Some Recent Helicopter Research Investigations

By WM STEWART, B Sc

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H B SQUIRE, ESQ, M A, F R Ae S
in the Chair

INTRODUCTION BY THE CHAIRMAN

The CHAIRMAN, in his introductory remarks, said Mr Stewart left Glasgow University in 1942, since when he has been at R A E and has specialized in helicopter work since 1945 He has made some extremely valuable contributions to the study of helicopters and is now the leader of a group doing flight testing at R A E He gave an important lecture to the Royal Aeronautical Society on the research of helicopters in 1948, and to-night he is giving an account of some more recent work

MR W STEWART

In this lecture, there is only time to discuss a few of the recent items of helicopter research In making this selection, I have tried to avoid subjects which have been discussed during the recent lectures However, while the selection was not easy to make, it is most encouraging to helicopter development that there is such a number of items which could have been included Nevertheless, we are still at a very early stage in the evolution of suitable helicopters for military and for economic commercial operation, and in this respect, the research work we have been able to do is but a small contribution by comparison with the effort needed, if these appropriate military and civil helicopter types are to become available in a reasonable time

A general programme of helicopter research covers very many aspects, *e g*, performance, stability and control, fundamental airflow investigations, operational problems and many other items The attack on these problems may be made by theoretical investigation, by flight testing, by use of a rotor tower, by testing models in the wind tunnel or by any combination of these methods In fact, one of the most important aspects of research is the proper correlation of theoretical investigations with practical results This

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is particularly important in the interpretation of wind tunnel tests where very little work with helicopter models has been done so far and we must be careful with the application of these results In fact, we have only started to establish to what extent the wind tunnel can assist in helicopter work

We have had some excellent lectures in the Helicopter Association covering flight work, such as those by Mr O'HARA and Capt FAY I have therefore tended to leave out flight testing and made the selection of research items from the other methods of approach While introducing theoretical aerodynamics, I have attempted to deal with it in a non-mathematical way The effect of frequency ratio on rotor behaviour is one of the more important recent extensions to rotor aerodynamics This effect is discussed and it is then used in conjunction with the wind tunnel tests of an oscillating rotor to illustrate the interpretation of such results

Now that the helicopter is becoming established in operational use, general interest at present seems to be concentrated on what increases in size and in forward speed we may expect The question of size has been most stimulatingly dealt with by Mr FITZWILLIAMS and I have therefore selected an item contributing to forward speed improvements

FREQUENCY RESPONSE THEORY

In dealing with many problems in stability and control of the helicopter, quite sweeping assumptions have sometimes to be made One of these assumptions which used to be made was the use of quasi-static conditions during transient motion Strangely enough, flight tests with various helicopters seemed to confirm that this method was satisfactory whereas wind tunnel tests—which can of course be conducted under much more closely controlled conditions—made the quasi-static theory appear to be inadequate or to indicate a serious scale effect The development of what is referred to as frequency response theory will now be discussed This theory takes into account the detailed behaviour of the blades during transient helicopter motion

It is well-known that, if we take an ordinary rotor with flapping hinges and tilt the shaft through a given angle, the rotor will follow the shaft and will finally take up the same position relative to the shaft It has also been established that, as a rotor shaft tilts with constant angular velocity, the rotor disc will lag behind the shaft tilt by an angle proportional to the tilting velocity In quasi-static theory, it is assumed that, if a transient motion is imposed on the shaft, the disc lag at any instant is proportional to the shaft tilting velocity at that instant

Let us now consider a shaft which is tilted in a sinusoidal motion If the period of oscillation is very long compared with the rotational period (time for one revolution of the rotor) the quasi-static conditions should be quite satisfactory As the two periods approach each other, we would anticipate some divergence in practice from the quasi-static theory The frequency ratio is therefore a fundamental parameter in work on transient motion If the sinusoidal motion applied to the shaft is denoted by

$$\alpha = \alpha_0 \sin \nu t$$

and Ω is the rotor speed, the frequency ration is given by

$$\bar{\nu} = \frac{\nu}{\Omega}$$

The other important parameter in blade response is the specific damping of the blade This term is well understood and its value has been verified in many experiments For an ordinary blade, the specific damping is given by

$$K = \frac{\gamma B^4}{16}$$

where γ is the blade inertia number
B is a tip loss factor

The method can also be applied to other gyratory systems, such as the Hiller servo or Bell stabiliser layouts, if the appropriate specific damping is used

For the Hiller,

$$K = \frac{\gamma_s}{16}(1 - B_s{}^4)$$

where γ_s is the inertia number of the servo blades,
B_s is the beginning of the profile of the servo blade as a fraction of its radius

For the Bell, the specific damping is obtained from the equation

$$\text{Damping moment} = 2KI\Omega\beta$$

where I is the moment of inertia of the bar system about the pivot, and β is the flapping velocity

Since the Bell stabiliser specific damping is generally referred to in terms of the " following time " T_f, the value of K can be given in the form

$$K = \frac{2\,3}{T_f\Omega}$$

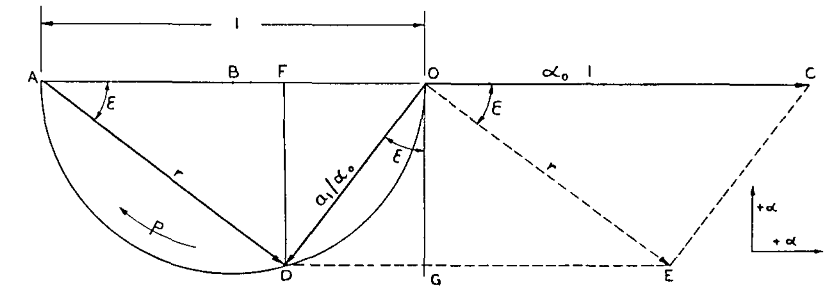
If we write the complete equations of motion for the blade system due to the enforcing oscillation of the shaft, we can derive solutions for the longitudinal and lateral flapping motion in terms of the frequency ratio and specific damping It is not intended to deal with the derivation of the equations of motion or their solution here but only to discuss briefly the results obtained To do this, a vector system has been derived

If we apply a sinusoidal shaft tilt of amplitude α_0 and obtain a rotor disc flapping amplitude of a_1 relative to the shaft, we may plot these as vectors at the appropriate phase angle to each other Alternatively, we may denote the shaft displacement by unity and plot the rotor response as a_1/α_0

In ordinary quasi-static theory, where the rotor lag angle is only proportional to the tilting velocity of the shaft, the disc flapping is at a phase angle of 90 degrees to the shaft displacement, *i e*, along the negative α direction Taking the complete equations of motion, the amplitude and phase angle depend on the function frequency ratio divided by specific damping $\bar{\nu}/K$ In the sinusoidal oscillation case, the locus is a semi-circle with its diameter on the negative α axis and lying in the the negative α and negative α quadrant (see Fig 1)

The a_1 vector can be considered as consisting of two components, one in counterphase with attitude and one in counterphase with angular velocity In the present discussion, the former of these is the most significant as it increases rapidly with increase in frequency ratio whereas it does not exist in the simple quasi-static theory This attitude component has sometimes been referred to as an acceleration derivative but this can lead to serious confusion in the appreciation of rotor behaviour

An idea of the order of the frequency ratio effect may be obtained by considering a few practical examples If we take the longitudinal stability of the ordinary present day helicopter with a period of about 16 sec the value of $\bar{\nu}$ is about 0 025 The Hiller or Bell systems may have a "following time" of as much as 3 sec, which on a longitudinal oscillation of 25 sec period gives a $\bar{\nu}/K$ of about 0 3 In some R A E tests with a Bell 47 the "following time" was evaluated as about 0 5 sec, giving $\bar{\nu}/K$ = 055 The effect at these values of $\bar{\nu}/K$ can be obtained from Fig 2 In general, the frequency ratio effect is not of much significance in the stability of the full-scale helicopter but for oscillations of short period it could be important We may say that for $\bar{\nu}/K < 0$ 3 the quasi-static theory is reasonably good



$$AF = \frac{K^2}{K^2+\bar{\nu}^2} = \frac{1}{1+p^2} \qquad DO = \frac{\bar{\nu}}{\sqrt{K^2+\bar{\nu}^2}} = \frac{p}{\sqrt{1+p^2}}$$

$$FO = \frac{\bar{\nu}^2}{K^2+\bar{\nu}^2} = \frac{p^2}{1+p^2} \qquad AD = \frac{K}{\sqrt{K^2+\bar{\nu}^2}} = \frac{1}{\sqrt{1+p^2}}$$

$$FD = \frac{\bar{\nu}K}{K^2+\bar{\nu}^2} = \frac{p}{1+p^2} \qquad \text{WHERE } p = \bar{\nu}/K$$

Fig 1 Vector diagram for rotor oscillation

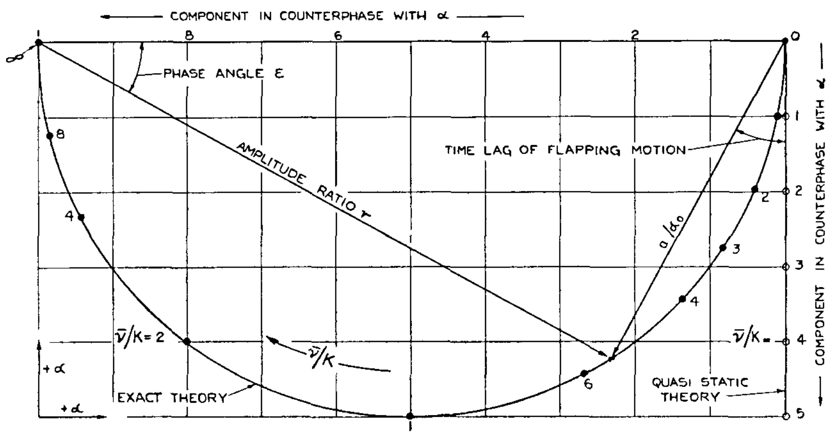


Fig 2 Vector loci of flapping motion (longitudinal tilt due to pitching oscillations)

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Wind Tunnel Tests on Oscillating Rotor

These wind tunnel tests were made with a 3-bladed, 12 ft diameter rotor in a 24 ft diameter wind tunnel The experiments are of particular importance because they illustrate that successful results can be obtained with a model rotor, not only in the simpler static tests such as measurements of thrust, torque, etc, but also under dynamic conditions It is most encouraging to know that the wind tunnel can be of such assistance to helicopter work but it must also be noted that careful interpretation of the results in relation to theory or full-scale behaviour is of primary importance

The oscillation tests were in two parts

(*a*) measurement of the free damped motion of the rotor system, and
(*b*) measurement of the rotor motion when a constant amplitude oscillation was applied through the shaft

Damping Test

The sting support for the model was attached to a spring and weight system Two spring/weight combinations were used giving general arrangements with natural periods of oscillation for the system of 0 97 sec and 4 0 sec The oscillations of the model were initiated by hand and then left to damp out Tests were made with the rotor at various rotational speeds

The results were analysed to give the damping coefficient k for the exponential envelope of the decaying oscillations The values are shown in Figs 3 and 4 for the two rigs and a comparison is made with the quasi-static and frequency response theories The two graphs give an excellent example of different ranges in frequency ratio where, in one case, the simplified theory gives good agreement while, in the other, it is inadequate

Forced Oscillations

In these tests, cine records of the rotor disc and sting behaviour were obtained while a constant amplitude oscillation was being applied The period of oscillation was 0 9 sec, while the angular speed of the rotor was 62 8 rad /sec, giving a value of ı/K = 0 57 The tunnel tests gave an amplitude ratio of 0 84 and a phase angle of 40 degrees, while the theoretical analysis gives 0 87 and 30 degrees Again, referring to Fig 2, the comparison of the quasi-static and frequency response theories shows how important the effect of the latter is at the conditions pertaining in the tunnel tests

High Speed Possibilities

One of the most controversial topics at the present stage of helicopter development is concerned with the possibilities of achieving higher forward speed performance We have reached the stage where the forward speed is liable to be limited by vibration, etc, arising mainly from blade stalling, even although there may still be adequate engine power available for higher speeds Small improvements in speed may be expected by the development of better blades with higher maximum lift coefficients and improved compressibility characteristics However, these improvements may be largely offset by the present trends in design, particularly the use of higher disc loading

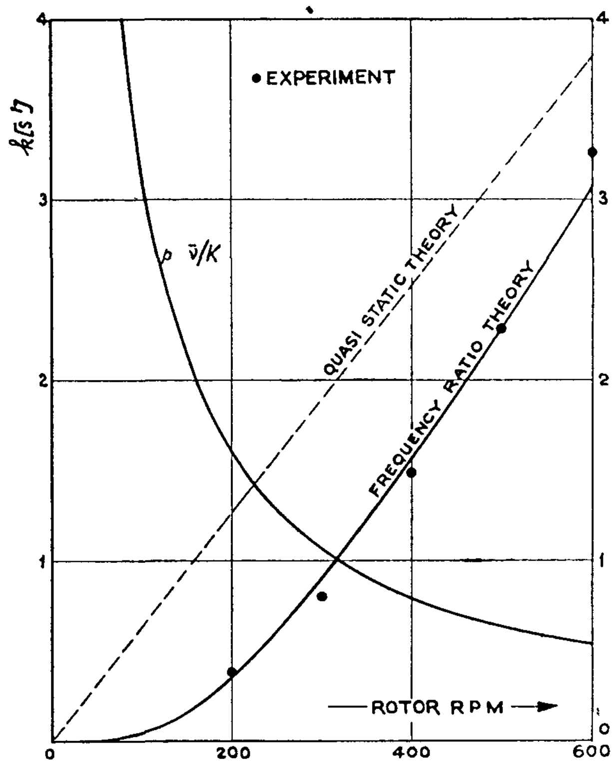
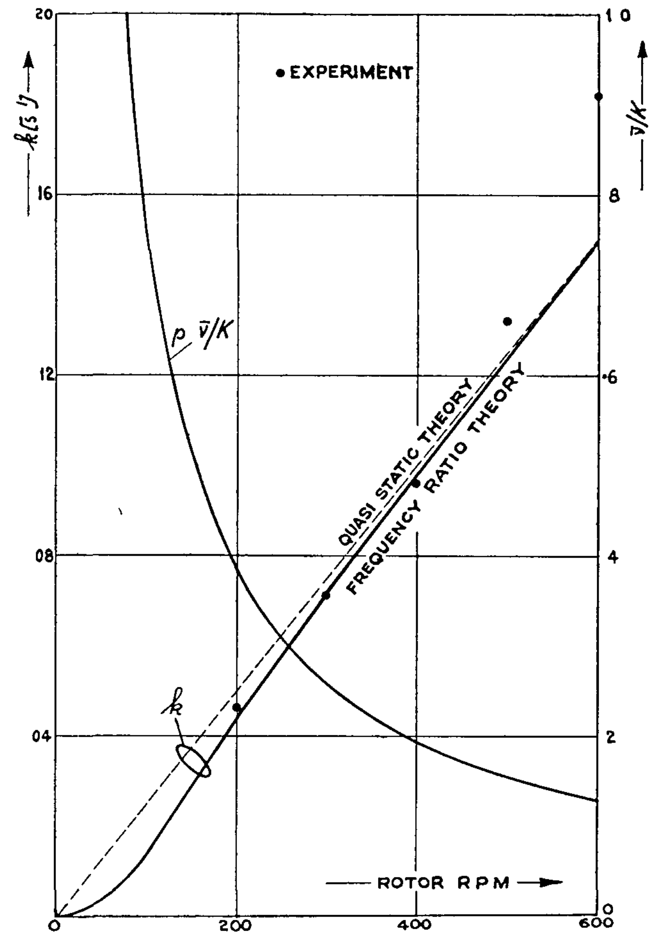


Fig 3 Variation of damping with rotor speed (Rig "A", period 0 97 secs)

Fig 4 Variation of damping with rotor speed (Rig "B", period 4 0 sec) →



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There are possibilities for developing forward speeds beyond these present limitations and four of these methods are worthy of detailed investigation These are, broadly speaking, the four fundamental ways of tackling the problem Firstly, the rotor loading could be reduced by the addition of a fixed wing to the helicopter Secondly, the rotor loading could be redistributed over the disc by such means as a second harmonic control Thirdly, if we increase forward speed at the same tip speed ratio, the tip speed must be increased considerably and this leads to the supersonic rotor Finally, if we do not wish to increase the tip speed, we must operate at much higher tip speed ratios This might be possible by making direct use of the reversed flow on the retreating blade

The combination of a rotor and a fixed wing is a fairly straightforward principle and there are several projects in current design using this idea In forward flight, the wing lift deals with part of the helicopter weight allowing the rotor to operate at lower thrust and consequently at lower blade incidences The supersonic rotor is a problem for future research Recent developments in supersonic propellers are encouraging and the problems of the supersonic rotor are likely to be on the structural aspects With regard to operation at high tip speed ratios, the region of reversed flow on the retreating side becomes considerable and the incidence of the retreating blade could be " reversed," so creating lift This problem should be a matter for wind tunnel investigation in the first instance The other method—the use of second harmonic control—will be discussed in more detail

The ordinary rotor with flapping hinges and cyclic pitch control maintains a roughly uniform lift round the disc As forward speed increases, the resultant airflow over the retreating blade decreases and a higher incidence is required Stalling incidence is soon reached, imposing a limitation on the forward speed which can be attained If we could have some form of control over the loading distribution on the disc, such a limitation could be avoided Higher harmonic control is a method of controlling to some extent the loading distribution Briefly, the idea is to use second harmonic control to reduce the loading on the lateral sectors of the disc and to increase it fore and aft

It is fairly easy to devise a mechanism for applying this second harmonic pitch A form of swashplate, rotating at 3 Ω or at Ω in the opposite direction in relation to the rotor speed Ω, could give the appropriate control application This, of course, does mean additional complication in the rotor head Further gears, bearings, etc , would be required, adding to a system which is already regarded by many as too complicated mechanically

In the ordinary first harmonic control, we are applying the control at the natural frequency of the rotor The flapping motion is very easy to calculate, the amplitude being equal to the feathering amplitude and the phase angle 90 degrees With second harmonic pitch, these simple conditions no longer exist and the amplitude and phase angle depend on inertia of the blades, etc , as in forced oscillations Again, the mathematics is very complicated and only a brief outline of the results is given The method consists of writing the equations of motion for the blade, where the cyclic pitch applied is in the form

$$\theta = \theta_0 - A_1 \cos \psi - B_1 \sin \psi - A_2 \cos 2 \psi - B_2 \sin 2 \psi$$

Solutions for the flapping coefficients can then be obtained in terms of

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blade inertia, tip speed ratio, etc The values of a_2 and b_2 consist of two parts, one due to the general flow distribution pertaining to the forward flight conditions and one due to the application of the A_2 and B_2 control These parts can be treated separately, the former being well-known from earlier helicopter work Considering the order of the incidence reduction required on the retreating side, the former of these two components is comparatively small

The simplest way to present the results is to consider the amplitude ratio of flapping $\sqrt{a_2^2 + b_2^2}$ to second harmonic control $\sqrt{A_2^2 + B_2^2}$ and the corresponding phase angle These can be plotted in terms of blade inertia number and tip speed ratio as in Figs 5 and 6 Some tests on the Sikorsky tower, described by JENSEN in his lecture on the design and operational features of the tower, deal with application of second harmonic control Although intended for another purpose, viz, the attempt to reproduce flight stresses on the tower, the results can be used to verify these calculations for the near hovering conditions In fact, the agreement is very good

It is important to note in the results that forward flight has practically

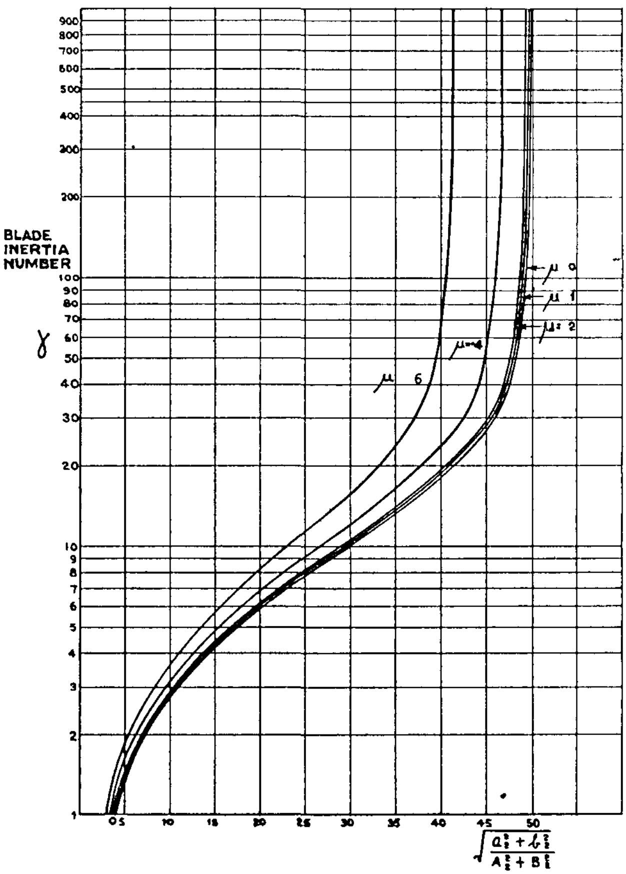

Fig 5

Ratio of flapping amplitude to feathering amplitude

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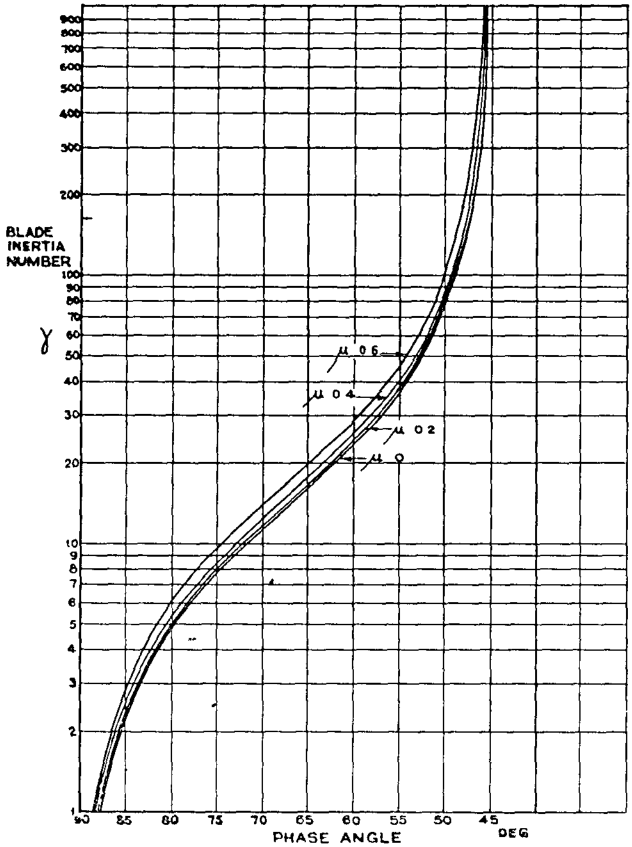

Fig 6
Phase angle of flapping relative to second harmonic pitch

no influence on the resulting flapping due to second harmonic control, so that only a constant phase angle setting of the control would be necessary It might also be possible to use a fixed amplitude setting too, thus avoiding the need for any additional control by the pilot This would merely mean that the redistribution of loading would already exist in hovering but the loss in rotor efficiency would be negligible

Having obtained the flapping coefficients, etc, these can be used to calculate the incidence distribution on the disc In applying the second harmonic control, the phase angle relative to rotor azimuth must be arranged to give maximum reduction of incidence at the region of high incidence on the retreating side The incidences on the retreating and advancing positions of the disc are therefore decreased and the incidences in the fore and aft sectors increased This leads to incidence distributions giving highest values at about the 125 and 315 degree azimuth positions The amplitude of the second harmonic control must be selected so that the incidence at these positions does not become excessive

An example of the benefits to be gained by the use of second harmonic control is shown in Figs 7 and 8, in the comparison of incidence distributions for a typical rotor operating with and without this control at a tip speed ratio of 0 4 The reduction of the very high incidences occurring on the retreating side of the ordinary rotor and the much more even distribution of incidence

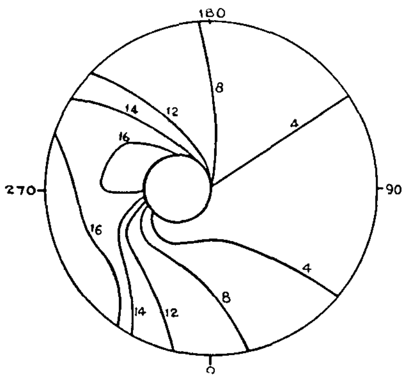

Fig 7 Incidence contours ordinary rotor $\mu = 0\ 4$

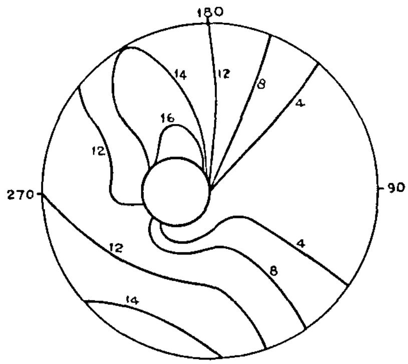

Fig 8 Incidence contours second harmonic control applied $\mu = 0\ 4$

due to the second harmonic control are illustrated In general, this method could lead to increases in the forward speed of helicopters of the order of 40 to 50 m p h , assuming that the limit had been imposed by stalling conditions and that there was sufficient power to achieve the increased speed

Conclusions

These are but a few of the recent items of helicopter research I hope that the selection has provided something of interest which will lead to an interesting discussion, not only on the items of research dealt with, but on the wider field of the further research work which is necessary for the successful development of the helicopter

In conclusion, I wish to express my appreciation and aknowledgment to the Chief Scientist, Ministry of Supply, for permission to present this paper

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