On the Wind Tunnel Testing of Helicopter Models

By M S HOOPER, F R Ae S
(*The Fairey Aviation Company Ltd*)

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Professor J A J BENNETT (*Chairman, Lecture Committee*) *occupying the Chair*

The CHAIRMAN, in introducing the Author, said that Mr HOOPER was presenting to the Association its first lecture on the subject of wind tunnel testing of helicopter models Mr Hooper had a long experience of wind tunnel techniques and had also been able to apply some of these techniques recently in investigating the aerodynamic features of one of the latest rotary-wing prototypes—namely, the Rotodyne

Mr Hooper had been engaged on aerodynamic testing for many years, and next year would be his thirtieth year with the Fairey Aviation Company He had investigated a wide range of subjects such as the aerodynamics of sails for application to racing yachts and had also been concerned with the attainment of flight speeds greater than Mach 1 Thus it was not surprising that he had taken the wind tunnel testing of helicopter models in his stride and was tonight able to give an authoritative assessment of the value of this work

MR M S HOOPER

(1) INTRODUCTION

When in 1922 Cierva hinged his rotor blades to permit up and down flapping, and so reduced the awkward rolling moment that comes with rigid blades, a decisive step to practical success had been taken, as is well known The first successful gyroplane flight followed in January, 1923 [1] That aircraft was designed initially on the basis of wind tunnel tests [2]

A chief aim of this paper is to be of wide interest among the members of the Association No earlier paper devoted to the wind tunnel testing of helicopter models is known to the author, but exhaustive reference to any of the several aspects has not been attempted There is a partly historical interest, in the emergence of new ideas, the growth of techniques, and the interaction of theory and experiment A fairly extensive list of references is given, and most of the papers and books listed carry additional references Some mention is made of scientific background as to airflow, and of the technical basis of scale model testing, as both are fundamental to the design and assessment of tests and experiments, whether for industry or academic research The growth of wind tunnel results since 1923 is outlined by reference to a number of examples, which show the corresponding growth in understanding of the problems and also indicate the important scope of tunnel data and guidance made available for design purposes Aerodynamic aspects of helicopter design were the subject of a paper[3] to the Association in 1956 Model details and apparatus are referred to in the present paper only very briefly as these are of more specialist interest Rotor test towers are outside the scope of the paper Some examples of tunnel results for a complete model Rotodyne are given and include the interesting condition of very low flight speeds, roughly between limits separating two branches of rotor theory

By 1928, when in fixed-wing aircraft design the quantitative importance of streamlining was being widely realised for the first time, basic theory of the autorotating rotor had been developed and had been verified in essentials by wind tunnel tests [4] The theory[5] showed a windmilling rotor with flapping blades to be equivalent aerodynamically to one with suitable cyclic variation of blade pitch angle Flapping blades gave advantages, however, not only in reducing rolling moment, but also in reducing stress in the blades and in the airframe In practical aerodynamics it had just been discovered by 1928 that transition to turbulence in a boundary layer could occur at different positions at different times on the same model if tested in different streams, or if surface roughness was sufficiently changed in the same stream Fixing the position of transition brought drag measurements in different tunnels into line

Flutter had been studied in this country, first in theory, which was verified by wind tunnel tests in 1927 The problem of propeller flutter, however, was still unsolved in 1932 About this time it was being noted that methods giving only time-average results may sometimes obscure important information, *e g*, about stalling characteristics Ground effects were being studied in 1933-34 and tunnel technique was increasing correspondingly Interest in the true helicopter revived in Europe and in U S A, and in 1937 (in Germany) there was a renewal of successful helicopter flight [6]

In 1936 the British Aeronautical Research Committee had recorded that as a result of new and modernised equipment provided, there was far more confidence in application of wind tunnel tests on models to full scale design than there had been for many years The chief uncertainties remaining were insufficient knowledge of the influence of Reynolds number and of micro-turbulence in the tunnel stream

Further development of the autogiro and the helicopter in U S A in 1939-44 was based largely on wind tunnel work In 1944 British interest had returned to the true helicopter, and rotor tests in the 24 ft tunnel at R A E were started In an A R C review[7] of the period 1939-48 it was recorded that while basic theory of the lifting rotor had long been established, more experimental data on rotor characteristics were badly needed Compared with the stable aeroplane the flying characteristics of helicopters were still unsatisfactory Preliminary investigation for provision of adequate stability for multi-rotor helicopters had been made, but in 1948 this was not yet assured Tunnel-testing increased, and the airflow around rotors was studied in more detail By 1956 longitudinal cyclic pitch control methods included pitch-cone coupling, the design being based on wind tunnel tests [8] In Australia a complete model for tunnel testing had been made, each rotor of a tandem pair having one control jack for collective pitch angle and two jacks orthogonally mounted [9]

So far no wind tunnel specially designed for helicopter models seems to have been built, but the advantage has been pointed out of a tunnel which could be tilted round the model so as to direct the air stream at any required angle, while keeping the appropriate direction of gravity on the model [10] Centrifugal force/weight ratio for model blades is often large enough, however, to make this facility unimportant in many tests Experience in conventional wind tunnels has shown that much valuable information and guidance for design of helicopters is obtainable from reduced-scale model tests The techniques used with fixed-wing models[11] are also used in helicopter testing, and this is largely taken for granted in the paper The few special features involved are chiefly in model design and in safety precautions The typically small effect of blade-flapping on time-average aerodynamic performance of a rotor is seen to permit a simplifying approximation in model design and construction if the blades may be relatively heavy and stiff In many tests elastic similarity between model and full scale is not essential, but design for model rotor strength will usually require as much care as for full scale, periodicity effects being commonly more important than the problem of time-average stresses [12]

(2) THE BASIS OF SCALE MODEL HELICOPTER TESTING

The technical basis of scale model testing is briefly discussed here chiefly because of the number of assumptions almost always included in helicopter-model testing, the status of which it is therefore desirable to examine

It will be sufficient illustration of the complicated general problem to note the conditions for dynamical similarity[13] of a model which contains no ducted flow or thermal effects but which is geometrically and elastically similar to the full scale helicopter It will be assumed that centrifugal effects on airflow round the rotor blades may be neglected In this somewhat simplified example ten separate physical variables are known from experiment to affect the airflow round the model and the motion of the blades, and hence, say, the aerodynamic time-average resultant force in a vertical plane (A list of symbols is given at the end of the paper) Thus,

$$R = F(V, d, D, \rho, \nu, a, n, E, \gamma, g) \qquad (1)$$

where F has the same physical dimensions as R and denotes any function whatsoever of the ten physical quantities The statement in (1) presumes that so far as is known from experiment the force R depends on nothing else

Applying dimensional analysis, and using the usual geocentric system in which mass, length and time are the fundamental units, (1) is transformable into at least one functional relation involving seven independent non-dimensional variables As an example,

$$R = \rho\nu^2 \phi_1 \left(\frac{d}{D}, \frac{VD}{\nu}, \frac{V}{nD}, \frac{V}{a}, \frac{\rho}{\gamma}, \frac{\rho V^2}{E}, \frac{V^2}{Dg}\right) \qquad (2)$$

where ϕ_1 denotes any function of the seven dimensionless parameters, each of which must simultaneously have its full scale value in a dynamically similar model test

Quite apart from the fact that here this indicates full scale loads on the model, it is known the condition of respective equalities cannot be achieved in practice unless the model is full scale This may be seen from consideration of the parameters VD/ν and V^2/Dg as it is readily shown that, for equality of model and full scale values, the tests must be made in a fluid having a kinematic coefficient of viscosity $(1/s)^{3/2}$ times that of the air in flight conditions, where $1/s$ is the scale fraction of the model, *e g*, 1/10 No suitable fluid appears to be known if model size differs appreciably from full scale Equality respectively of the remaining parameters in (2) is fairly readily obtained for a model in an atmospheric wind tunnel provided that nD on the model can safely be made equal to its full scale value The rotor tip speed ratio, here represented by V/nD, is thus required to be the same for model and full scale

Ideally, the flow pattern round the model should be geometrically and dynamically similar to that prevailing round the aircraft, so that the equations of air motion become identical for aircraft and model Paths of corresponding points would be geometrically similar, although the model's time scale would in general be different But it becomes necessary, it is seen, to examine the usefulness of not strictly similar model tests If only because of great difficulties in designing an experiment in which seven parameters must be varied one at a time, a simpler set of conditions than indicated by (2) must be used if it can be justified as an approximation Fortunately several useful simplifications can often be made One, which involves no further approximation, is the omission of the ratio d/D when the linear scale of a complete model is always represented by its rotor diameter

For model tests measuring time-average values only, considerable simplification is sometimes justified For example it is often sufficient to use a model rotor, of correct scale diameter, but having relatively stiff, heavy blades When time-variable quantities have to be measured as such, however, it would be expected that the elastic properties of the blades might be significant A frequency coefficient, $\eta/(V/D)$, say, is readily shown to be a function of the seven arguments in equation (2) In structural considerations involving frequency[14] an alternative grouping of the parameters is sometimes more convenient Thus,

$$\frac{\eta}{V/D} = \phi_2\left(\frac{VD}{\nu}, \frac{V}{nD}, \frac{V}{a}, \frac{\rho}{\gamma}, \frac{\rho V^2}{E}, \frac{\gamma g D}{E}\right) \qquad (3)$$

It happens there is no essential need for further simplifying assumptions when designing tests based on (3) It is not as yet specially difficult to arrange for V/nD and V/a to have their full scale values in a reduced-scale model test, and it is sometimes possible to build the model of material which will ensure ρ/γ and $\rho V^2/E$ having their full scale values in the test The variation of $\eta/(V/D)$ can then be measured over ranges of VD/ν and of $\gamma gD/E$ in turn There remains, however, the limitation due to D on a reduced-scale model, and this leads to the well known problem of Reynolds number effect

When the effect of blade weight and elasticity can be neglected, the number of parameters which influence time-average air loads reduces to three For example,

$$\frac{R}{\rho V^2 D^2} = \phi_3 \left(\frac{VD}{\nu}, \frac{V}{nD}, \frac{V}{a}\right) \tag{4}$$

the force coefficient depending only on Reynolds number, tip speed ratio and Mach number As compressibility effects have been kept small on most helicopters, the important parameters in a model test sometimes reduce to Reynolds number and tip speed ratio Since the latter can usually be given its full scale value in a model test, the limit of simplification is reached when time-average air loads may be regarded as a unique function of Reynolds number—an assumption familiar in fixed-wing model testing at low subsonic speeds In any example, however, only experiment, or, complete analytical theory, can show which variables have significant influence and in what form Thus, neglect of centrifugal effects in the boundary layer on rotor blades has appeared to be justified in many tests to date, despite the fact that radial acceleration in the blade tip region on a model may be as much as fifteen or more times greater than at full scale But caution is clearly desirable in interpreting any new test

(3) GROWTH OF TUNNEL RESULTS FOR HELICOPTERS

In 1923 wind tunnel experiments were made at N P L on propellers at zero torque, with application to a helicopter descending[15] First use of hinged blades on a model rotor in this country was reported on in 1926 A 2 2 ft diameter rotor was used in a 7 ft closed wind tunnel at R A E for lift and drag measurements over a range of rotor disc incidence[16]

The most important early relevant report is probably reference 4 in 1928 Experiments had been made on a 6 ft diameter model of an autogiro rotor in the 14 ft × 7 ft closed tunnel at N P L Range of pre-set blade pitch angle, θ_0, was 0 to 3^0 and the extreme range of disc incidence was from 2^0 to 20^0 Lift and drag were measured and observations made of the angular travel of the blades in flapping Two horizontal component forces were measured in some tests L/D max occurred at $\theta_0 = 1\ 8^0$ with disc incidence 3^0 to 4^0, and was 7 5 for four blades and 8 0 for two blades Scale effect on lift coefficient was measurable at any disc incidence It was concluded, however, that the order of scale effect shown for L/D made it unlikely that the corresponding values at full scale were appreciably higher There was evidence of scale effect on rotational speed in autorotation conditions and performance was then sensitive to changes of θ_0 The change from highest L/D to conditions of failure to rotate corresponded with a θ_0 change probably less than 1^0 Failure to rotate was noted to be connected with stalling on the retreating blade It was evident that, as θ_0 increased, the effect of stalling became increasingly sudden Apart from this effect the tunnel results verified the conclusion in reference 5 that efficiency tends to increase with θ_0 Comparison between two and four blades was in good agreement with the Prandtl theory of interference given in reference 17 Observed flapping motion was also in good agreement with theory Tunnel wall constraint correction was based on the usual fixed-wing technique and it was concluded that the usual formula can be applied to an autogiro model Calculated interference velocity, on the assumption that the general flow pattern was the same as round an elliptic wing with equal lift and of span equal to the rotor diameter, was in fair agreement with experiment

Investigations of the performance of the autogiro in this country were reviewed in 1928 and it was noted that theory and wind tunnel results were in satisfactory agreement on all essential points[18] For a practical rotor autorotating, C_L max based on πR^2 was between 1 and 1 2 and L/D max was about 8

Tests of a full scale autogiro rotor in the N A C A 60 ft × 30 ft open-jet wind tunnel were reported[19] in 1935 L/D max in the tests was not much increased by increasing θ_0 above about 4 5° at the tip Protuberances on the blades caused more than 5% of the total rotor drag Induced downwash and yaw angles were measured in a plane 1 5 ft above the tip path plane, and large variations in downwash were observed in some portions of the disc

A 10 ft model gyroplane rotor in a 20 ft diameter tunnel was reported on[20] in 1935 The standard tunnel balance system and two lateral force balances were used The rotor hub contained feathering mechanism to control the rotor rolling moment but not its pitching moment

The true helicopter was discussed in December, 1944, as to types and scope of wind tunnel tests desirable[21] It was recommended the model should be large, and preferably in an open jet tunnel to reduce wall constraint The R A E 24 ft tunnel was the largest available in this country and rotor diameter should then be 10 to 12 ft It was suggested no attempt at elastic similarity be made initially, though precautions against blade twist would be necessary The possibility of a dynamically similar model should be considered as this is required for similarity of flapping motion Scope of tests envisaged covered ordinary performance tests over the full range of disc incidence and ranges of blade angle and of tip speed ratio The most critical item of performance was thought to be the static thrust of the rotor and that the effect of change of blade design on this might be investigated Exploration of the flow field and the possibility of pressure plotting the blades should be considered if a real advance in the theory of the interference velocity in forward flight was to be obtained

Static thrust and torque measurements by strain gauges, on six rotor blades of different designs were reported[22] in 1945 A complete full scale helicopter was mounted in the N A C A 60 ft × 30 ft tunnel Maximum tip speed was about 450 ft /sec It was found that blade surface condition had a large effect on performance, and it was concluded this will be an optimum only if blades have a smooth and accurately contoured surface which will not deform significantly in flight

Two reports were issued in 1949 on tests of 12 ft diameter helicopter rotor models in the R A E 24 ft tunnel In reference 23 results were given of thrust, torque and flapping angle measurements over a range of θ_0, shaft tilt, and tip speed ratio The purpose was to get information on the validity of the standard rotor theory and on effects of stalling on the retreating blade Good agreement with theory was shown over the normal operating range if the aerofoil data used were from measurements in the static thrust condition Stalling was found to develop progressively, showing first as an increase in torque and flapping angle, and later as a fall in thrust as compared with calculated values On profile drag it was recalled that its increase with blade incidence for propellers was usually more rapid than for wings, but that on the rotor tested the drag rise was even more rapid than for propellers

It was remarked in the same report that development of helicopters would be considerably assisted by wind tunnel tests if the necessary technique could be established Difficulties had arisen in the past with autorotation tests of small diameter rotors and had led to doubts as to reliability of model tests in general A 6 ft diameter rotor was considered a suitable size for tests in a 11 5 × 8 5 ft tunnel (reference 36) It was recalled that wind tunnel tests are preferable for this kind of work since parameters can be varied one by one in a way which is not usually feasible in free flight testing

Downwash measurements behind the 12 ft rotor were given in reference 24 and covered ranges of shaft tilt and tip speed ratio The results were in reasonable agreement with theory for the appropriate type of loading A difference from the theory was that a jet displacement occurred in all cases tested At that time experimental data on the downwash field behind a helicopter rotor were very scanty, but the problem had been considered in a first order theory[25] The problem of rotor interference was expected to be important on multi-rotor helicopters, especially for a rear rotor

Photographs of flow patterns shown by smoke filaments around and through the disc of a single rotor, for different states of working, are given in reference 26 A two-bladed, fixed-pitch, see-saw rotor of about 1 ft diameter was used in a wind tunnel in conditions of normal operation outside the ground cushion It was claimed all possible working states could be represented, the chief of which were

(1) The propeller working state , in hovering, horizontal and climbing flight Air at a distance and that through the rotor moves downward relative to the tip path plane

(2) Windmill brake state , in descent with power-off Air at a distance and that through the rotor moves upwards relative to the tip path plane

(3) The vortex ring state , occurring between the conditions for (1) and (2) Air at a distance moves upwards, that through the rotor is downwards relative to the tip path plane

A complete vortex ring round the tip circle was never seen, but there was alternate shedding from the sides of the disc Roughness and loss of control effectiveness, often observed with the vortex ring state, associated with moderate rates of vertical descent, was attributed to this fluctuating portion of the flow pattern Rough behaviour seen with the vortex ring state disappeared at higher forward speed and it was noticed the vortices then detached and blew away before spreading far round the rotor disc These observations, it is recalled, were made on a see-saw or teetering rotor

Inflow distributions over a rotor disc, derived by analysis of aerodynamic loading and blade motion data from tunnel tests, are given in reference 27, dated October, 1953, for a 5 ft rotor in hovering and in forward flight The chief example analysed was for a tip speed ratio, μ, of 0 30, the rotor having alternatively zero—and 13% offset flapping hinges At the time no force and moment data for offset flapping hinge rotors were available and measurements were made on a typical offset hinge rotor model having no cyclic pitch change In the main results the plots of inflow showed distribution was usually not uniform over the disc At $\mu = 0\ 30$, with offset of the blade hinge, there were larger variations of inflow than predicted by theory Upflow over the front portion of the disc and growth to relatively large induced downwash at the rear were confirmed Inflow patterns for the zero— and 13% offset rotors under the same conditions of operation (except for hub moments in the offset hinge case), were found to be markedly different in general form Except for the hovering case, there was in 1953 only a small amount of published information on comparison of theory with experiment on inflow, and it was noted that available experimental data on inflow distribution were inadequate for a thorough check on existing theories

Results were reported in June, 1954, from flow field measurements around single and tandem rotors in the N A C A 60 × 30 ft tunnel[28] Downwash angles near the tandem rotor were compared with theory, which appeared to be sufficiently accurate for preliminary design purposes It was concluded time-average flow behind a rotor is much like that behind a wing A single trailing vortex pair as for a wing was shown in tuft-grid tests The time-average downstream flow pattern from a lightly loaded tandem rotor

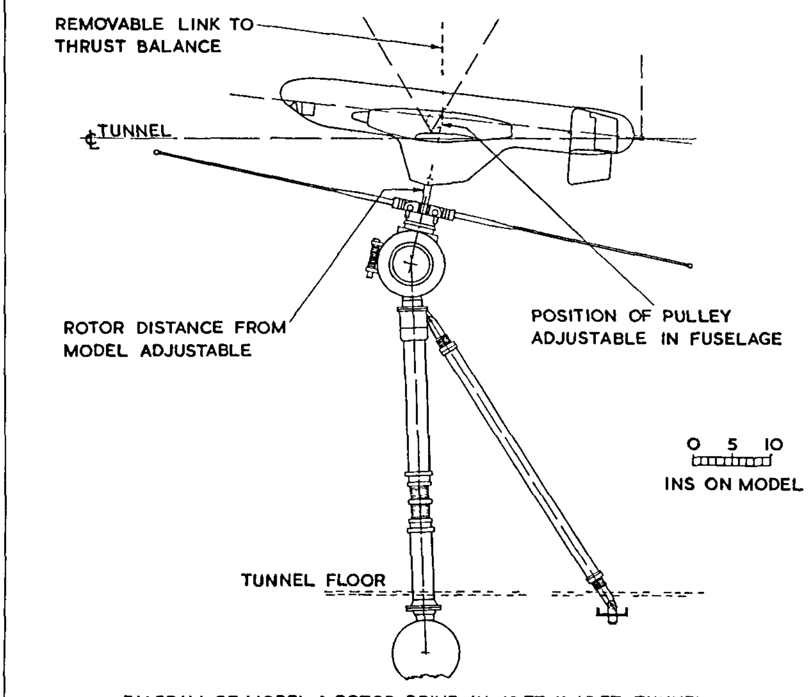


Fig 1

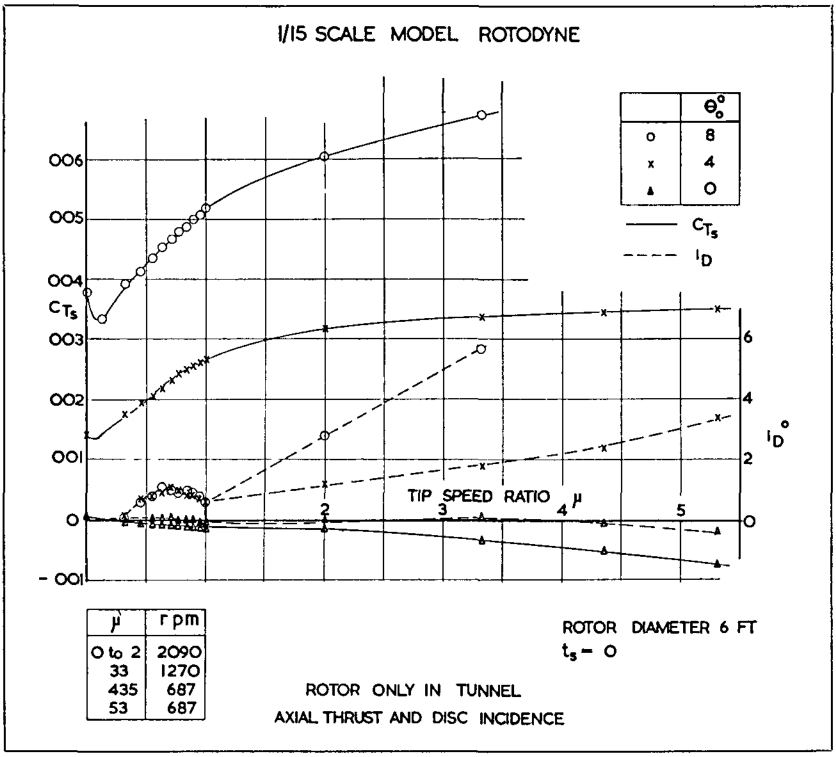


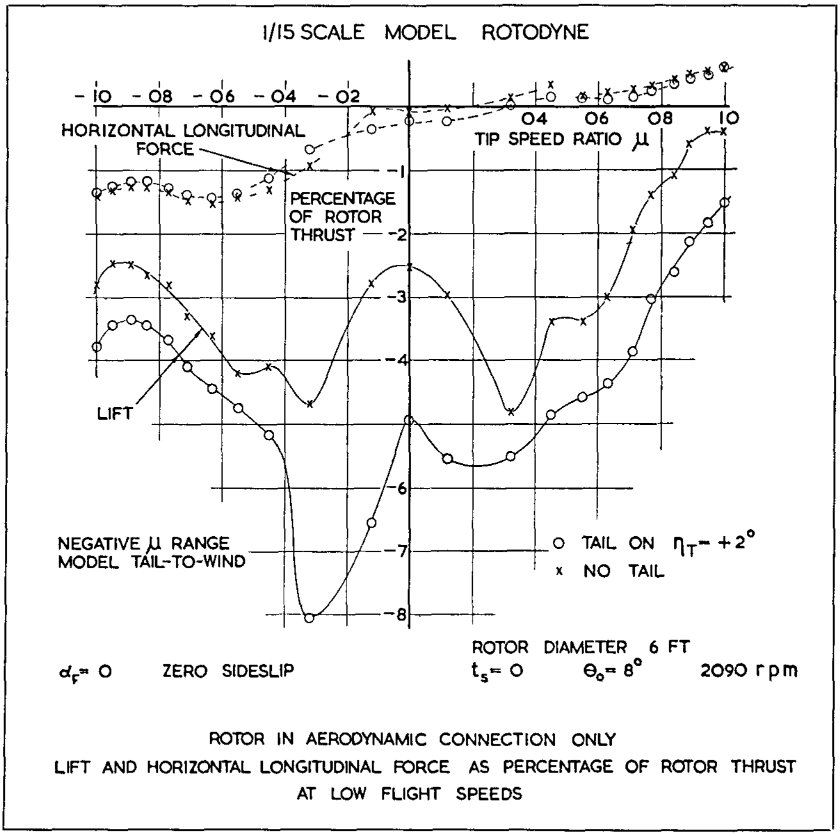
Fig 2

was much like that from a single rotor, except at high disc incidence or at very high rotor lift coefficients With tandem rotors theoretical prediction was better for angle than for velocity of downwash Error was greatest at the rear of the disc but reasonably small at the front It was found addition of a rear rotor added a small but significant upwash at the front rotor, well forward In the region of the rear rotor, necessarily in the downwash field of the front rotor, the local downwash values were thus considerably increased

More extensive measurements in the rotor flow field were given in reference 29 of February, 1956 A single rotor was used in the 60 × 30 ft tunnel The results showed, if realistic non-uniform load distribution over the disc was assumed, that available theory could be used to estimate with reasonable accuracy the induced flow over the front three-quarters of the disc for cruising and high speed flight conditions tested Aft of the three-quarter diameter station, calculated induced velocity was increasingly inaccurate due to rapid rolling up of the vortex system Well aft of the rotor the flow pattern could be represented more accurately by the flow behind a uniformly loaded rectangular wing when rotor lift coefficient was sufficiently high The wake flow pattern was, however, seen to be different from that assumed as a basis for the calculations because of rapid rolling up of the vortex system close behind the rotor

A chief purpose of this work was to get fuller information on the induced velocity field, to benefit investigation of blade vibration and design requirements for compound helicopters It was remarked that vibration analyses require in general data on instantaneous values of induced velocity, and that experiment suggested the fluctuating component of flow may sometimes be so large that there is little apparent relation between instantaneous and time-average values Quantitative measurements were noted as extremely scarce in 1956, and were inadequate either for defining the flow pattern or for checking theoretical estimates

An example of flutter tests in a wind tunnel, on a dynamic model of a two-bladed, jet driven rotor, is given in reference 30 Effects of control stiffness and of forward speed on flutter speed were investigated on a 1/10 scale model The first torsion and the flapping modes were found to be those of most significance Rotor speed at flutter was reduced as tip speed ratio, μ, was increased from zero, and the form of flutter motion changed from sinusoidal with distinct frequency to a nearly random form of comparable amplitude These last two results were observed between $\mu = 0$ and 0 12,



ROTOR IN AERODYNAMIC CONNECTION ONLY
LIFT AND HORIZONTAL LONGITUDINAL FORCE AS PERCENTAGE OF ROTOR THRUST
AT LOW FLIGHT SPEEDS

Fig 3

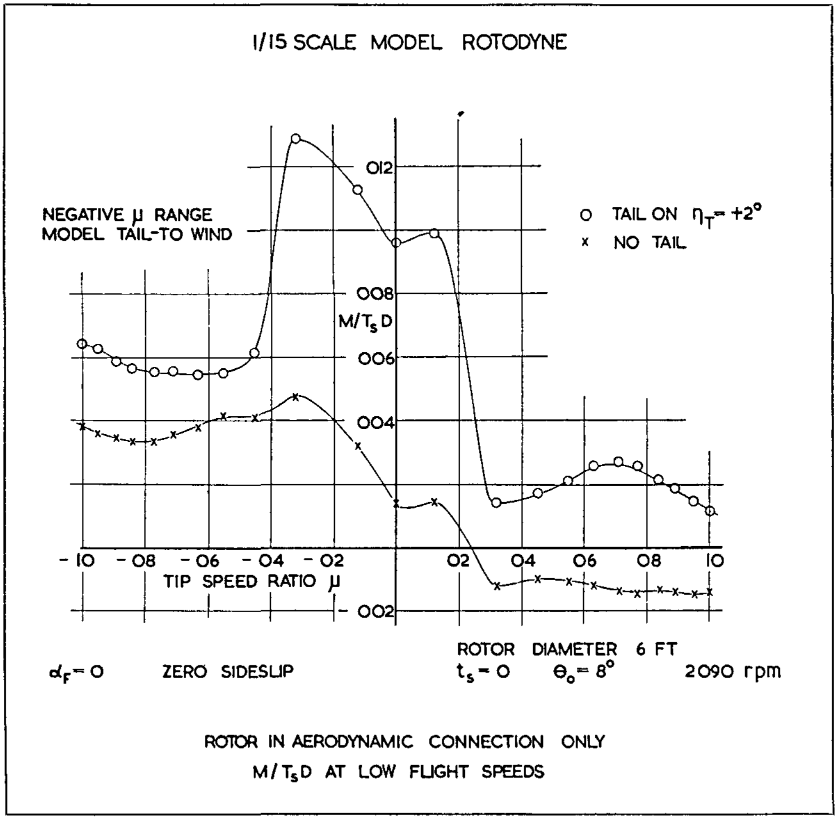


Fig 4

an interesting interval which is referred to again in the present paper

Measurements of static thrust loading on a rotor blade were reported[31] in February, 1956 A chief reason for more detailed measurements was that the observed complicated flow in rotor wakes indicated that calculation of aerodynamic loading on a blade was as yet only possible after a number of simplifying assumptions as to distribution of induced velocity across the rotor disc Calculated thrust from blade element theory, when modified by a suitable tip loss factor from the tests, was found to agree fairly well with thrust measured on the tunnel balance Previously there had been little experimental data available to compare with calculated spanwise loading Pressure distribution chordwise at five spanwise stations was measured, as time-average values, on a blade of a 15 ft diameter, 2-bladed, see-saw rotor in the 60 × 30 ft tunnel Tip speed was 400 to 500 ft $\sec^{-1}$ and disc loading was 0 to about 2 5 lb ft^{-2} The blade was fitted with N A C A miniature electric pressure gauges[32] Simultaneous measurements of thrust and torque input were made, torque being measured by electric resistance strain gauge on the rotor shaft Differential pressures were measured between upper and lower surfaces of the blade at ten chordwise stations for each of the five spanwise stations Forty-five slip rings were provided for electric connections, but as this was insufficient for all blade stations at once, either of two groups of stations could be switched in

Balance readings for rotor thrust required correction for download on the fuselage-type body For this purpose a 1/15th scale model fuselage was tested at —90° incidence in a smaller open-jet tunnel The " vertical drag " coefficient obtained was made the basis of an estimate of download on the fuselage, and in these tests amounted to about 10% correction on measured thrust A small correction was applied to measured torque on account of shaft bearing friction above the strain gauge and wind resistance of the hub

It is noteworthy that chordwise pressure distribution curves were not much changed from shapes familiar on fixed wings Load on successive blade elements increased radially until about 0 95R and then decreased due to tip loss But not entirely due to tip loss the loading near the trailing edge was relatively lower at the outboard station than for those inboard and was considerably lower than the value indicated by theory It was suggested there was possibly a thickening of the boundary layer towards the blade tip due to rotational effects, such as might make an effective negative camber

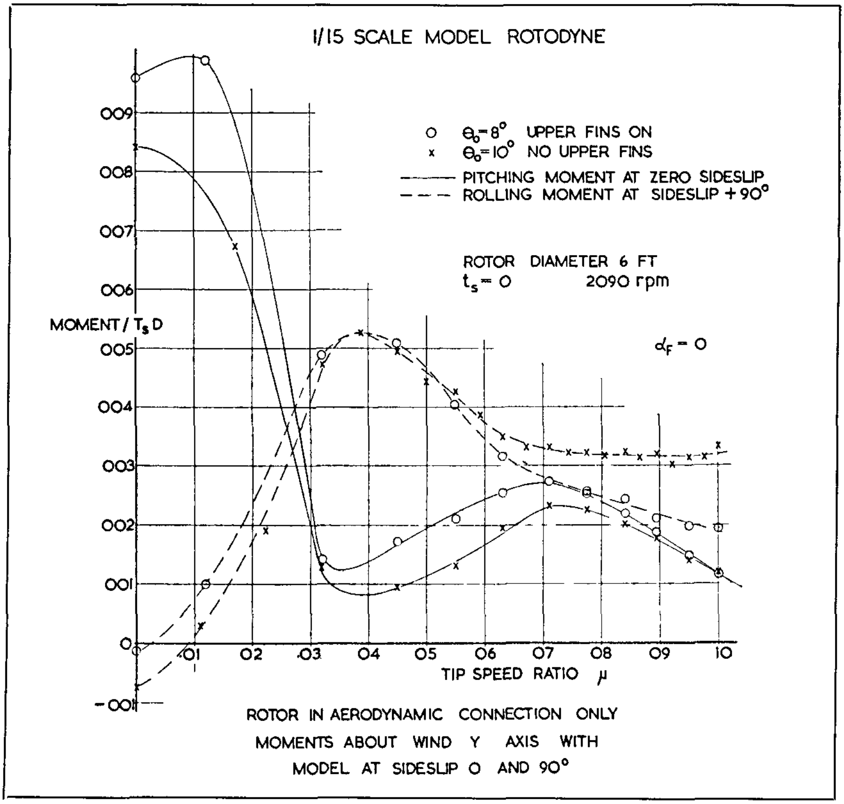


Fig 5

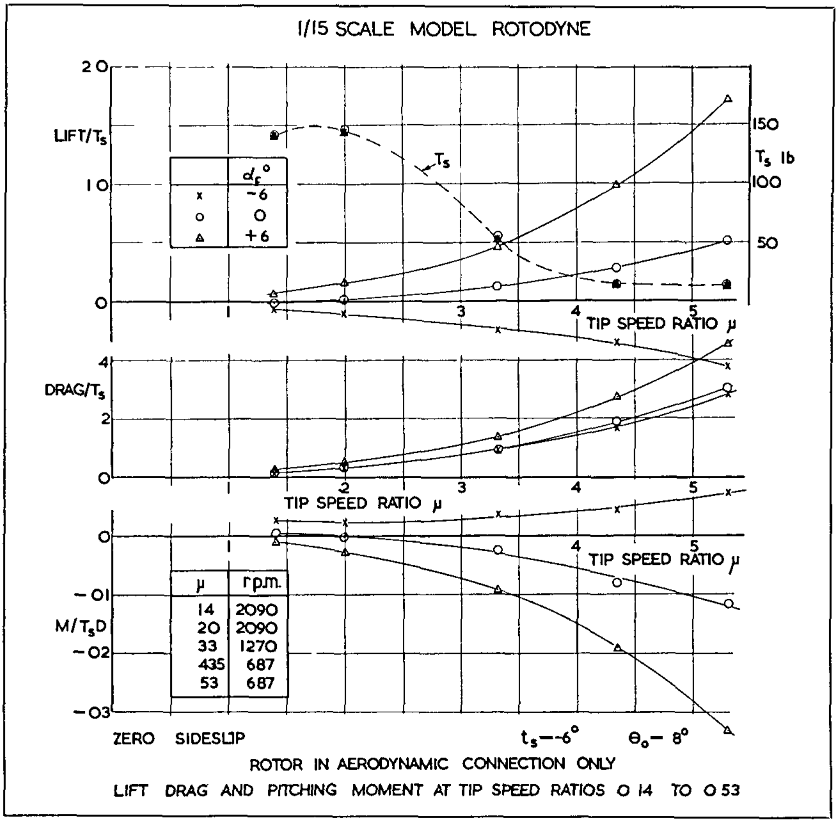


Fig 6

locally For the C_T range tested the loss factor based on C_T varied from 0 94 at maximum thrust to 1 0 at T = 0, the average factor being about 0 97, which was close to a value in common use

It seems that few complete-model helicopter tests have as yet been made and little information is available Most tests in the past have been of rotor or rotor plus body forces Tandem rotors on a fuselage-type fairing containing the driving motors have been investigated for blade flapping and for overall lift, drag and pitching moment in a wind tunnel at N P L[33] Tunnel tests of a 1/4 scale unloaded rotor convertible helicopter, and later of the full scale aircraft, were mentioned in reference 8 of July, 1956 This aircraft had a significant amount of fixed wing area With the rotor off-loaded and autorotating, the aircraft was tunnel tested up to a tip speed ratio of 1 2, and was flown at μ = 0 95—about twice the orthodox helicopter value The tests are some of the very few known where body component forces and moments were measured Downwash measurements at the tail were the basis for design of tailplane incidence change with forward speed Effect of the fixed wing handling characteristics in helicopter flight was noted as small except in sideslip at very low flight speed, *i e*, at low values of μ, when an appreciable rolling moment was found and was attributed to unequal downwash on the wings

The interval of tip speed ratio between $\mu = 0$ and about 0 1 is of both theoretical and practical interest The low speed performance of a helicopter has for a number of years been recognised as involving a difficult theoretical problem Estimation of performance is well known to depend on accurate knowledge of the induced flow pattern at the rotor For μ greater than about 0 1 the momentum theory is fairly accurate For $\mu = 0$ an empirical curve of rotor coefficients has commonly been used, but in the interval, between $\mu = 0$ and 0 1, there has been no generally accepted simple method of estimation[34] More recently, in the range of $\mu = 0$ to 0 14, the independence of rotor derivatives under non-uniformity of induced velocity distribution has been considered on a semi-empirical basis[35] It was concluded that the effects of non-uniformity were almost negligible except for one very small derivative—that of vertical component force due to angular velocity in pitch Some recent tunnel measurements between $\mu = 0$ and 0 1 on a model Rotodyne with zero angular velocity of the body and the

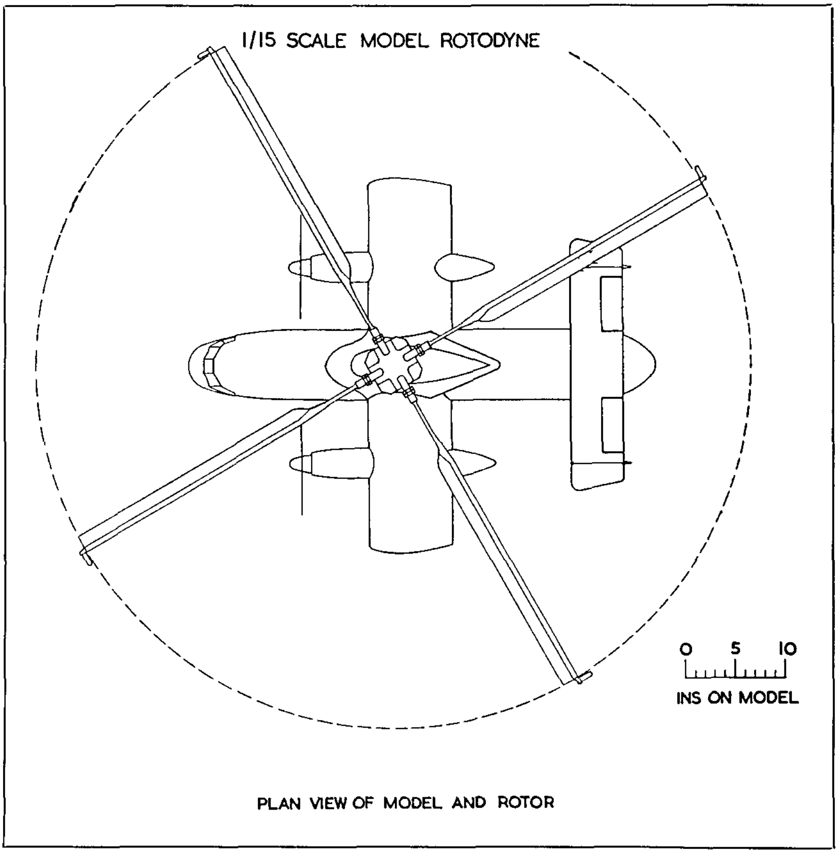


Fig 7

rotor in only aerodynamic connection with the remainder of the model, are given in the next section From the observed distributions of forces and moments as affected by rotor interference there is a hint that change in distribution of induced velocity over the rotor disc as μ increases to about 0 1 may sometimes be significantly more complicated than the scheme assumed in reference 35

(4) SOME ROTODYNE RESULTS

Models at 1/6 and 1/15 scales of the Fairey Rotodyne Mk 1, which is now being developed under Ministry of Supply contract, have been used in the firm's 12 ft × 10 ft closed wind tunnel, the larger model for basic tests and development, including twin-engine propeller slipstream effects, the smaller model being used with a 6 ft diameter rotor (Figs 1, 7, 8) The rotor, with offset flapping hinges, was not intended as a dynamically similar model, but was required to give correct scale thrust and representative downwash Collective pitch angle, θ_0, was pre-set as required Cyclic pitch change mechanism was not used Comparison of coefficients from the usual six-component measurements on the two aircraft models showed quite good agreement over the Reynolds number range of the proposed tests Tunnel speeds up to 132 ft $\sec^{-1}$ were used Maximum rotor tip speed was 660 ft $\sec^{-1}$, as was proposed for the aircraft Tunnel constraint corrections were moderately small for the larger model in forward flight conditions, and also for the rotor, for which some special static thrust tests were made by removing substantial areas of roof and floor from the tunnel's working section

The results selected as examples and briefly discussed below are from tests clear of ground cushion effect They were measured as time-averages on the 1/15 scale model less propellers with the rotor detached but in appropriate aerodynamic connection with the remainder of the model The measured results thus include the interference effects due to the flow-field of the rotor

Fig 2 gives C_{T_S} and i_D over the ranges of μ from 0 to 0 53 when the rotor was alone in the tunnel and θ_0 was successively 0, 4^0 and 8^0 When θ_0 was 4^0 or 8^0 the value of C_{T_S} initially decreased and then increased on an almost smooth curve Greater change in form was found in the curve for i_D in the range of μ from 0 to 0 1 This interval is seen to correspond with that in which difficulty has been found in formulating reasonably simple accurate rotor theory Tests with the remainder of the model in place showed that interference on the rotor was small for practical purposes, but that interference on the rest of the model from rotor downwash could be considerable, in particular in the interval of μ from 0 to 0 1 This is illustrated in Figs 3 to 6 for the components lift, horizontal longitudinal force, pitching and rolling moments Fig 6, for $\mu = 0$ 14 to 0 53, shows nearly smooth simple distributions, but it should be noted considerable off-loading of the rotor by $\mu = 0$ 35 had been made in this test Fig 9 is a photograph of the full scale Rotodyne in low speed flight

The result to which it is desired to draw attention here is occurrence of critical effects only at μ values less than about 0 1 (Figs 3, 4, 5) These effects were not present in corresponding tests with the rotor removed and therefore cannot be said to be largely due to low Reynolds scale of some of the tests Change in form of the i_D curve between $\mu = 0{\cdot}1$ and 0, noted in Fig 2, is almost certainly of significance in the interference process It would also be present with a tail wind, it is seen, and Figs 3 and 4, over the μ range from $-0{\cdot}1$ to $+0{\cdot}1$, show the presence of critical effects over this range It is also seen that removing the tail did not much change the form of curves or the distribution of critical values of μ, whether in a nose wind or tail wind Fig 5 shows that a side wind effect on rolling moment was of the same form and sense as that of fore and aft wind on pitching moment Magnitude of these effects in Figs 3, 4, 5, although not relatively large for the configuration of this model, is sometimes of practical interest, not only as to hovering control, but also in design for stability and control over a given range of aircraft c g position These examples are typical of an important class of detailed information obtainable from wind tunnel tests of helicopter models

(5) Concluding Remarks

As the equations of motion of air in practical flight cases have not as yet been solved to give the detailed pressure distribution, aerodynamics remains very extensively an experimental subject The chief purpose of wind tunnel testing being to make desired measurements, this paper, in the space available, does not aim to go beyond this stage It is clear from a

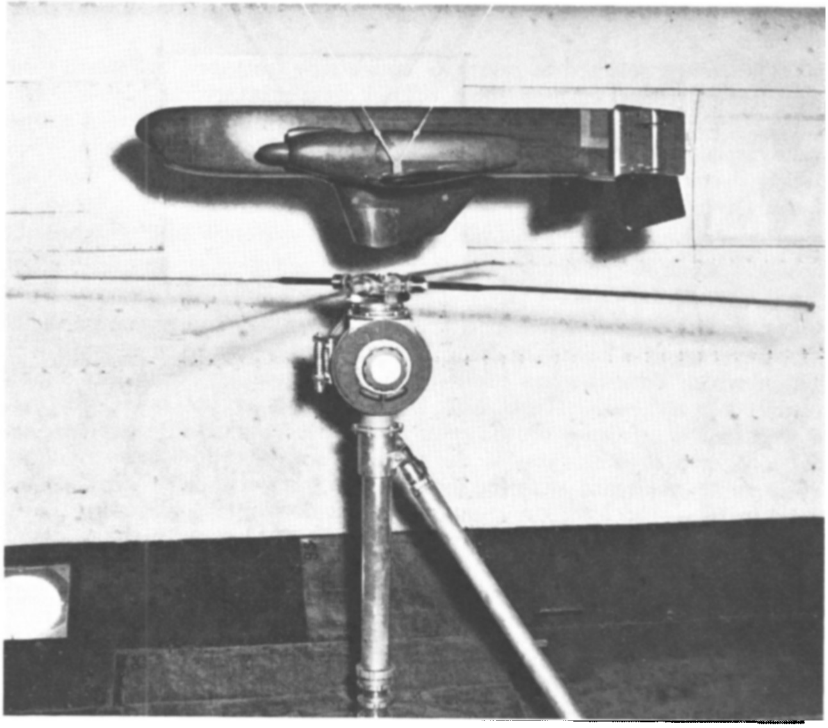


Fig 8 1/15 scale model Rotodyne with rotor in wind tunnel

Fig 9 Rotodyne in flight

survey of the main results of wind tunnel work for rotorcraft, done at intervals over the last thirty-five years, that this form of experiment and testing has made large and important contributions, in particular for rotors The importance of tunnel testing for fixed-wing aircraft design and development —which so far has been much greater in amount than for rotorcraft—has long been widely recognised Tunnel constraint effects have not been completely solved theoretically in some practical conditions for either class of model, but this has not led to any serious restriction of usefulness The greatest difficulties with helicopter models would seem to arise rather from mechanical and structural features and on this score compromise is sometimes a matter of expediency The technical basis of model testing is available for guidance

The design of rotors of conventional type appears to have been put on a fairly satisfactory footing in recent years and has been greatly helped, it is seen, by wind tunnel testing Effects of the rotor flow-field on the rest of the aircraft or model, however, are a comparatively recent study, still in its early stages Later tests are necessarily more and more concerned with investigation of secondary features, and the importance of this class of test may be expected to increase as helicopters are developed to higher duty Model rotors having even approximate elastic similarity with full scale blades have rarely been used in wind tunnel tests At the stage now reached in practical helicopter design it is possible they will seldom be required There remains, however, considerable interest in realistic local time-variant aerodynamic processes in blade-flow and dynamically similar models are desirable in a few special tests Almost inevitably such models will be expensive, both in time and money

In the usual time-average aerodynamic component testing the stage has been reached with helicopter models, as happened for fixed-wing aircraft models, where accuracy of experiment can sometimes be better than that of the transfer of model data to apply at full scale For the time being this level of test accuracy is worthwhile as much detailed knowledge has yet to be acquired and understood Most of the aerodynamic quantities, and hence at least their first derivatives, which form a basis for helicopter performance and stability calculations, can be measured in wind tunnel tests —although some are difficult and expensive For compound helicopters it seems as much testing per design will be required for some time to come as was found necessary for high-duty, fixed-wing aircraft designs Much model testing may be required in developing special features, such as auto-stabilisation, and rotors with jet flaps and possibly boundary layer control for low drag cruising and autorotation In addition to specialised development problems and research, it is seen that wind tunnel testing of helicopter models can continue to give much valuable help in assessing aerodynamic properties of a new design and in developing handling qualities that depend on airflow

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(7) LIST OF SYMBOLS

R	aerodynamic resultant force in a vertical plane, lb
R	rotor tip radius, ft
V	tunnel speed, flight speed, ft sec $^{-1}$
d	representative length (*e g* , fuselage length), ft
D	rotor diameter, ft
D	drag, lb
ρ	mass density of air, slug ft $^{-3}$
ν	kinematic coefficient of viscosity of air, ft sec $^{-1}$
a	velocity of sound in air, ft sec $^{-1}$
n	revs per second of rotor, sec $^{-1}$
E	elastic modulus of structural material, *e g* , Young's Modulus lb ft $^{-2}$
[illegible]	mass density of structural material, slug ft $^{-3}$
g	gravitational acceleration, ft sec $^{-2}$
F	function of the specified physical quantities
ϕ_1, ϕ , ϕ_3	functions of the specified non-dimensional parameters
s	reciprocal of scale-fraction of model
η	frequency, cycles sec $^{-1}$

θ	rotor blade pitch angle, degrees
θ_0	rotor blade collective pitch angle, degrees
i_D	incidence of rotor tip path plane to undisturbed wind direction, degrees
Ω	angular velocity of rotor, radians sec^{-1}
μ	rotor tip speed ratio, $V\cos i_D/\Omega R$
T	rotor thrust, lb
C_T	rotor thrust coefficient, $T/\rho\pi R^2(\Omega R)$
T_S	rotor thrust along shaft axis, lb
C_{T_S}	rotor axial thrust coefficient, $T_S/\rho\pi R^2(\Omega R)^2$
t_S	tilt of model rotor shaft to vertical, degrees, positive tilted rearward (on a model the right way up)
α	wing incidence, degrees
β	sideslip angle, degrees
L	lift of rotor, lb
L	lift of remainder of model with rotor in aerodynamic connection only, lb
L	rolling moment on remainder of model, with rotor in aerodynamic connection only, lb ft , non-dimensional plot as L/T_SD
M	pitching moment on remainder of model with rotor in aerodynamic connection only, lb ft , non-dimensional plot as M/T_SD

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