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An Experimental Investigation of the Flow Through a Helicopter Rotor in Forward Flight

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Summary.—Experiments have been made to determine the flow conditions through a helicopter rotor in forward flight using the smoke filament technique. This method consisted of flying the helicopter behind an aircraft from which smoke generators were suspended on a long wire. The smoke trails passed through the main rotor of the helicopter, and photographs were taken from another aircraft in a side position. Flow conditions at the rotor disc over a narrow bend on the side of the advancing blade were investigated in this way. The range of speeds covered was from 44 m.p.h. to 60 m.p.h. corresponding to a range of tip speed ratios 0·138 to 0·188.

An increase in induced velocity from front to rear of the rotor disc was obtained. The results are in reasonable agreement with theoretical predictions.

1. *Introduction.*—Flight tests have recently been made at the Royal Aircraft Establishment to investigate the mode of air flow through a helicopter rotor when hovering, R. & M. 2521[1], and in vertical descent, R. & M. 2735[2]. In both of these conditions of flight the velocity distribution over the rotor is essentially symmetrical, and varies with radial position only. In forward flight, however, the velocity distribution is much more complicated, and is a function of radius, azimuth position, and of tip speed ratio.

For certain purposes, *e.g.* the estimation of general performance, the rotor may be considered to operate with a uniform induced velocity distribution, and this assumption gives reasonable accuracy. However in the study of blade motion which is necessary for estimating stability, control, and vibration characteristics of the helicopter, a knowledge of the actual induced velocity distribution is required.

An increase in induced velocity from front to rear of the rotor disc in forward flight has long been suspected in a general sense. The magnitude of this increase has largely been a matter for speculation, although theoretical estimates have been made (Ref. 3 and R. & M. 2642[4]). In making the estimate of Ref. 3 it was assumed that vortices were shed only at the blade tips, that there was no contraction of the wake, and that there were an infinite number of blades. This gives only a mean value of the induced velocity distribution across the fore-and-aft diameter of the disc and the derivative at the centre in this direction. In Mangler's method, R. & M. 2642[4], an infinite number of blades is again assumed. The disc is assumed to be lightly loaded to allow the use of a linearised theory but various types of loading are considered. Distribution over the entire disc area is obtained.

* R.A.E. Report Aero. 2330, received 25th January, 1950.

The present report deals with flight tests made on a *Hoverfly I* helicopter at the Royal Aircraft Establishment during May to August, 1948, to investigate the flow through the rotor disc in forward flight, and in particular to determine experimentally the magnitude of the increase in induced velocity from front to rear of the rotor disc. The range of forward speed was 44 to 60 m.p.h. giving a tip speed ratio range from 0·14 to 0·19. The main investigations covered an area of the rotor disc in the form of a strip of width roughly 0·27 of the rotor radius and parallel to the direction of flight. The centre line of the strip was offset by about 0·27 of the radius from the longitudinal axis of the fuselage to the starboard side (the side of the advancing blade). The experimental work was limited to obtaining a general appreciation of flow conditions in flight and complete disc surveys were not made. Complete disc surveys would be more applicable to wind tunnel-testing where conditions can be more easily controlled.

2. *The Smoke Filament Technique*.—2.1. *Development Work*.—For the measurement of induced velocities in hovering flight, R. & M. 2521[1], a double venturi pitot-static was used, and a traverse made along a single radius beneath the rotor. The order of the velocities measured was 45 ft/sec in the developed slipstream, the induced velocities at the rotor disc being half this value. In forward flight the value of the induced velocity, to maintain the same thrust, decreases rapidly, *e.g.* at a forward speed of 60 m.p.h. the mean value is of the order of 6 ft/sec. The problem of measuring a difference in velocity of this order in flight is an extremely difficult one. Traversing behind and below the rotor in the oblique slipstream introduces difficulties of mechanical and structural arrangement. Also, the problem of relating measurements made in the wake to the corresponding conditions at the rotor disc is very difficult.

It was established theoretically (section 5), that if the direction of flow through the rotor disc in forward flight could be indicated, then the induced velocity could be deduced from the downwash angle, and the need for pressure measurements obviated. The use of smoke filaments to indicate the direction of flow was a logical development of the previous work in hovering flight, where they were used to correlate the positions of measurements made in the contracted wake beneath the rotor with the corresponding positions in the plane of the rotor disc.

As a preliminary test a single smoke generator was towed on a 60 ft wire from a *Fiesler Storch* aircraft. The generator was suspended below the aircraft in order to be as free as possible from local disturbances and the downwash from the wing which would otherwise quickly disperse the smoke. The generator was fired electrically. A *Hoverfly I* helicopter was flow so that the resulting smoke filament passed through the rotor. Photographs were taken from an accompanying aircraft. The definition of the streamline positions was sufficiently accurate to allow evaluation of the induced velocities by this method.

An illustration of the general flight technique during the development work is given in Fig. 1. This shows the *Fiesler Storch* towing two smoke generators in this case with the helicopter in position.

In the final form, five generators were suspended from the cable trailing vertically below each other. This allowed complete coverage of the rotor disc in a vertical plane and thus a complete flow pattern could be obtained on one photograph.

2.2. *Description of Smoke Apparatus*.—The smoke generators used in the tests were Wessex daylight distress signals fitted with electrical ignition; they emitted a deep orange smoke for a duration of forty seconds.

The five generators used in each test were fitted with detachable nose fairings and drum type stabilising tails. They were suspended from the *Fiesler Storch* aircraft by means of a 60 ft cable in such a way that they trailed vertically one below the other at intervals of 3 ft. Each generator was attached at its centre of gravity to give static balance, and to minimise coupling effects on the dynamic stability of the system.

The smoke generators were lowered and raised from the aircraft when in flight. Provision was made to fire all five generators simultaneously.

An attempt was made in some of the tests to produce an intermittent smoke filament. In this was it was hoped that particular parts of the smoke could be identified in successive photographs taken at known time intervals, and from the displacement of smoke in each interval it was hoped to calculate velocities. A rotating shutter operated by air stream driven vanes was fitted at the smoke orifice. A clean break in the smoke filament however was difficult to achieve. Although it was possible to measure air speeds approximately by this method, it was not accurate enough for the tests and the scheme was discontinued.

3. *Flight Technique.*—The smoke generators were lowered from the *Fiesler Storch* aircraft by the observer, and a steady course and airspeed maintained. The *Hoverfly I* helicopter manœuvred to a position level with and about one rotor diameter behind the trailing smoke generators. A second *Fiesler Storch* aircraft flew in formation with the helicopter at the same height and a position 200 ft to starboard. Radio contact was maintained between the two *Fiesler Storch* aircraft. When the formation was steady the smoke generators were fired and the helicopter was flown so that the rotor passed through the smoke. Slight lateral deviations were made by the helicopter so that the plane of the smoke slowly traversed the inner starboard side of the rotor disc. Photographs were taken by an observer from the formating *Fiesler Storch.* As each photograph was taken, radio contact with the leading *Fiesler Storch* was made and a simultaneous photograph was taken from this position in front of and above the helicopter. Thus when the films were aferwards correlated, the spanwise position of the smoke across the rotor corresponding to each side elevation photograph could be found. On an average flight sixteen of these photographs were taken.

Several flights were made at each of the following forward speeds :— 44, 53 and 60 m.p.h. corresponding to tip speed ratios $\mu = 0 \cdot 138$, $\mu = 0 \cdot 167$ and $\mu = 0 \cdot 188$ respectively. The speed of 44 m.p.h. was the lowest at which the *Fiesler Storch* could maintain really steady conditions, and 60 m.p.h. was the fastest speed at which the *Hoverfly I* could maintain reasonable formation. It will be seen therefore that the range of the tests was governed solely by the performance characteristics of the aircraft, and not by the experimental technique.

The importance of extremely smooth flying conditions must be stressed. The slightest turbulence of the air caused waves and raggedness in the smoke filaments rendering photographs useless for analysis. The best conditions were usually found to exist early in the morning.

4. *Analysis of Photographs.*—Large prints were made from the side elevation negatives, and the position of the smoke in a spanwise direction in each case was determined from the corresponding plan view negatives. Typical photographs of the flow pattern are given in Fig. 2.

It will be seen that the smoke issues from the generators as five straight and parallel filaments. As the flight paths of the *Fiesler Storch* and the helicopter are parallel, the filaments before they reach the field of action of the rotor represent the direction of the flight path of the helicopter.

The main analysis of the prints was to determine the angles between the local air flow directions and the tip path plane, and to determine the angles of incidence of the rotor *i.e.* the angles between the tip path plane and the flight path.

With regard to the general question of obtaining directions of flow from the smoke patterns, the smoke filaments represent particle path traces. These, correspond to streamlines unless vorticity is present, in which case a mean direction of flow only can be obtained. Thus when vorticity was present the direction of flow was taken to be a line joining the centres of successive vortices along the smoke filament.

The procedure adopted in analysing the smoke photographs was as follows (Fig. 3). The blade tips appear as three points in a straight line or on a shallow ellipse the major axis of which represents to a very good degree of approximation the side elevation of the tip path plane. This was lined in on the prints. The fore-and-aft limits of the disc in the plane of the smoke were calculated from the data on the corresponding plan view negatives, and marked along the line of the tip path plane. Smooth lines were drawn through the smoke filaments, and if vorticity was present as the smoke passed through the disc, the lines were drawn through the centres of successive vortices. Tangents to the lines of flow at the points of intersection with the tip path plane were then drawn, and the angles between the airflow and the tip path plane measured.

The angular displacement of the photographing aircraft from the line abreast position was small being never greater than 5 deg in the vertical plane, and 20 deg in the horizontal plane. The angles of flow through the rotor disc and the rotor disc incidences were corrected to ' true ' angles by allowing for any angular displacements of the photographing aircraft from the line abreast position.

The angles of flow are plotted against the longitudinal position on the rotor disc in Figs. 4, 5 and 6 for the various tip speed ratios.

5. *Method of Evaluating Induced Velocities.*—Consider first of all the case of a helicopter in forward level flight and having a uniform distribution of induced velocity at the rotor disc (Fig. 7a). At the tip path plane there are induced velocities v_D in a horizontal direction, and v_W in a vertical direction. From momentum considerations they are such that the horizontal change of momentum equals the drag, and the change of vertical momentum equals the weight of the helicopter. Denote the resultant of v_D and v_W as v_i'. Then v_i' and the forward speed of the helicopter V are the two components of the resultant velocity through the rotor disc V'. The resultant force exerted by the rotor is equal in magnitude and opposite in direction to the resultant of the drag and weight forces. If the rotor was an ideal actuator disc, the resultant force would be perpendicular to its plane which in turn would be perpendicular to the resultant of the drag and weight forces.

In practice due mainly to the profile drag of the blades, there exists a drag force H in the plane of the rotor as well as the perpendicular thrust T. To maintain equilibrium under these conditions the tip path plane is tilted further forward by an angle whose tangent is H/T (Fig. 7b).

It should be noted that the tip path plane is tilted forward to allow for the H force, but as this force is a drag at the rotor disc, the air momentum associated with it does not appear in the developing slipstream.

Let v_i be the component of v_i' perpendicular to the actual position of the tip path plane; then since the angles $\tan^{-1} H/T$ are less than $0{\cdot}5$ deg over the range of tip speed ratios dealt with in this report, the error in assuming that $v_i' = v_i$ may be neglected.

Consider any streamline passing through the rotor disc (Fig. 7c). The component of the velocity V' in the plane of the rotor is $V' \cos\theta = V \cos\alpha$. The component of V' perpendicular to the plane of the rotor disc is u.

Therefore $\quad u = V \cos\alpha \tan\theta$

now $\quad v_i = u - V \sin\alpha$

$$= V (\cos\alpha \tan\theta - \sin\alpha)$$

θ and α were measured direct from the smoke pictures, and as α was never greater than $4{\cdot}5$ deg the results were analysed using the formula

$$v_i = V (\tan\theta - \sin\alpha). \qquad (1)$$

The induced velocities found from the above equation were expressed non-dimensionally as fractions of the ' thrust ' velocity $U_T = \left(\dfrac{T}{2\rho\pi R^2}\right)^{1/2}$, which corresponds to the mean value of the induced velocity in hovering flight. The values of v_i/U_T are plotted against their longitudinal position on the rotor disc in Figs. 8, 9 and 10, for the three forward speeds of 44, 53 and 60 m.p.h.

6. *Discussion of Results.*—6.1. *The Smoke Photographs.*—Several points of interest emerge from a study of the smoke photographs (Fig. 2). Photograph 2a was taken in slightly turbulent atmospheric conditions, and emphasises the need for smooth air conditions if results are to be obtained with sufficient accuracy. Photograph 2b is typical of the best obtained, and 2c illustrates tests made with intermittent smoke filaments. It will be seen that the dotted effect is not sharply defined and cannot therefore be used to indicate velocities with a sufficient degree of accuracy for this particular work.

The trailing vortex system is particularly interesting and is clearly defined in all photographs. The frequency at which the vortices are shed is three times the rotor speed (deduced from helicopter forward speed and distance between vortex centres). This indicates that a vortex is formed in the smoke each time a rotor blade cuts it and the persistence of the vortex circulations downstream shows the system to be strongly established.

The rotation of the slipstream can be seen by the rolling up of the smoke filament plane, showing in the photographs as an apparent taper. This effect was particularly noticeable from visual observation during the tests.

6.2. *Induced Velocity Distribution.*—It will be seen from Figs. 8, 9 and 10 that at each of the three forward speeds the induced velocity increases from front to rear of the disc. The variation is substantially linear. A small upflow occurs over the leading 20 per cent or so of the rotor disc. The induced velocity at the rear edge is more than 100 per cent greater than the mean value of the induced velocity.

Over the area covered in the tests, *i.e.* from $0 \cdot 13R$ to $0 \cdot 4R$ on the side of the advancing blade, there does not appear to be any systematic variation in the distribution with lateral position. However due to the difficult nature of the tests and the scatter in the results, no definite con-conclusion may be made on this point.

6.3. *Comparison with Theory.*—Theoretical estimates of the induced velocity distribution for Coleman's method[3] and for Mangler's method (R. & M. 2642[4]) have been made and are also shown in Figs. 8, 9 and 10 for comparison with the flight tests.

In Coleman's work, the distributions are tangent approximations to the exact solutions which differ materially only at the extremities of the rotor disc. The assumptions made were given in section 1 of this report and the value of the induced velocity at the centre of the rotor is obtained from the formula

$$T = 2\rho\pi R^2 v_i V' \quad \ldots \quad (2)$$

i.e. the momentum equation giving a mean induced velocity under uniform distribution.

It will be seen that the induced velocity at the centre in the flight tests is somewhat lower than this value for each of the three forward speeds considered. Also, the rate of increase of induced velocity determined experimentally is greater than that estimated by the theoretical method of Ref. 3. It must be remembered that only a limited area was covered in the flight work and that some asymmetry to port and starboard sides of the rotor disc may exist.

Expressing the increase in induced velocity towards the rear of the rotor disc by the factor K (Ref. 3) where $K + 1$ is the ratio of induced velocity at the rear of the disc to that at the centre, and using the mean value at the centre as defined by equation (2) together with the slope of the best line through the experimental points, the value of K for the three speed conditions is of the order of 1·3. It is doubtful if the differences in K for the three conditions have any real significance as they are within the probable experimental error. If the values of K are based on the value of the experimental curves at the centre, the value of K becomes of the order of 1·6.

In Mangler's work, induced velocity contours are given over the disc area for several angles of incidence. It should be noted that the non-dimensional basis used in Ref. 3 differs from that used in this report and values of VC_T must be replaced by U_T.

For each of the forward speed conditions, the Mangler distributions for hemispherical load distribution over the disc (Type I in Ref. 3) and for 0 and 15 deg incidence and for a plane at $0 \cdot 4R$ from the centre have been plotted in Figs. 8, 9 and 10 together with the corresponding experimental results. It will be seen that these distrbutions give generally higher values of induced velocity over the aft part of the rotor disc. The agreement is considerably better at the highest forward speed than at the lowest and this may indicate that the applicability of the linearised theory is breaking down at the lower speeds. This would seem to be further confirmed by the fact that the greatest discrepancy is at the rear of the disc where the induced velocity is highest and also that at the rear of the disc the values are more sensitive to variation in incidence.

Another feature to be considered is that the Mangler distributions are symmetrical about the longitudinal axis and that the values vary rapidly across the lateral radius. In the flight tests the measurements were made on the side of the advancing blade and it is known that in forward flight conditions the spanwise loading varies considerably on the two sides. Hence a more uniform condition would give lower values of induced velocity towards the centre and would help to explain the higher values of the theoretical prediction.

7. *Conclusions.*—7.1. A technique for indicating the conditions of flow through a helicopter rotor in forward flight has been developed using smoke filaments to indicate the flow pattern.

7.2. The increase in induced velocity from front to rear of the disc has been determined over a limited area with reasonable accuracy.

7.3. The values of induced velocity are in fairly good agreement with existing theory ; the rate of increase of induced velocity determined experimentally is greater than given by Coleman's theory but less than that given by Mangler.

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No.	*Author*	*Title, etc.*
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2	P. Brotherhood	Flow through a Helicopter Rotor in Vertical Descent. R. & M. 2735. July, 1948.
3	Coleman, Feingold and Stempin ..	Evaluation of the Induced Velocity Field of an Idealised Helicopter Rotor. N.A.C.A./L5E10. June, 1945.
4	K. W. Mangler and H. B. Squire ..	Calculation of the Induced Velocity Field of a Rotor. R. & M. 2642. May, 1950.

FIG. 1. General flight technique.

a. Speed 44 m.p.h. Plane of smoke 0·3R to starboard

b. Speed 53 m.p.h. Plane of smoke 0·4R to starboard

c. Speed 60 m.p.h. Plane of smoke 0·3R to starboard

FIG. 2. Typical smoke photographs.

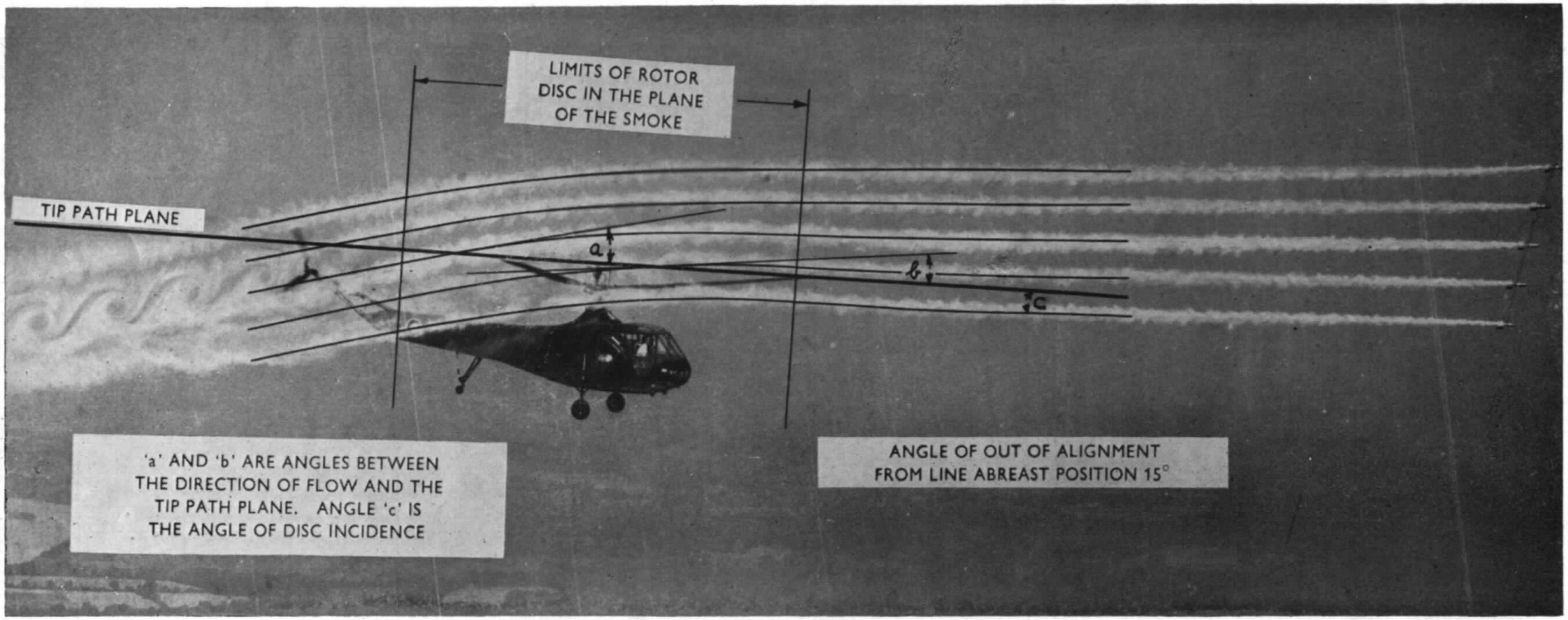

FIG. 3. An illustration of the method of analysis. Forward speed 53 m.p.h.

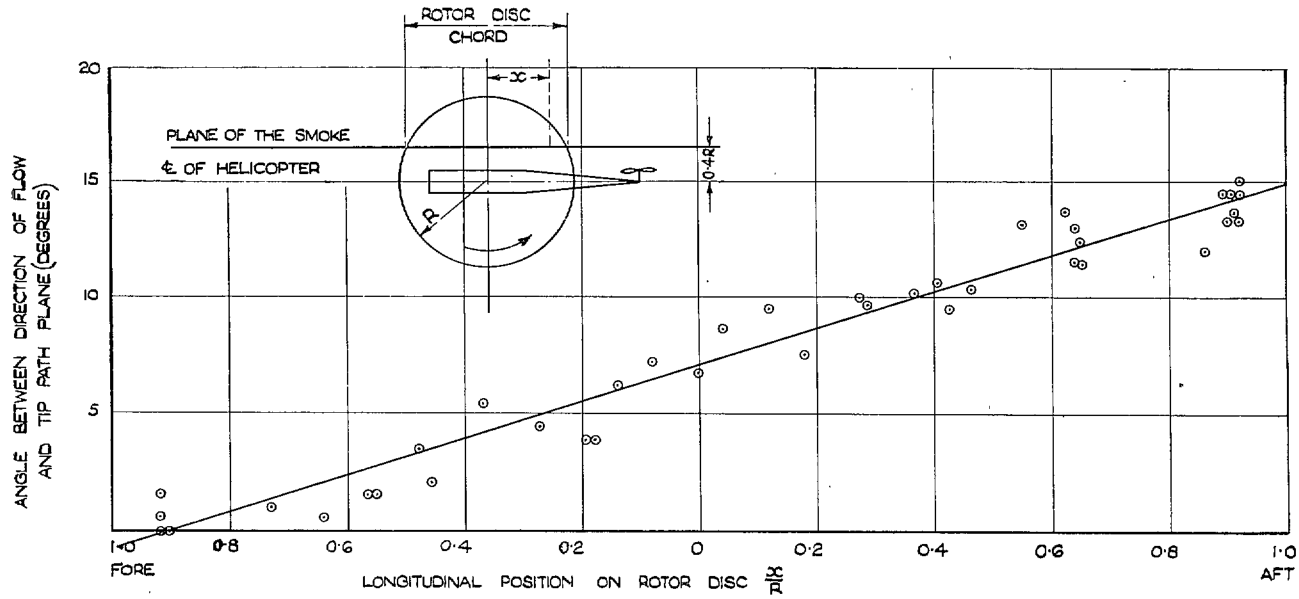

FIG. 4. Angles of flow at a forward speed of 44 m.p.h. ($\mu = 0 \cdot 138$). Plane of smoke $0 \cdot 4R$ to starboard.

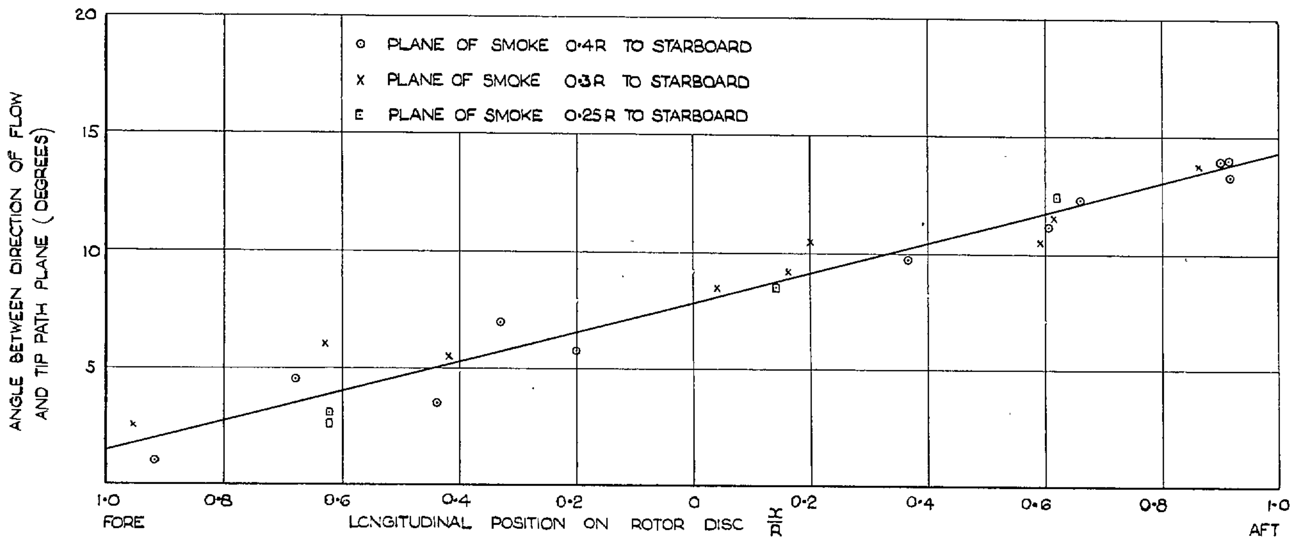

FIG. 5. Angles of flow at a forward speed of 53 m.p.h. ($\mu = 0 \cdot 167$). Plane of smoke $0 \cdot 25R$, $0 \cdot 3R$, and $0 \cdot 4R$ to starboard.

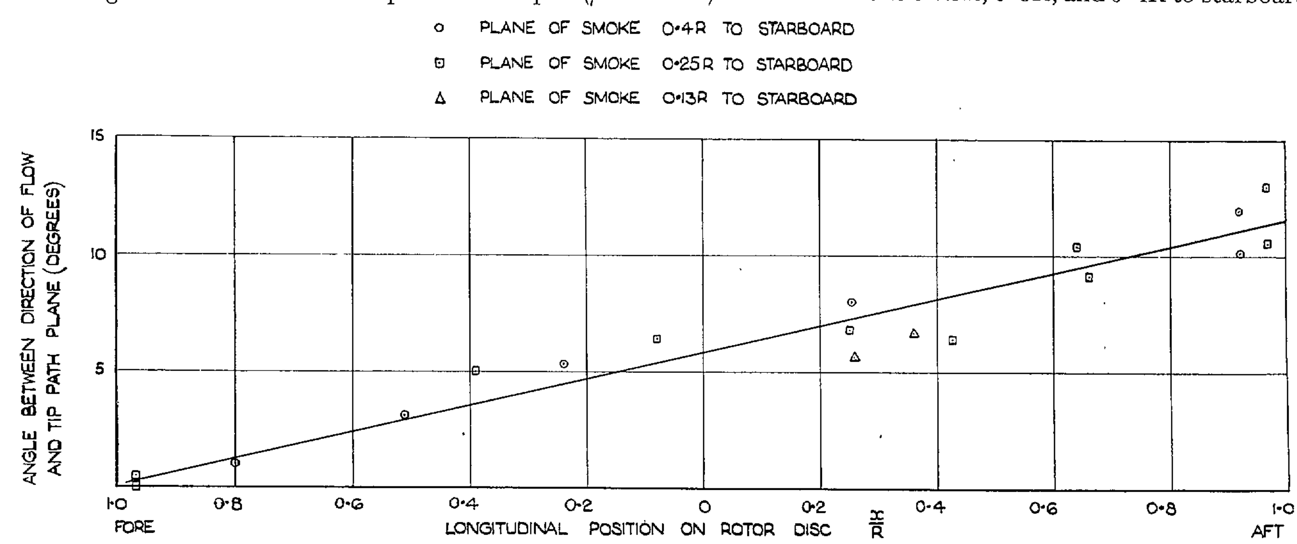

FIG. 6. Angles of flow at a forward speed of 60 m.p.h. ($\mu = 0 \cdot 188$). Plane of smoke $0 \cdot 13R$, $0 \cdot 25R$ and $0 \cdot 4R$ to starboard.

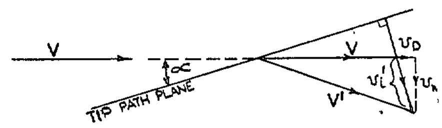

FIG. 7a.

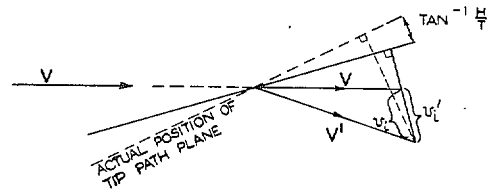

FIG. 7b.

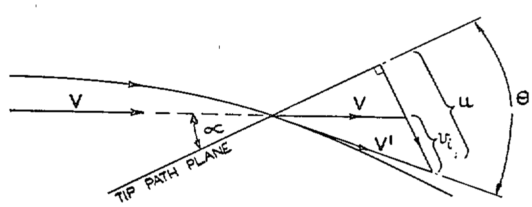

FIG. 7c.

Velocity diagrams.

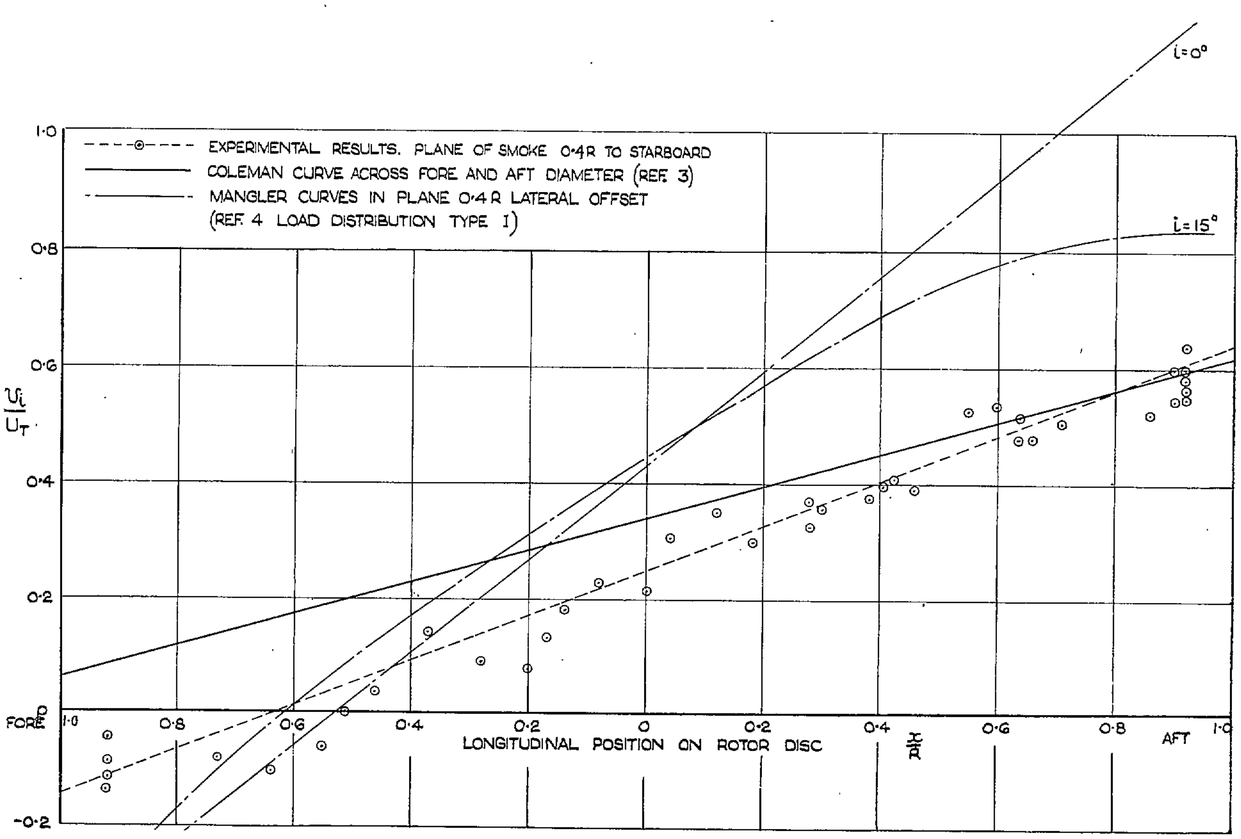

FIG. 8. Induced velocity distribution. Forward speed 44 m.p.h. ($\mu = 0 \cdot 138$).

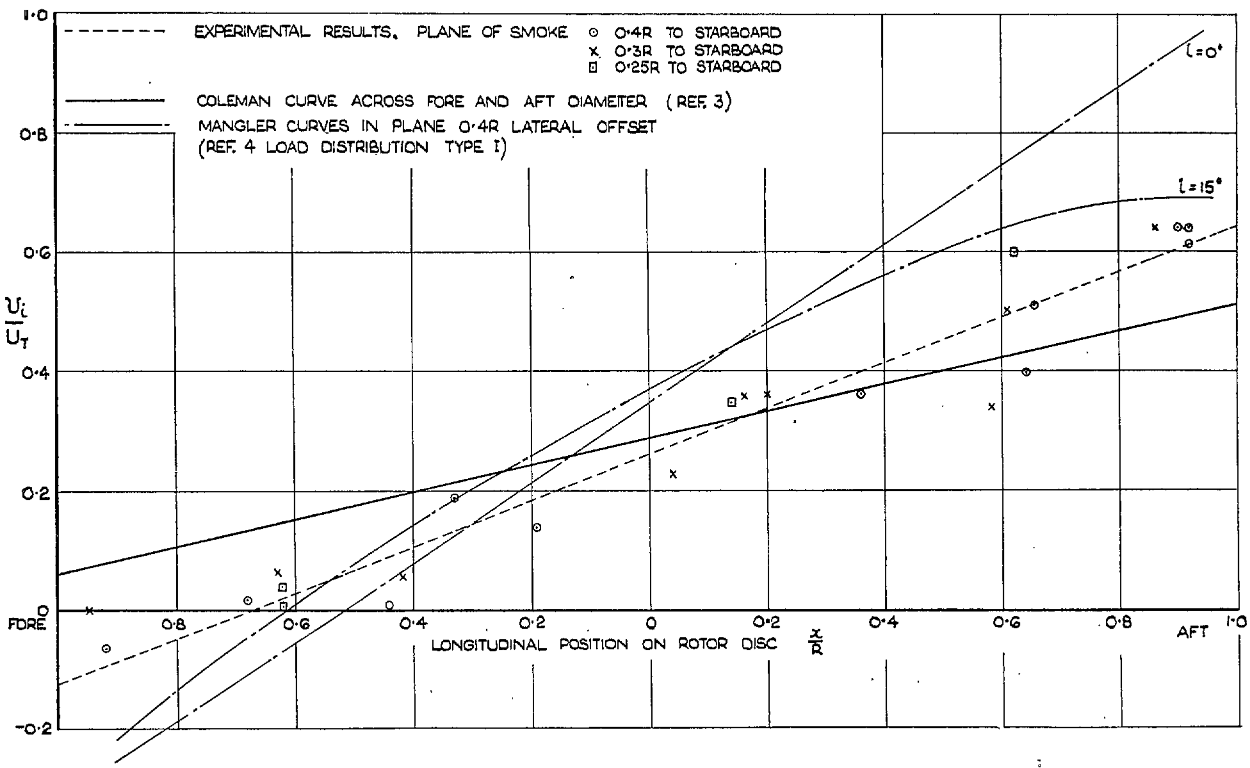

FIG. 9. Induced velocity distribution. Forward speed 53 m.p.h. ($\mu = 0 \cdot 167$).

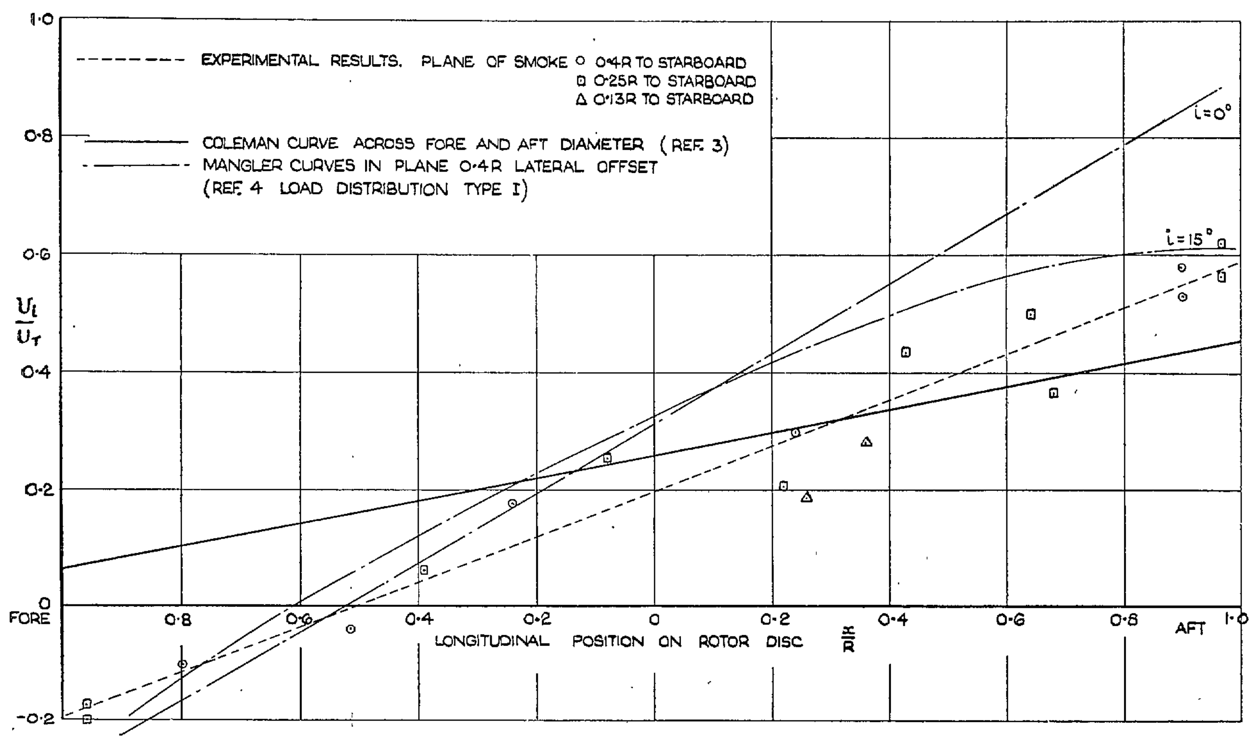

FIG. 10. Induced velocity distribution. Forward speed 60 m.p.h. ($\mu = 0 \cdot 188$).

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