	0·272	0·0690	62·8
1·10	0·279	0·0707	69·0
1·20	0·273	0·0714	73·0
1·30	$0\cdot261_5$	0·0715	75·7
1·40	0·248	0·0708	78·1
1·50	$0\cdot233_5$	0·0695	80·2
1·60	$0\cdot217_5$	0·0675	82·1
1·70	0·201	0·0648	83·9
1·80	$0\cdot183_5$	0·0617	85·2
1·90	0·165	0·0579	86·2
2·00	0·146	0·0538	86·4
2·10	0·126	0·0487	86·5
2·20	0·104	0·0429	85·0
2·30	$0\cdot080_5$	0·0364	81·0
2·40	$0\cdot054_5$	0·0287	72·5
2·50	0·026	0·0199	52·0
$2\cdot58_5$	0	0·0118	0
2·70	—0·037	0·0006	—

TABLE 5—*continued*

4-Bladed Airscrew No. 5 twisted to P/D 2·5

V/nD	k_T	k_Q	η %
0·27	0·234$_5$	0·0803	12·6
0·30	0·235$_5$	0·0806	14·0
0·40	0·238	0·0809	18·7
0·50	0·237	0·0800	23·6
0·60	0·233	0·0788	28·2
0·70	0·230	0·0780	32·9
0·80	0·231	0·0774	38·0
0·90	0·235$_5$	0·0768	44·0
1·00	0·247$_5$	0·0764	51·6
1·05	0·257$_5$	0·0774	55·6
1·10	0·267	0·0780	60·0
1·20	0·277	0·0812	65·2
1·25	0·279	0·0826	67·2
1·30	0·283$_5$	0·0835	70·3
1·35	0·286	0·0842	73·0
1·40	0·283	0·0846	74·6
1·45	0·277$_5$	0·0850	75·4
1·50	0·272	0·0850	76·5
1·60	0·259$_5$	0·0845	78·2
1·70	0·246	0·0832	80·0
1·80	0·231$_5$	0·0813	81·6
1·90	0·217	0·0791	83·0
2·00	0·201$_5$	0·0763	84·0
2·10	0·185$_5$	0·0730	85·0
2·20	0·168$_5$	0·0690	85·5
2·30	0·151	0·0644	85·8
2·40	0·132$_5$	0·0592	85·5
2·50	0·113	0·0535	84·0
2·60	0·091$_5$	0·0469	80·8
2·70	0·068$_5$	0·0394	74·8
2·80	0·041$_5$	0·0307	60·2
2·90	0·012$_5$	0·0209	27·6
2·94	0	0·0167	0
3·10	—0·048	—0·0017	—

APPENDIX

Further Details of Apparatus and Corrections to Experimental Results

A.1. *Rotational Speed. Maxwell's Capacity Bridge.*—A novel method was suggested by Mr. Relf of indicating and determining the rotational speed of the airscrew. This method (described in Clerk Maxwell's " Electricity and Magnetism ", section 775, p. 421) is based on the charging and discharging of a condenser by means of a commutator rotating with the airscrew. The apparatus consists of an ordinary Wheatstone Bridge of the post office box type, with a 12-volt accumulator and sensitive moving coil galvanometer. In the arm of the bridge which normally contains the unknown resistance there is connected a standard capacity of 0·1 microfarads in series with a commutator. The arrangement of the commutator is such that the condenser is alternately charged through the bridge and then short circuited; it is recharged four times for each revolution of the airscrew. Thus to a first approximation the average current between the two terminals of the bridge is equal to the potential difference times the capacity of the condenser times the number of reversals per second, and so the reciprocal of (capacity times number of reversals) is equivalent to an unknown resistance and is determined in the usual way by adjusting the resistances of the remaining arms of the bridge until the reading of the galvanometer is zero. To this approximation the rotational speed of the airscrew is inversely proportional to the resistance and can be determined absolutely if capacity and resistances are known. The more exact theory is given by Clerk Maxwell and involves a small correction to the above result, but in practice the instrument was calibrated directly against the usual revolution counter and stopwatch. The approximate value of resistances used was 1,000 ohms in the variable arm and 10 ohms and 1,000 ohms in the fixed arms of the bridge, for a rotational speed of about 1,500 r.p.m., so that the equivalent resistance of the unknown arm was 100,000 ohms. When working satisfactorily this apparatus gave an instantaneous reading of rotational speed to well within one part in a thousand.

A.2. *Tunnel Velocity Guage. Open Jet Tunnel.*—In the No. 3, 7-ft. tunnel the ordinary automatic control of tunnel speed was employed. In the open jet tunnel a new type of pressure guage similar to that designed by Mr. Relf for the Compressed Air Tunnel was used. This consisted of two equal brass cylinders containing xylol connected by a horizontal tube joining their lowest points and supported on an ordinary gravity balance. A tube from the tunnel datum pressure point was connected to the upper end of one cylinder through a section of rubber tubing lying along the axis of the balance, the other cylinder being open to the atmosphere. The air pressure corresponding to the tunnel velocity produced a displacement of fluid between the two cylinders and the weight of this head of fluid was counterbalanced by weights in the scale-pan of the balance. The immediate object of using this type of pressure guage was to cover the whole range of tunnel speed for which the maximum pressure amounted to about 9 in. of water. A further advantage was that the velocity balance could be made to give an optical indication by means of a mirror and lamp which was visible to the observer on the thrust and torque balances.

A.3. *Blade Angle Setting.*—The angles of individual blades of each airscrew were adjusted by means of a bubble protractor carrying a straight edge which was clipped on to the flat undersurface of the section at a radius of 0·6R, the airscrew being mounted on a spindle which had been adjusted to be accurately vertical. The protractor could be read to an accuracy of 1′ or 2′ and the

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blade angle could be set to within 3′ or 4′. In a few cases slight changes of the angle of one blade of the order of 3′ or 4′ occurred during the test of an airscrew.

A.4. *Tunnel Velocity Correction.*—In the 7-ft. No. 3 closed tunnel the usual correction for tunnel interference was applied according to the formula of McKinnon Wood and Harris (R. & M. 662) quoted in R. & M. 829. The formula is

$$\left(1 - \frac{V}{V_0}\right) = \frac{yz}{2\sqrt{1 + 2y}}$$

where $y = \frac{T}{\pi R^2 \varrho V_0^2}$ and z is the ratio of the area of the airscrew disc to the cross sectional area of the tunnel.

In the open jet tunnel both theory and previous experiment have suggested that the correction for tunnel interference should be very small for a 3-ft. screw in a 7 × 9 ft. jet and accordingly no correction was applied. Repeat observations at the same Reynolds number in the two tunnels have shown that there is a slight discrepancy between the results which increases to ½ or 1 per cent.* at high values of thrust coefficient in a typical case. To bring the two curves into agreement it would be necessary to assume a small positive velocity correction for the open jet tunnel or to increase the correction for the closed tunnel by one quarter of the theoretical value. There is some evidence to suggest that the latter method would be more correct as the theoretical velocity correction for the closed tunnel tends to under-estimate the correction because the effective cross sectional area of the tunnel is less than the actual area due to the boundary effect of the walls. In view of the smallness of the discrepancy the recorded results refer to actual observation in the *closed tunnel* for pitch values from 0·3 to 1·0 and to the *open jet tunnel* for pitch values 1·0 to 2·5.

As a possible source of error in the open jet tunnel it was suggested that, owing to the high power factor, the slipstream of the model screw might be expected to persist round the return circuit and lead to a lack of uniformity in the jet. In order to check the possibility of this effect, measurements of total head were made across a section of the tunnel just in front of the airscrew when the latter was running. It was found that even at the static condition (the tunnel fan at rest) the total head was sensibly constant right across the section in front of the model screw and its magnitude corresponded closely to the value of the tunnel velocity as determined by the tunnel guage. The effect anticipated should therefore be negligible for all other working conditions of the screw.

In both tunnels the effective velocity through the airscrew was measured with a pitot tube over the area of the airscrew disc but with the airscrew removed and replaced by a dummy boss. The cylindrical guard body was designed to have a sufficient extension to the front of the airscrew to produce a sensibly uniform velocity distribution over this area with the airscrew removed. There was, however, a reduction of velocity near the body and in the wake of its supports. An extensive velocity exploration was carried out over the whole of the space occupied by the airscrew disc, with the pitot mounted on the dummy boss so as to be easily rotatable about the airscrew axis. Measurements were taken at four radii; and from a curve of velocity against angular position, the mean value at each radius was obtained by graphical integration. The results showed that the various supports reduced the mean velocity by ¼ per cent. and that the velocity near the body was some 2 per cent. below the mean over the airscrew disc.

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* This is the percentage change of the radial distance from the origin of a point on the thrust curve.

In order to secure the most logical calibration of tunnel velocity, the accepted value of V was taken as a mean velocity $\overline{V}$ defined by the equation

$$\overline{V}T = \int V dT.$$

where the integral is taken from the calculated thrust grading for a particular high pitched screw near maximum efficiency. This ensures an accurate value of the thrust power in spite of the small variations of V with radius.

A.5. *Rotation of the tunnel stream.*—A possible source of error in the open jet tunnel was a rotation of the air in the return flow from the tunnel fan. A yawmeter exploration in the plane of the screw, similar to the velocity exploration described in A.4, showed that a small rotation of the stream about the axis of the tunnel was present. The ratio of rotational speed (r.p.s.) to tunnel speed (ft./sec.) was found to be of the order 0·001 (approximately independent of radius within the limit of the airscrew disc) at the higher tunnel speeds, but decreased somewhat with decrease of tunnel speed. A correction amounting to less than 1 per cent. in the worst case, was applied to the rotational speed of the airscrew to allow for this defect.

A further yawmeter exploration was carried out at two radii in a plane at the nose of the guard body in front of the airscrew, to ascertain whether the slipstream from the airscrew itself persisted round the return circuit so as to cause an appreciable rotation in the inflow. Observations with a high pitch screw over a large range of torque coefficients showed, however, that the mean rotation round the circle was practically unaffected by the airscrew torque, although small differences of varying sign were observed at different points round the circle.

A.6. *Boss Drag.*—In order to determine the effective thrust on the airscrew blades, it was necessary to make a correction for the thrust on the airscrew boss which might be produced by a difference of pressure in the gaps on the two sides of the boss. This was accomplished by pressure plotting the fixed plates bounding the two gaps. In the original arrangement there was a series of seven pressure holes at varying radii in each plate and these were connected through rubber and composition tubing to an inclined multitube manometer. Readings of the fluid level in the tubes of the manometer were made simultaneously with the thrust and torque readings. The thrust on the boss was then determined by graphical integration of the pressures on the two sides. Attempts were made to determine the general relation between the boss drag coefficient and thrust coefficient but it was found to be more accurate and convenient to determine the boss drag directly for each thrust reading or for a sufficient number of readings to enable a smooth curve to be drawn. In the tests of the very high pitched screws in the open jet tunnel it was discovered that as a result of slight want of symmetry in the apparatus the pressure distribution near the edge of the gaps was not symmetrical about the axis of the screw and it was found necessary to employ additional pressure holes. At certain radii near the edge of the boss three extra holes were made so as to give four holes spaced at equal intervals round the circle and a mean value taken for the graphical integration. Investigation showed that the effect of want of symmetry was only appreciable on the screws of very high pitch, and that previous observations on screws of lower pitch were not appreciably in error.

A.7. *Wires Drag.*—A correction to the thrust reading was, as usual, made for the drag of the stranded cables supporting the airscrew motor and for the drag of the torque wire. In the open jet tunnel it was found necessary to shield the wire connecting the torque arm to the balance on account of vibration. The value of the wires drag correction was calculated and allowance was made for its increase with slipstream velocity on the basis of observations with a pitot tube in the plane of the wires; the effect of slipstream velocity is fortunately small as its calculation is somewhat uncertain.

The results were checked by direct observation of wires drag on the thrust balance with the screw replaced by a dummy boss, in which case the correction for boss drag was included ; also by a direct reading of the wires drag with the boss removed and the gap of the guard body covered over. The agreement between calculated and observed wires drag in the absence of the screw also provided a satisfactory proof that the balance readings were not affected by deformation of the structure of the tunnel such as might quite possibly occur especially in the open jet tunnel.

A.8. *Air Density.*—In all airscrew tests it is necessary to make an accurate correction for variations of air density since the rotational speed of the screw is measured directly while the tunnel speed is deduced from an observation of pressure. The density is determined from the barometric reading and the temperature of the air jet. In the closed tunnel the air temperature was taken by a thermometer projecting just inside the tunnel. In the open jet tunnel the bulb of the thermometer was situated in the turbulent region just inside the edge of the collector. In the latter case the temperature of the jet often rose rapidly when the tunnel was running at high speed and it was necessary to read the thermometer at fairly short intervals while the difference between the temperature in the jet and the temperature in the room was often quite appreciable.

The general accuracy of the correction is verified by the fact that observations taken after large variations of air density are brought into excellent agreement by the application of the correction.

A.9. *Variation of the zero reading on the torque balance with change of wind speed.*—Readings of the torque balance with a dummy boss fitted in place of the airscrew showed that the rotational speed of the boss had no effect on the torque zero. There was, however, a slight change of zero with increasing tunnel speed, probably due to strains in the tunnel structure. This discrepancy was considered of sufficient importance, especially for two-bladed airscrews, to warrant the inclusion of a correction based on the readings with dummy boss fitted.

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3. T.3659. The performance and longitudinal stability of the Puss Moth.—Bryant, Williams and Brown. (To be published.)
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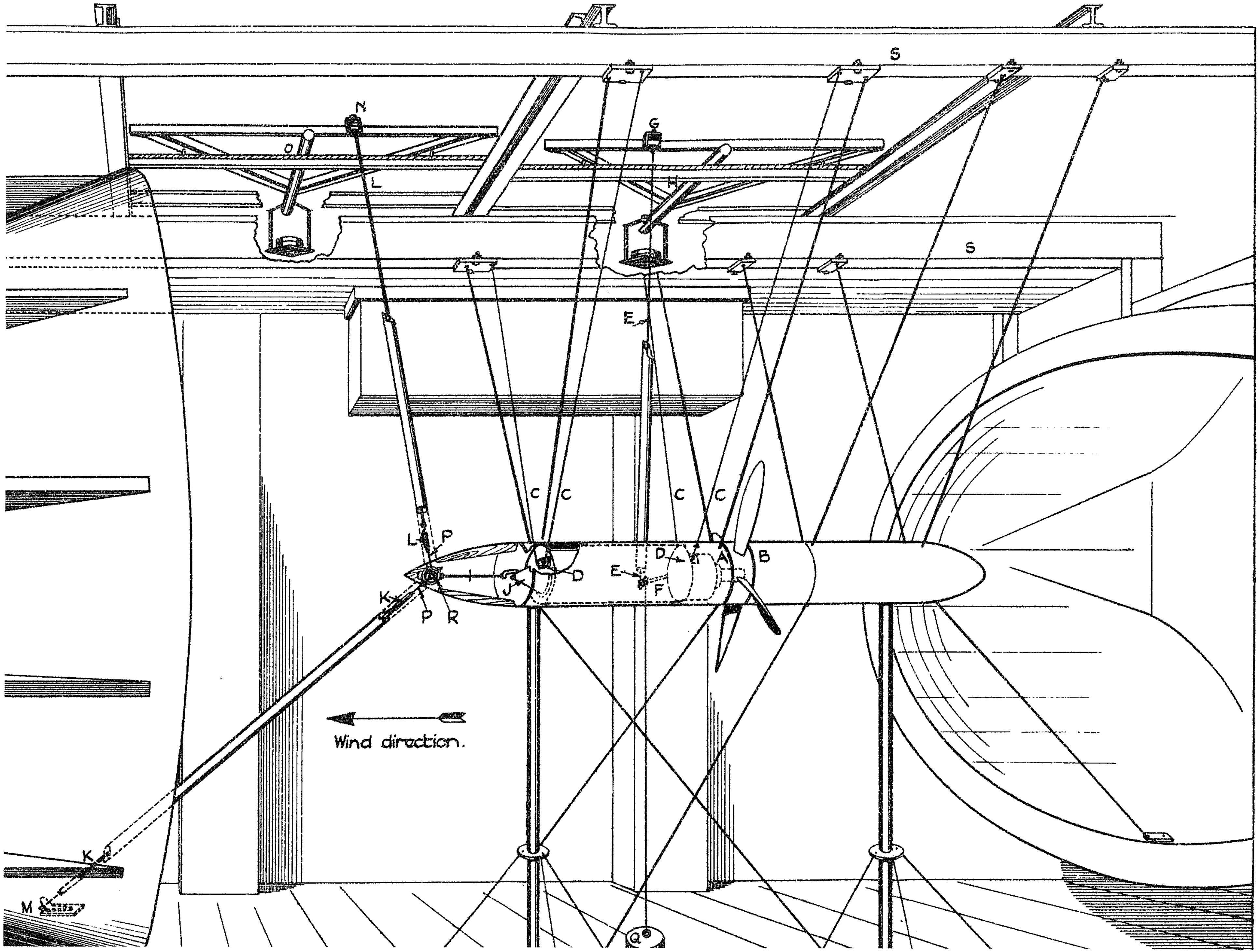
(27440) Wt. 531/972 500 12/35 Hw. G.377/1

S.O. Code No. 23-9999

General Arrangement of Apparatus.

Fig. 1.



Details of 4 Bladed Airscrew No. 5. P/D 1·5.

All dimensions are given as fractions of the radius.

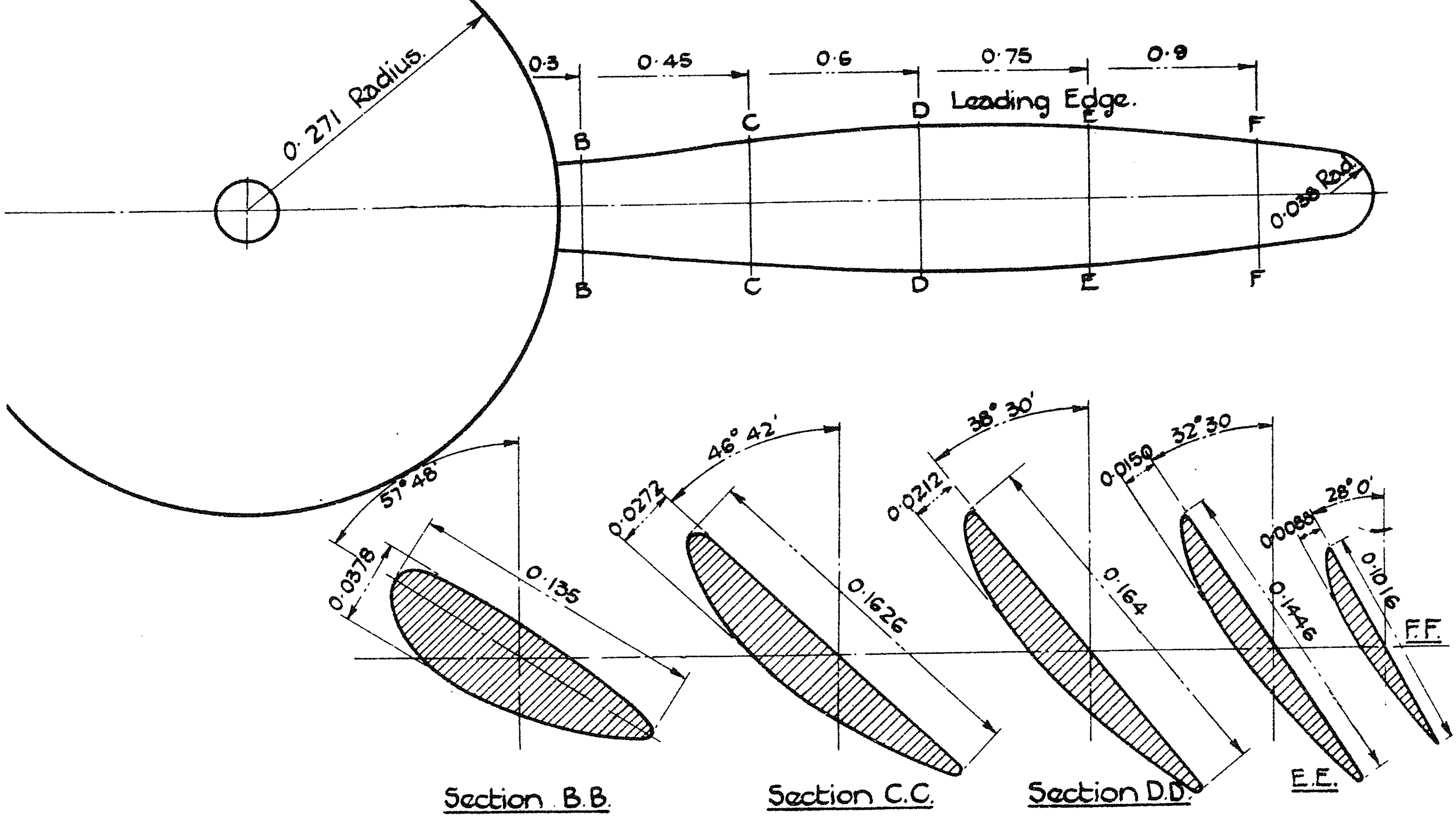


FIG. 2.

THRUST COEFFICIENTS.
2 BLADED AIRSCREWS.

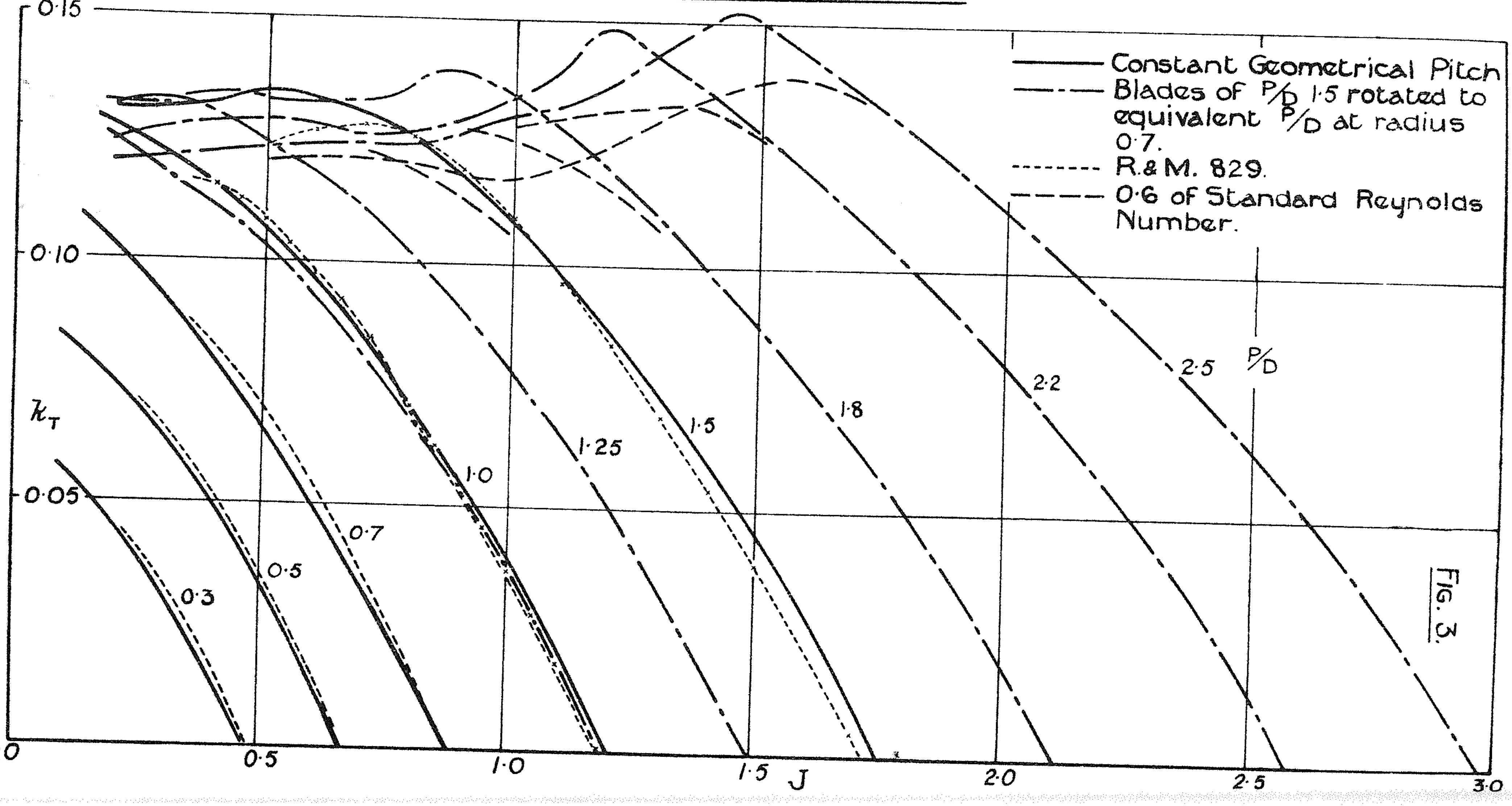


FIG. 3.

THRUST COEFFICIENTS.

FOUR-BLADED AIRSCREWS.

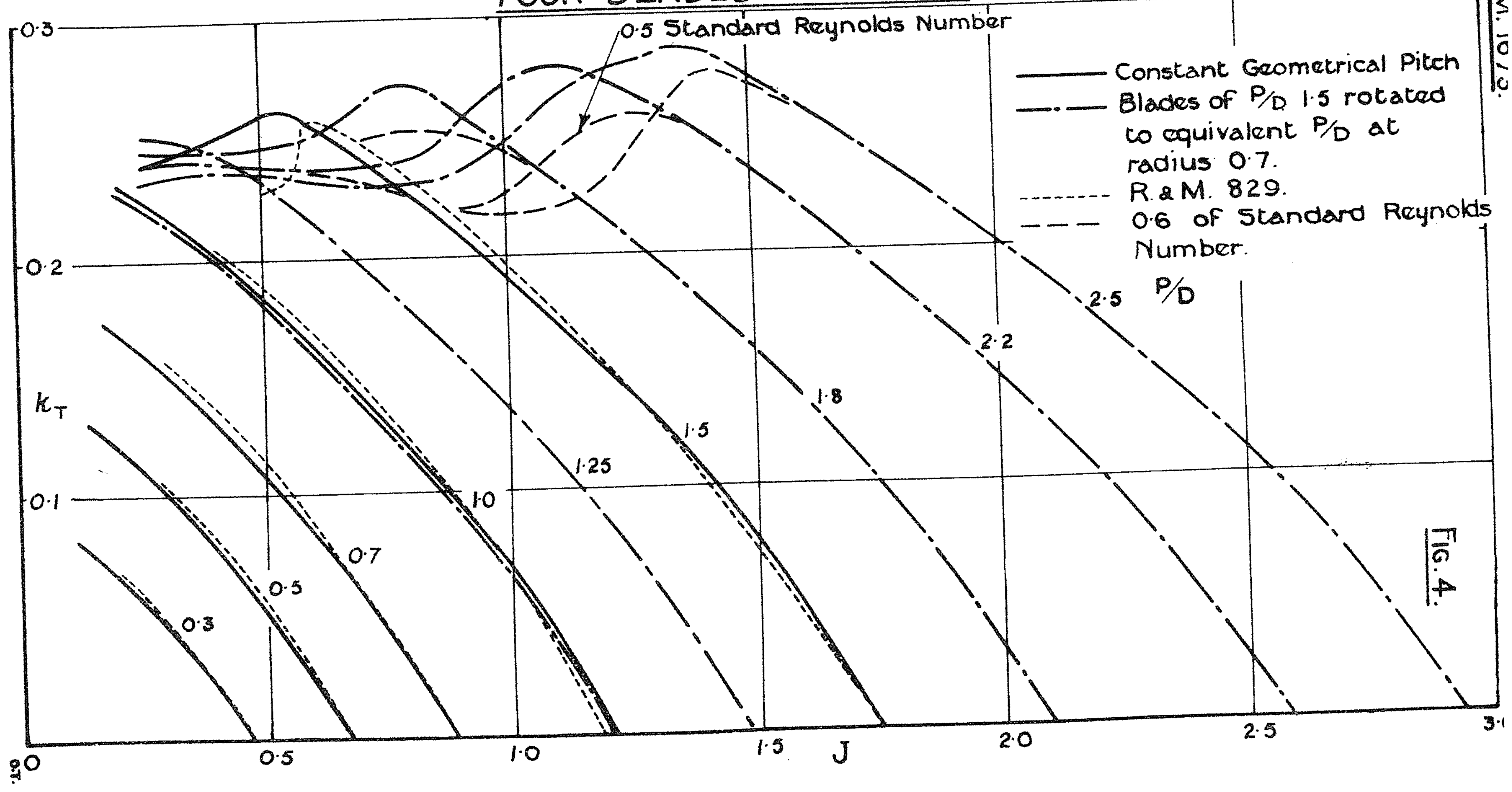
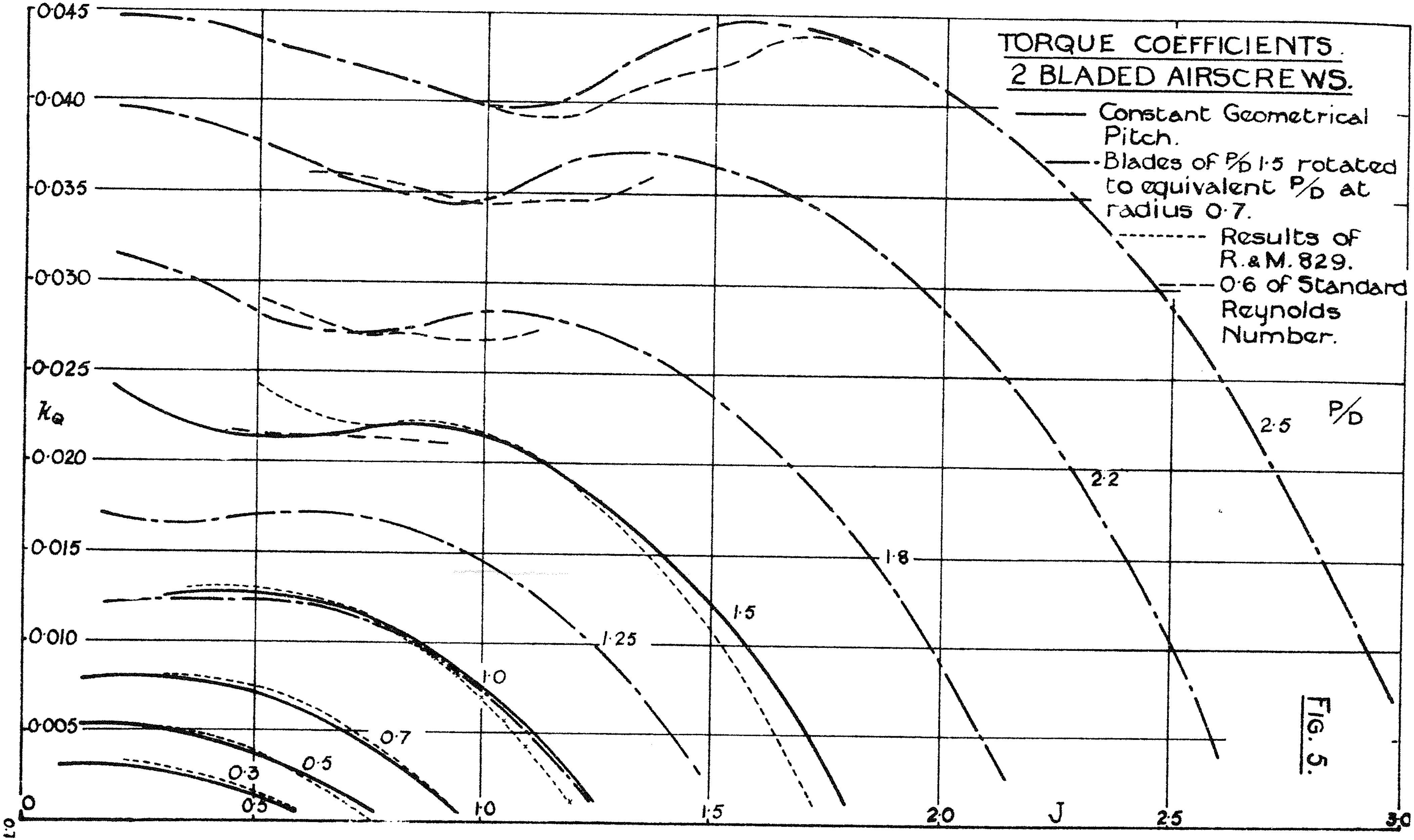
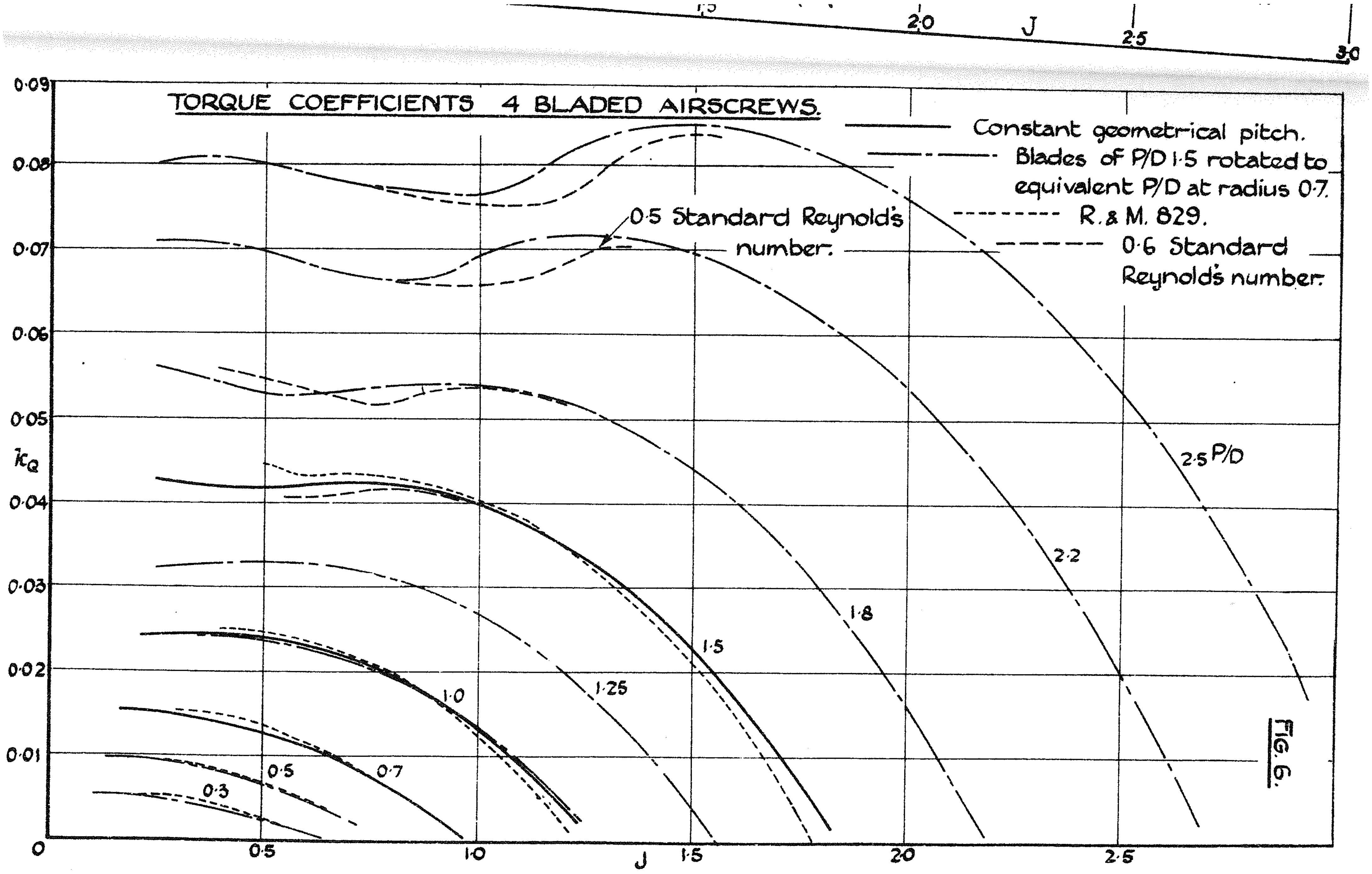


FIG. 4.



TORQUE COEFFICIENTS.
2 BLADED AIRSCREWS.

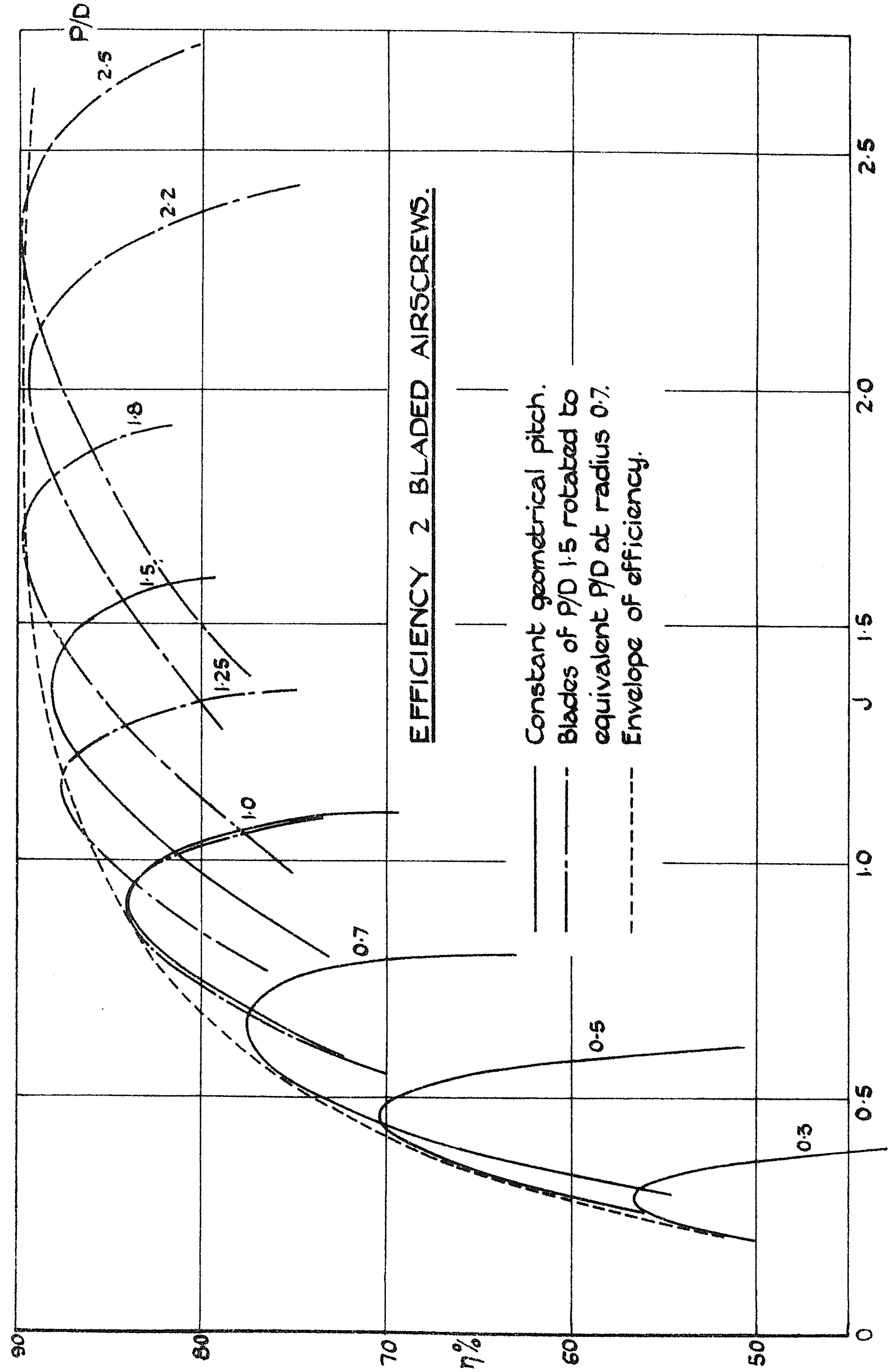
FIG. 5.



TORQUE COEFFICIENTS 4 BLADED AIRSCREWS.

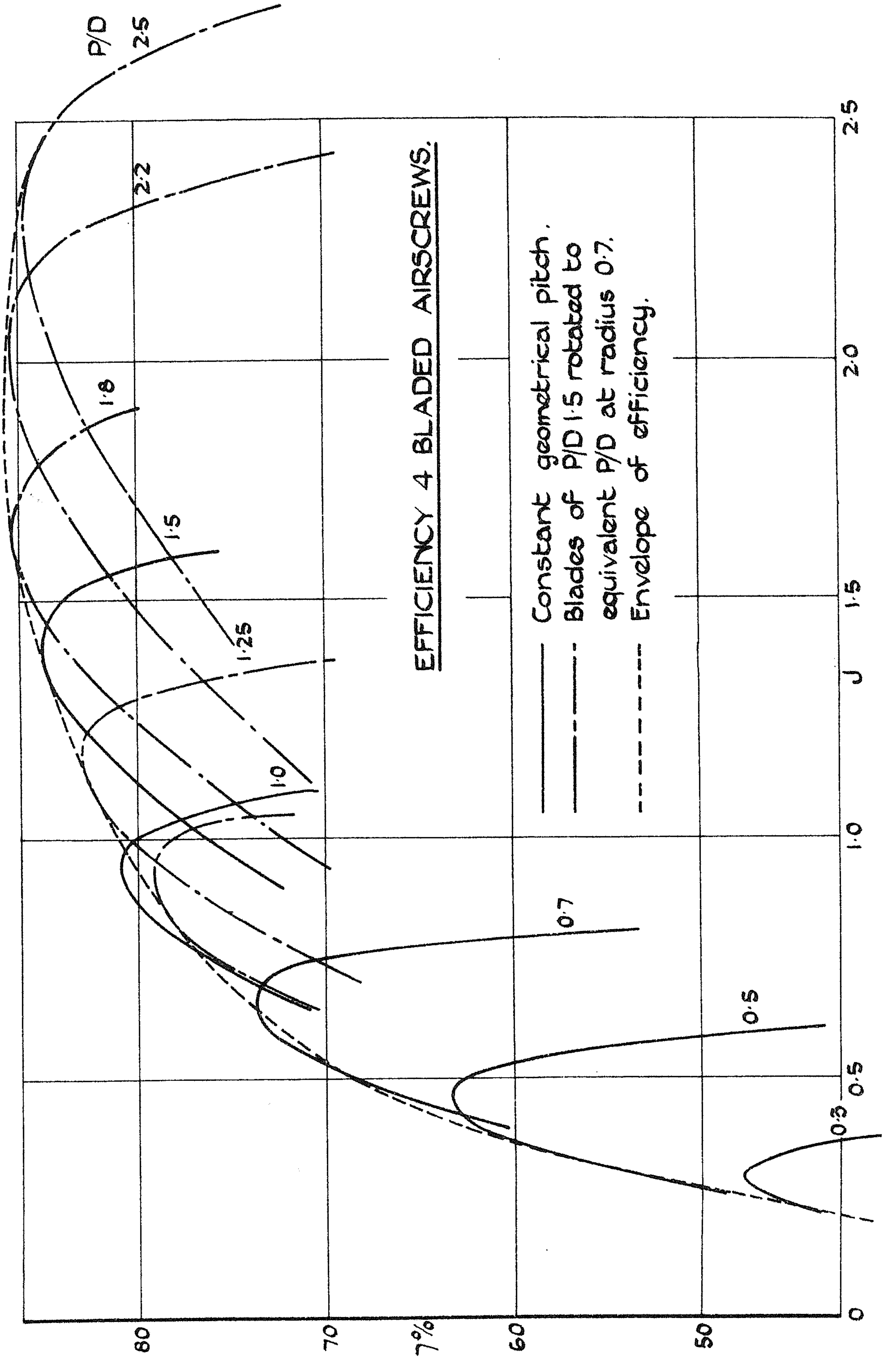
FIG. 6.

FIG. 7.



EFFICIENCY 2 BLADED AIRSCREWS.

FIG. 8.



EFFICIENCY 4 BLADED AIRSCREWS.

Static Thrust.

(Tunnel static)

FIG. 9.