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A METHOD OF CALCULATING THE EFFECT OF ONE HELICOPTER ROTOR UPON ANOTHER

By

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A method of calculating the effect of one helicopter rotor upon another

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Summary

A model of the induced flow around a lifting rotor is derived by considering a lifting line approximation to translational lift and a stream tube model for propeller lift. This theory is applied to a tandem rotor configuration in rectilinear flight. It is shown that the values derived are in good agreement with the available experimental results, which relate the case of no gap or stagger. In this special case the stream tube effect is negligible and only the lifting line approximation is used.

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1. Introduction

When helicopter rotors are moved into close proximity to one another, an interference flow is set up between these surfaces which results in a change of overall efficiency of the rotor configuration chosen. This change of efficiency will affect the performance of the rotor configuration and in certain cases may have a marked effect on the handling qualities. Thus any method which deals with rotor interference problems should, for completeness, treat the effect of any one rotor on any other independently. To do this it is necessary to determine the flow pattern around a single lifting rotor in free space. At least two methods (Refs. 1 and 2) have been developed to do this, but in Ref. 1 this has resulted in very complicated equations which have been graphed for a limited range of rotor operating parameters, while Ref. 2 gives a series of non dimensional curves which apply to certain flight conditions. Thus both methods are limited for practical application. Ref. 1 has been used by Squire (Ref. 3) to estimate the stability of a tandem rotor helicopter, while Ref. 2 is used in this report as one of a series of methods to be compared. Other methods have been developed to give the total interference power loss of a tandem rotor helicopter, those due to Stepniewski (Refs. 4 and 5) being notable for their simplicity. In Refs. 4 and 5 it is assumed that the flow line around a lifting rotor can be considered to be bounded by a stream tube, and that the interference experienced by one rotor can be found by calculating its intersection with the stream tube of the other rotor. While this method approximates to the total power loss of the system, it is not sufficiently detailed to give the performance of an individual rotor as is required for stability calculations. The method developed in the present report is an attempt to compromise between these two extreme approaches, in that it can be used in all flight states, for any number of rotors or rotor wing combinations, be sufficiently simple for rapid application, and still give sufficient accuracy for use in stability calculations.

2. Flow pattern in the vicinity of a lifting rotor

In forward flight the flow in the vicinity of a lifting rotor resembles that of an equivalent wing. In lifting line theory the flow pattern around a wing can be represented by a bound vortex located along the quarter chord line of the wing together with a trailing vortex from each wing tip. Such a model has been used to represent the flow around the rotor in the case of high forward speed flight. In hovering and flight at low forward speed the flow around the rotor resembles that in the neighbourhood of a propeller. By suitably combining these two pictures it is possible to develop a model which will apply over the whole speed range.

In lifting line theory the circulation K is given by

$$K = \frac{L}{2\rho sV}$$

where L is the lift of the wing of semi span s, V the airspeed and ρ the air density. It is proposed to use this expression to deduce the equivalent circulation when the lift referred to is not the total value but is simply that due to the rotor acting as a wing. If this fraction of the lift L is denoted by L_K, then L_K is obviously zero for vertical flight and increases with increasing airspeed. It is therefore assumed that L_K has the form

$$L_K = W\left\{1 - \frac{v}{v_o}\right\}$$

where W is the total weight of the helicopter, v the induced flow and v_o the induced flow in hovering. Thus

$$K = \frac{W\left\{1 - \frac{v}{v_o}\right\}}{2\rho RV} \qquad (1)$$

The trailing vortices of the conventional horseshoe pattern associated with the lifting line model are assumed to follow the total resultant flow

/immediately...

immediately beneath the rotor and they are thus inclined to the tip path plane at an angle θ which is given by

$$\tan \theta = -\frac{v + V \sin \alpha_D}{V \cos \alpha_D} = \frac{-u}{V \cos \alpha_D}$$

where α_D is the angle of the flight path relative to the tip path plane measured positive downwards from the rotor and u is the total flow normal to the tip path plane.

The flow due to the rotor acting as a propeller is assumed to be bounded by a cylinder of radius R and to move with a velocity -v; the cylinder is considered to make an angle θ to the tip path plane. It is appreciated that this does not allow for the vena-contracta and the associated increase in the value of v, but due to the uncertainty as to the distance below the rotor at which this contraction takes place, it is felt that the assumption made here is representative of the actual flow in the region considered.

A diagrammatic representation of the model is given in Fig. 1.

3. The interference between two rotors arranged in tandem

3.1 General. The layout to be considered is shown in Fig. 2, together with the flow pattern associated with each rotor. The gap G is the vertical separation and the stagger S the horizontal separation between the centres of the rotor tip path planes measured relative to the direction of the free stream. It should be noted that because the angle between the fuselage and the free stream direction depends on the flight condition the gap and stagger as defined of any particular helicopter will not be constant but will change with flight condition. The interference effect can be calculated by the sum of the effect due to the vortex pattern and that due to the propeller slip-stream. In each case the result is first expressed in terms of change in induced velocity at each rotor and this is then converted into equivalent expressions for the change in power and thrust.

3.2 Effect due to vortex pattern. The horseshoe pattern induces velocities V_x, V_y, V_z at a point X, Y, Z, relative to the axes shown in Fig. 2, which are given by the following expressions taken from Ref. 7.

$$V_x = \frac{K}{4\pi}\left\{\frac{Z}{x^2 + Z^2}\right\}\left\{\frac{y + R}{(x^2 + Z^2 + (y + R)^2)^{\frac{1}{2}}} - \frac{y - R}{(x^2 + Z^2 + (y - R)^2)^{\frac{1}{2}}}\right\} \quad (2)$$

$$V_y = \frac{-K}{4\pi}\left[\frac{-Z}{Z^2 + (y-R)^2}\left\{1 + \frac{x}{(x^2 + Z^2 + (y-R)^2)^{\frac{1}{2}}}\right\} + \frac{Z}{Z^2 + (y+R)^2}\left\{1 + \frac{x}{(x^2 + Z^2 + (y+R)^2)^{\frac{1}{2}}}\right\}\right] \quad (3)$$

$$V_z = \frac{-K}{4\pi}\left\{\frac{x}{x^2 + Z^2}\left[\frac{y + R}{\{x^2 + Z^2 + (y+R)^2\}^{\frac{1}{2}}} - \frac{y - R}{\{x^2 + Z^2 + (y-R)^2\}^{\frac{1}{2}}}\right] - \frac{y - R}{Z^2 + (y-R)^2}\left[1 + \frac{x}{\{x^2 + Z^2 + (y-R)^2\}^{\frac{1}{2}}}\right] + \frac{y + R}{Z^2 + (y+R)^2}\left[1 + \frac{x}{\{x^2 + Z^2 + (y+R)^2\}^{\frac{1}{2}}}\right]\right\} \quad (4)$$

/For...

For the tandem rotor configuration in rectilinear flight the induced flow due to one rotor on the other is symmetrical about the line of flight so that the mean value of V_y across the rotor will be zero. Due to the nearness of the two rotors, and to the simplifying assumption that the translational lift can be represented by a lifting line approximation, there is nothing to be gained by attempting to calculate a mean induced effect over the complete rotor disc; the usual biplane approximation of calculating the effect along the position of the lifting line will be used in this work.

The value of x and z in equations 2 and 4 is therefore that of the centre of the second rotor referred to the axes of co-ordinates based on the other rotor; these values may be denoted by x_o and z_o where

$$x_o = S\cos(\phi + \alpha_{D1}) - G\sin(\phi + \alpha_{D1})$$

$$z_o = G\cos(\phi + \alpha_{D1}) - S\sin(\phi + \alpha_{D1})$$

Thus mean values of V_x, V_y and V_z denoted by $\overline{V}_x$, $\overline{V}_y$ and $\overline{V}_z$ are given by

$$\overline{V}_x = \frac{1}{2R}\int_{-R}^{R}\frac{K}{4\pi}\left\{\frac{z_o}{x_o^2 + Z_o^2}\right\}\left\{\frac{y+R}{\{x_o^2 + Z_o^2 + (y+R)^2\}^{\frac{1}{2}}} - \frac{y-R}{\{x_o^2 + Z_o^2 + (y-R)^2\}^{\frac{1}{2}}}\right\}dy \tag{5}$$

$$\overline{V}_y = 0. \tag{6}$$

$$\overline{V}_z = \frac{-1}{2R}\int_{-R}^{R}\frac{K}{4\pi}\left\{\frac{x_o}{x_o^2+Z_o^2}\left[\frac{y+R}{\{x_o^2+Z_o^2+(y+R)^2\}^{\frac{1}{2}}} - \frac{y-R}{\{x_o^2+Z_o^2+(y-R)^2\}^{\frac{1}{2}}}\right]\right.$$

$$- \frac{y-R}{Z_o^2 + (y-R)^2}\left[1 + \frac{x_o}{\{x_o^2 + Z_o^2 + (y-R)^2\}^{\frac{1}{2}}}\right]$$

$$\left. + \frac{y+R}{Z_o^2 + (y+R)^2}\left[1 + \frac{x_o}{\{x_o^2 + Z_o^2 + (y+R)^2\}^{\frac{1}{2}}}\right]\right\}dy \tag{7}$$

Evaluating the integrals by simple substitutions it is found that

$$\overline{V}_x = \frac{K}{4\pi R}\;\frac{Z_o}{x_o^2 + Z_o^2}\left\{\left[x_o^2 + Z_o^2 + 4R^2\right]^{\frac{1}{2}} - \left[x_o^2 + Z_o^2\right]^{\frac{1}{2}}\right\} \tag{8}$$

$$\overline{V}_z = \frac{-K}{4\pi R}\left\{\frac{x_o}{x_o^2 + Z_o^2}\left[\left[x_o^2 + Z_o^2 + 4R^2\right]^{\frac{1}{2}} - \left[x_o^2 + Z_o^2\right]^{\frac{1}{2}}\right]\right.$$

$$\left. + L_n\left[\frac{\sqrt{x_o^2 + Z_o^2} + x_o}{\sqrt{x_o^2+Z_o^2+4R^2} + x_o} \times \frac{Z_o^2 + 4R^2}{Z_o^2}\right]\right\} \tag{9}$$

For a point upstream of the lifting rotor the expression for $\overline{V}_x$ remains unchanged; x_o is now negative in $\overline{V}_z$ and the L_n term will be small since the distance from the trailing vortices to the point in question will in general be large. It will be noted that

$$x_o^2 + Z_o^2 = S^2 + G^2$$

/and...

and this is a characteristic of the helicopter, being equal to the distance between the rotor hubs squared.

$\overline{V}_x$ and $\overline{V}_z$ are resolved into two components normal and parallel to the rotor tip path plane, the normal velocity component $\Omega R \delta\lambda$ is given by

$$\Omega R \delta\lambda = -\left[\overline{V}_z \cos\left\{\varphi - \alpha_{D2} + \alpha_{D1}\right\} - \overline{V}_x \sin\left\{\varphi - \alpha_{D2} + \alpha_{D1}\right\}\right] \quad (10)$$

and the component parallel to the disc, $\Omega R \delta\mu_D$ by.

$$\Omega R \delta\mu_D = \overline{V}_x \cos\left(\varphi - \alpha_{D2} + \alpha_{D1}\right) - \overline{V}_z \sin\left(\varphi - \alpha_{D2} + \alpha_{D1}\right) \quad (11)$$

where Ω is the rotational speed of the rotor.

3.3 Effect due to propeller slipstream. For the tandem rotor configuration illustrated in Fig. 2, it can be seen that part of the front rotor will experience a loss of lift due to the downwash from the rear rotor. The rear rotor will experience a loss in lift due to the flow into the front rotor, but since the change induced in the flow above and upstream of a rotor in the power on flight condition is much smaller than the change induced in the flow pattern beneath the same rotor, the loss in lift by the rear rotor will be small by comparison with the loss of lift of the front rotor and will be neglected. The increase δu in the mean value of the induced flow u over the whole disc can be expressed as

$$\delta u = u \frac{\delta A}{A} \quad (12)$$

where δA is the masked area of the rotor disc of area A, and assuming as in para. 2 that the increase in velocity below the rotor disc to the vena contracta is negligible in the region considered. Since the mean downwash from the rotor inclined backwards at an angle φ, δA will be the area of intersection between two circles of radius R with centres separated by S' where

$$S' = S - G\frac{V}{u}$$

Thus $\delta A/A$ is expressed by

$$\frac{\delta A}{A} = \frac{2}{\pi}\left\{\cos^{-1}\left(\frac{S'}{2R}\right) - \frac{S'}{2R}\left(1 - \frac{S'^2}{4R^2}\right)^{\frac{1}{2}}\right\} \quad (13)$$

provided that $S' < 2R$. Hence combining 12 and 13 and dividing by ΩR it is found that

$$\delta\lambda = \frac{2\lambda}{\pi}\left\{\cos^{-1}\left(\frac{S'}{2R}\right) - \frac{S'}{2R}\left(1 - \frac{S'^2}{4R^2}\right)^{\frac{1}{2}}\right\} \quad (14)$$

There will also be a small contribution to $\delta\mu_d$ but for the usual values of G and S this is negligible.

Combining equations (10) and (14) together gives the change in λ due to slipstream and vortex effects, so that the combined equation together with equation (11) will enable the performance of one rotor in the field of another to be calculated.

4. The performance of two rotors arranged in tandem

4.1 General. The performance of a rotor is given in blade element theory by the expression for thrust T and torque Q,

$$T = \frac{1}{2}\rho\, a\, b\, c\, \Omega^2 R^3 \left\{\frac{\theta}{3} + \frac{\lambda}{2} + \frac{1}{2}\mu_d^2\theta\right\} \quad (15)$$

$$Q = \frac{1}{2}\rho\, b\, c\, \Omega^2 R^4 \left\{\frac{\delta}{4}(1 + \mu_d^2) - a\lambda\frac{\theta}{3}\right\} \quad (16)$$

/when...

when a is the lift curve slope of the blade section, b the number of blades in the rotor, c the mean chord, θ the geometrical collective pitch, μ_d the tip speed ratio, λ the inflow ratio and Δ the mean drag of the blade at a mean lift coefficient C_L. When this rotor is moved into the vicinity of another rotor assuming that the controls of the rotors are fixed, the thrust T, and torque Q, are given by

$$T_1 = \frac{1}{2}\rho a b c \Omega^2 R^3 \left\{ \frac{\theta}{3} + \frac{\lambda}{2} + \frac{\delta\lambda}{2} + \frac{1}{2}(\mu_d + \delta\mu_d)^2 \theta \right\} \qquad (17)$$

and

$$Q_1 = \frac{1}{2}\rho b c \Omega^2 R^4 \left\{ \frac{\Delta}{4} (1 + [\mu_d + \delta\mu_d]^2) - a(\lambda + \delta\lambda)\frac{\theta}{3} \right\} \qquad (18)$$

Hence, to the first order of small quantities,

$$\frac{T_1}{T} = 1 + \frac{1}{2}\left\{ \frac{\delta\lambda + 2\mu_d\, \delta\mu_d \theta}{\frac{\theta}{3} + \frac{\lambda}{2} + \frac{\mu_d^2}{2}\theta} \right\} \qquad (19)$$

and

$$\frac{Q_1}{Q} = 1 + \frac{\frac{1}{2}\Delta\mu_d\,\delta\mu_d - a\,\delta\lambda\,\theta/3}{\frac{\Delta}{4}(1 + \mu_d^2) - a\lambda\frac{\theta}{3}} \qquad (20)$$

$\delta\lambda$ is very much larger than $\delta\mu_d$ for normal values of G and S and hence it can be seen from equations (19) and (20) that the effect of one rotor on another is to decrease the thrust and increase the torque when $\delta\lambda$ is negative i.e. when the rotor being considered is above the datum rotor.

4.2 <u>Calculation of the interference power loss for a tandem rotor configuration operating at twice the weight of an equivalent single rotor helicopter.</u> If in any flight condition a rotor operating at particular values of μ_d, λ, Ω, θ and producing a thrust T, is brought into the vicinity of another rotor it will experience a decrease in thrust if Ω and θ are kept constant. To maintain constant thrust θ is increased to $\theta + \delta\theta$, where

$$\delta\theta \left\{ \frac{1}{3} + \frac{\mu_d^2}{2} \right\} = -\left\{ \frac{\delta\lambda}{2} + \mu_d\, \delta\mu_d\, \theta \right\} \qquad (21)$$

to the first order of small quantities provided that Ω is kept constant. In keeping Ω constant the torque Q will increase to Q_2 given by

$$Q_2 = \frac{1}{2}\rho b c \Omega^2 R^4 \left\{ \frac{\Delta}{4}(1 + (\mu_d + \delta\mu_d)^2) - \frac{a}{3}(\lambda + \delta\lambda)(\theta + \delta\theta) \right\}$$

$$= Q + \frac{1}{2}\rho b c \Omega^2 R^4 \left\{ \frac{\Delta}{2}\mu_d\,\delta\mu_d - \frac{a}{3}(\theta\,\delta\lambda + \lambda\,\delta\theta) \right\} \qquad (22)$$

Substituting from equation (21) for $\delta\theta$, equation (22) becomes

$$Q_2 = Q + \frac{1}{2}\rho b c \Omega^2 R^4 \left\{ \mu_d\,\delta\mu_d \left[\frac{\Delta}{2} + a\frac{\lambda}{3}\frac{\theta}{(\frac{1}{3} + \mu_d^2/2)} \right] - \frac{a\,\delta\lambda}{3}\left[\frac{\lambda}{2(\frac{1}{3} + \mu_d^2/2)} - \theta \right] \right\} \qquad (23)$$

/Hence...

Hence the increase in power δP is given by

$$\delta P = \tfrac{1}{2}\rho b c \Omega^3 R^4 \left\{ \mu_d \, \delta\mu_d \left[\frac{\Delta}{2} + a \frac{\lambda}{3} \; \frac{\theta}{(\frac{1}{3} + \mu_d^{\,2}/2)} \right] - a \frac{\delta\lambda}{3} \left[\frac{\lambda}{2\,(\frac{1}{3} + \mu_d^{\,2}/2)} - \theta \right] \right\} \qquad (24)$$

5. Comparison of theory and experiment

The theory developed here has been compared with some of the theories discussed in para. 1 for the case of a tandem rotor helicopter with rotors comparable to those of the Bristol type 173 Mks. 1 and 2, and in a flight condition where G = 0 and S = 2R. It is seen from Fig. 3 that the earliest theory of Stepniewski (Ref. 4) is in closest agreement with the present method. The theory of Ref. 4 was designed for this configuration only and was used in the development of the Piasecki H.21 helicopter which has G = 0 and S = 2R and the agreement with it of the present theory is encouraging. Although it must be noted that the propeller slipstream effect is negligible when there is no gap,and stagger is equal to twice the rotor radius and that only the "lifting line"part of the theory is confirmed by this argument. The more advanced method of Stepniewski(Ref.5),which was designed to allow for variation in S, shows poorer agreement with the present theory. Comparing with the more elegant method of Castles and de Leeuw (Ref. 2) reasonable agreement is found particularly at speeds where δ P is a maximum. The present theory is therefore found to be in reasonable agreement with the established methods of References 2 and 4 for the case G = 0 and S = 2R; which uses only the "lifting line" part of the theory; its advantages over these methods have been discussed in para. 1.

In Reference 8 Dingldein has made an experimental study of a model tandem rotor configuration again with no gap and S = 2R and has compared the results obtained with the theory of Castles and de Leeuw. In this comparison it was shown that reasonable agreement existed at low forward speeds but that the theory was optimistic at high speed. A comparison of the experimental results of Reference 8 and the present theory is shown in Fig. 4 from which it can be seen that the agreement is good over the whole speed range.

Figure 5 shows the interference power curve calculated for the Bristol 173 which has G,= 0.20, S = 1.7 R. Comparison with the curve for S = 0 and G = 2R copied from Fig.3 shows that the effect of the change of gap and stagger is only noticeable at low speeds.

6. Conclusion

The theory which has been developed in this report is applicable to any multi-rotor configuration and to any flight condition other than when a rotor is working in the vortex ring state. Comparison of the theory and the only reliable set of experimental results has shown good agreement over the whole of the speed range tested, the experimental conditions being such that only the "lifting line" part of the present theory could be confirmed.

This method can obviously be extended to cover the case of lifting wing-rotor configurations. It may also be modified to cover the case of yawed flight of a tandem rotor helicopter which is important for stability considerations.

7. Acknowledgements

I wish to record my appreciation of the assistance given me by G. F. Langdon in his helpful criticisms and suggestions (in particular the form of the equation for L_K), and by S. White who carried out much of the computation work.

/References...

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/List of Symbols...

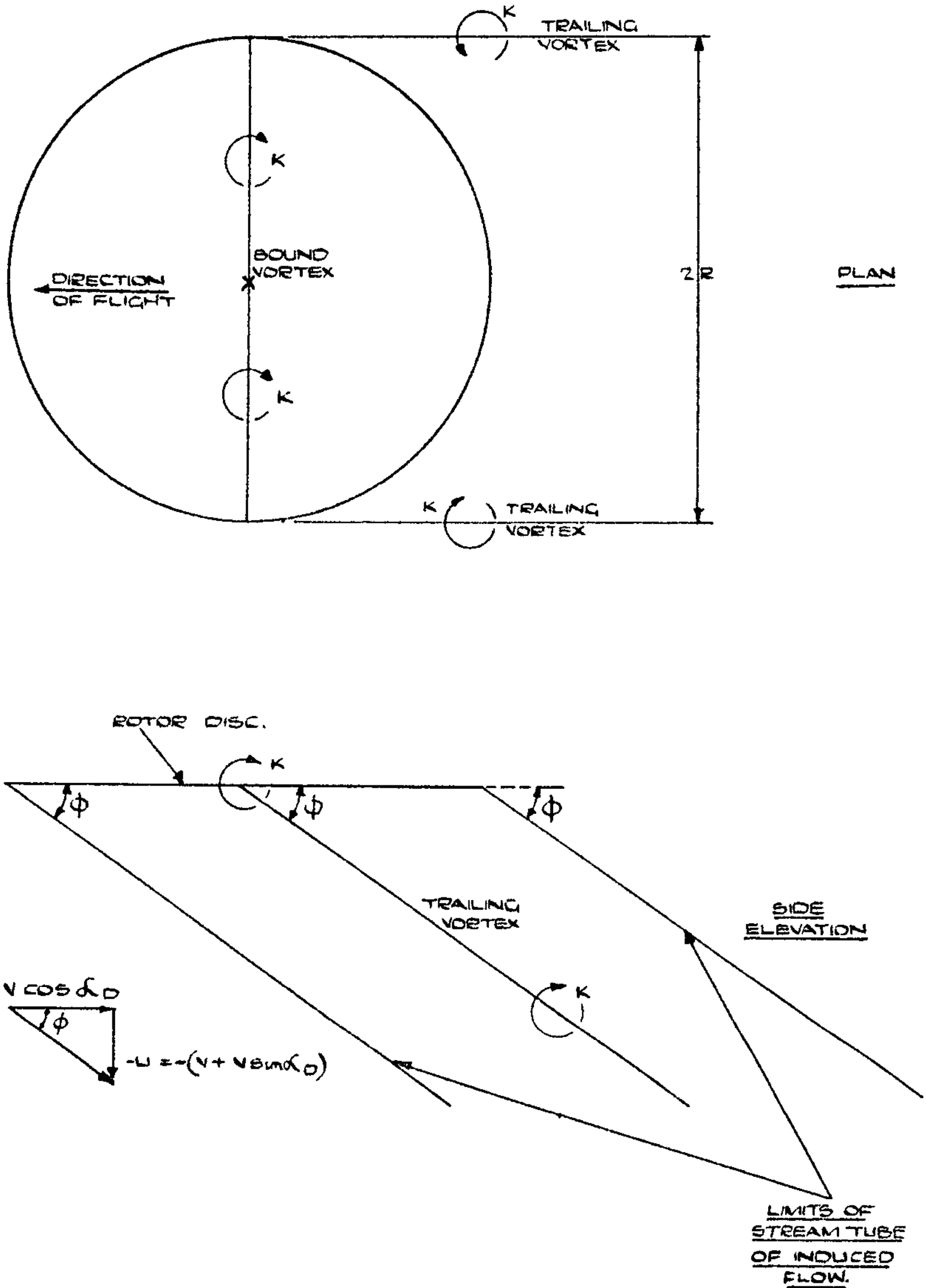
List of Symbols

a	lift curve slope of rotor blade section
A	area of rotor
δA	area of front rotor masked by rear motor
b	number of blades per rotor
c	rotor blade mean chord
G	gap between rotors - see Fig. 1.
K	circulation over aerofoil
L	lift of wing
L_K	translational lift of helicopter rotor.
P	rotor power
δP	change in rotor power due to interference effects
Q	rotor torque
Q_1	rotor torque defined by equation 20.
Q_2	rotor torque defined by equation 24.
R	rotor radius
s	wing semi span
S	stagger between rotors - see Fig. 1.
S'	$S - G\ V/u$
T	thrust of single rotor
T_1	rotor thrust defined by equation 19.
u	total flow normal to the rotor, negative for flow downward
V	forward airspeed
v	induced flow of rotor at a forward speed V, negative for flow downward
v_o	induced flow of rotor in hovering, negative for flow downward
V_h	$\left(W/2\pi\rho_o R^2\right)^{\frac{1}{2}}$, negative for flow downward
V_x, V_y, V_z	velocities at point x, y, z, induced by horseshoe vortex pattern.
W	all up weight of helicopter
x, y, z	co-ordinates of point relative to axes shown in Fig. 2
x_a	$S\cos(\varphi - \alpha_{D1}) - G\sin(\varphi - \alpha_{D1}) - R\cos(\varphi + \alpha_{D2} - \alpha_{D1})$
x_b	$S\cos(\varphi - \alpha_{D1}) - G\sin(\varphi - \alpha_{D1}) + R\cos(\varphi + \alpha_{D2} - \alpha_{D1})$
α_D	angle of flight path relative to tip path plane - negative upwards

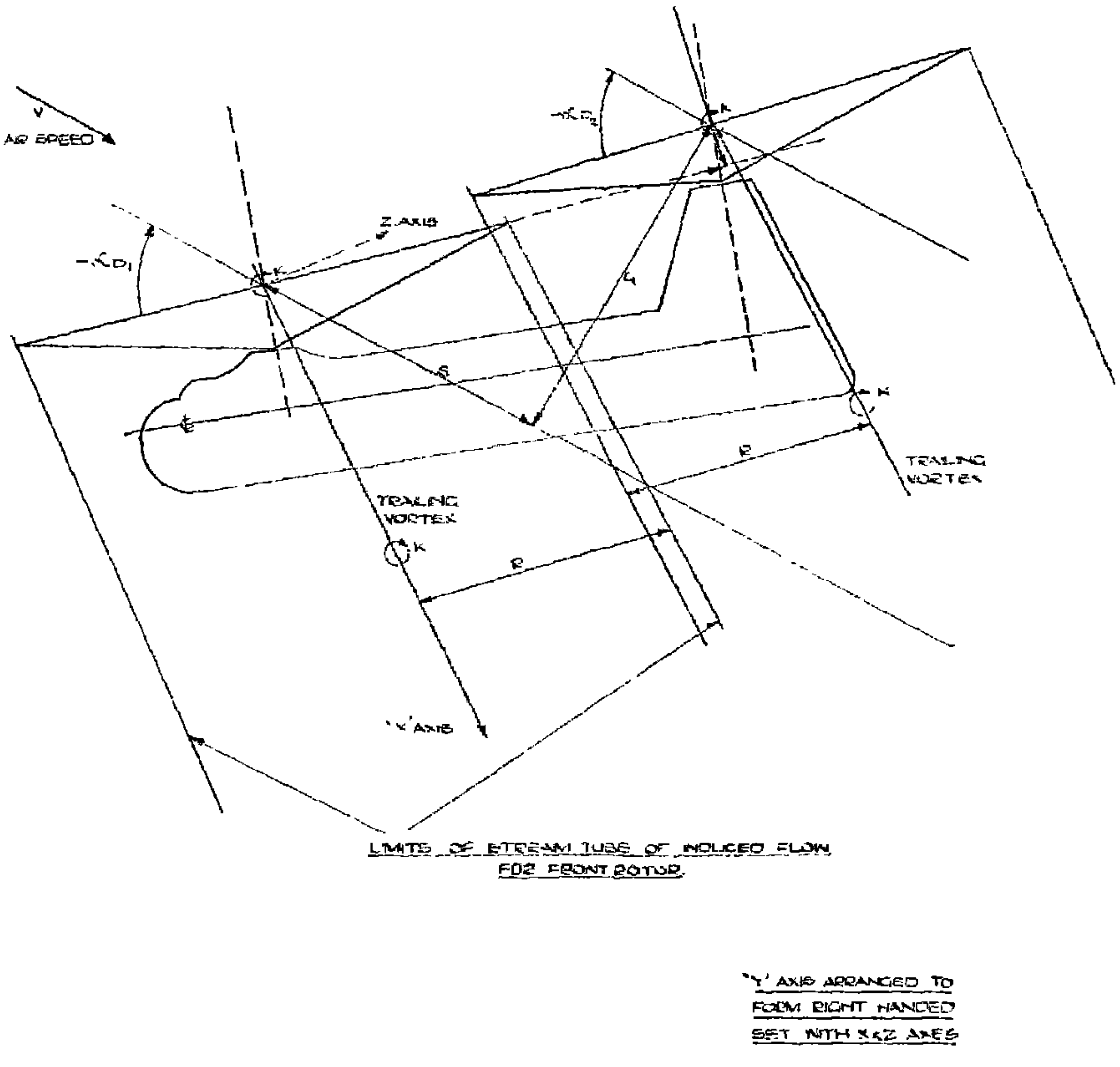
/Δ...

δ	mean drag of rotor blade operating at a mean C_L
θ	geometrical collective pitch
λ	$u / \Omega R$
μ_d	$V \cos \alpha_D / \Omega R$
ρ	air density
ϕ	$\tan^{-1} \left\{ -u/V \cos \alpha_D \right\}$

FIG. 1.

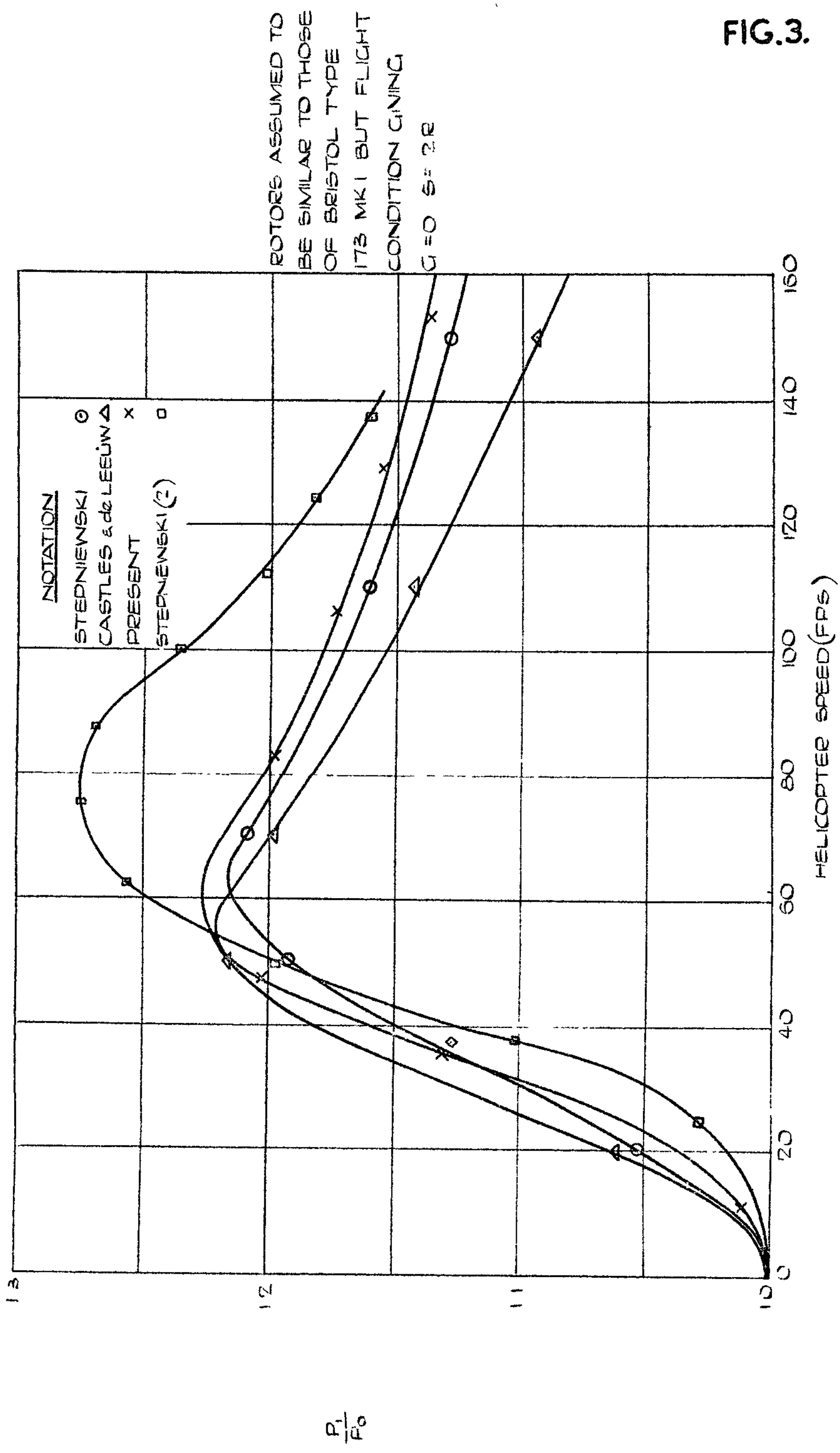


DIAGRAMMATIC REPRESENTATION OF FLOW AROUND A LIFTING ROTOR.



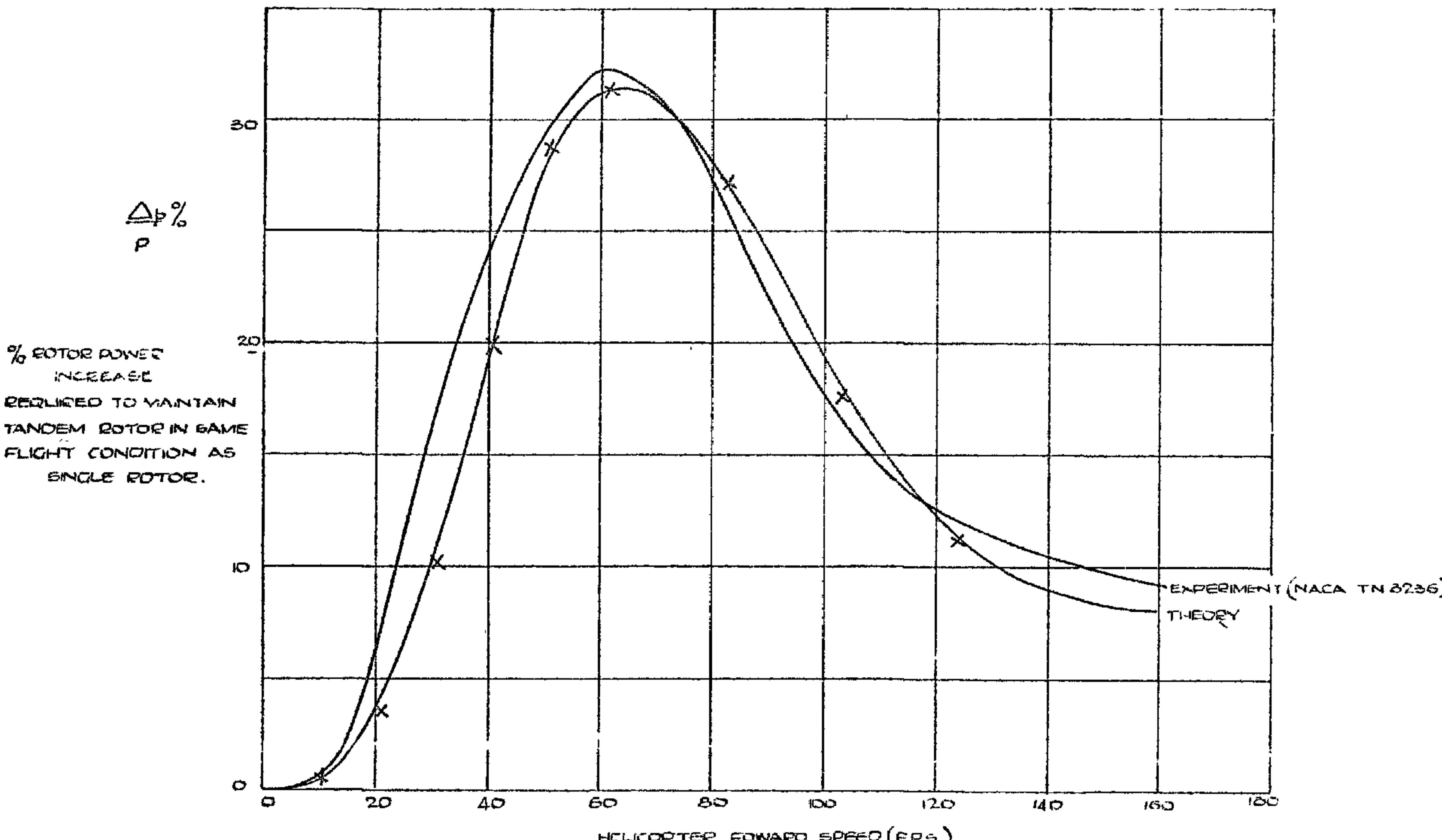
DIAGRAMMATIC REPRESENTATION OF FLOW AROUND A TANDEM ROTOR CONFIGURATION.

FIG.3.



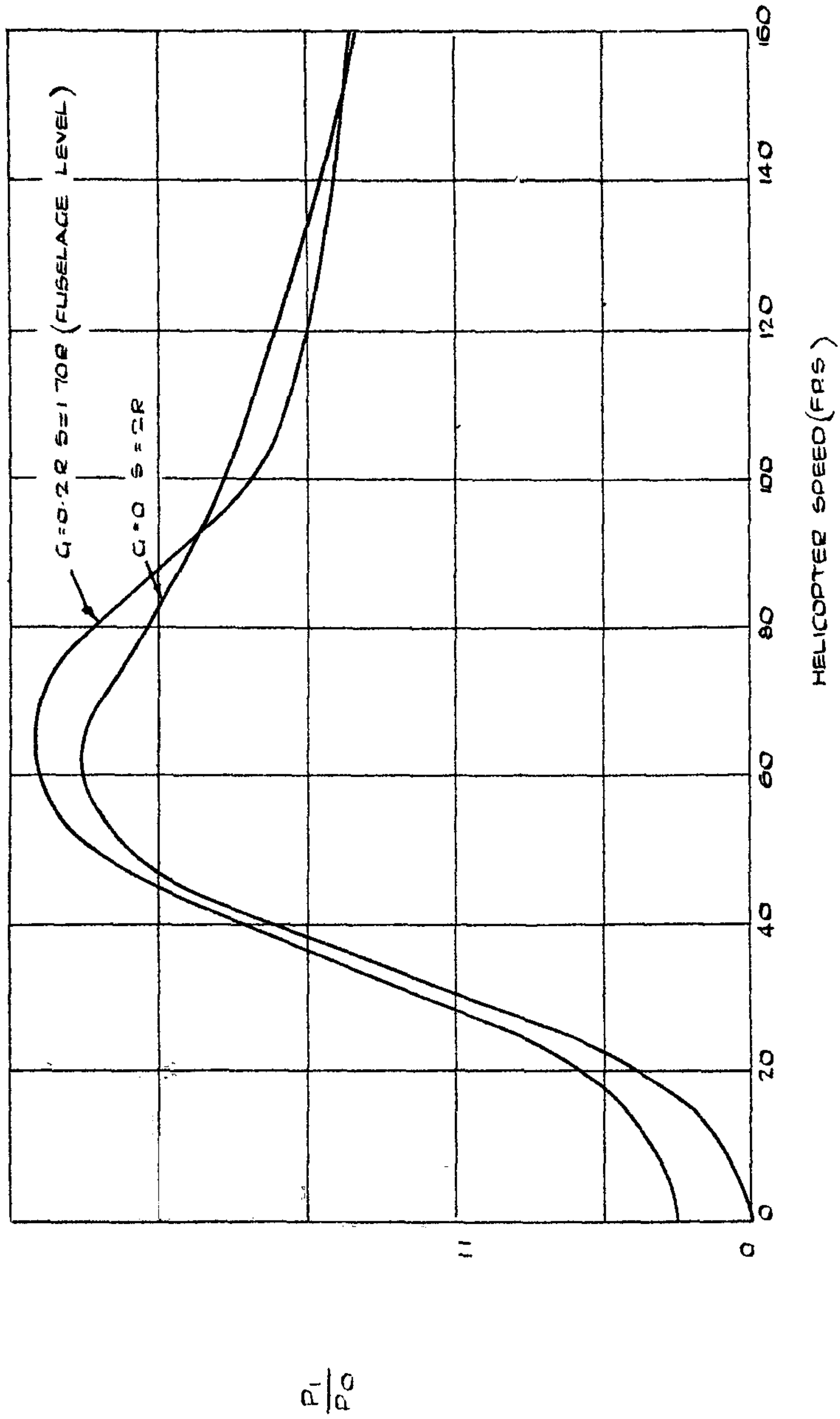
COMPARISON OF THEORETICAL METHODS.

FIG.4.



ROTOR POWER INCREASE REQUIRED BY A ROTOR OPERATING IN A TANDEM CONFIG-URATION OVER THAT OF A SINGLE ROTOR AGAINST AIRSPEED G=O S=2R.

FIG 5.



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