Automatic Stabilisation of Helicopters *

By G J SISSINGH, DR ING

A lecture presented to the Helicopter Association of Gt Britain, on Saturday, 23rd October, 1948, in the library of The Royal Aeronautical Society, London, W 1

H A MARSH, A F C, A F R Ae S, *in the Chair*

INTRODUCTION BY DR J A J BENNETT

Mr Chairman, Ladies and Gentlemen,

It is a pleasure to introduce our lecturer this afternoon Although as a fellow-member he has remained modestly in the background until now, DR SISSINGH is known internationally as a leading aerodynamicist in the rotary-wing field

Perhaps his first notable contribution was a paper published in " Luftfahrtforschung " exactly 10 years ago , this was later translated into English and became an N A C A Technical Memorandum In his calculations DR SISSINGH was not content with a rough estimate of the average values of drag coefficient and induced velocity but took into account their distribution along the blade This unwillingness to make empirical assumptions merely for the sake of mathematical simplicity is typical of his subsequent work

For a number of years DR SISSINGH has devoted his attention to helicopter stability and has written extensively on this important problem His investigations were conducted first at the Flettner Company near Berlin, then at the well-known Kaiser Wilhelm Institut at Gottingen, and recently at the Royal Aircraft Establishment

There is no one more competent, therefore, to talk on the " Automatic Stabili ation of Helicopters " We have all had a vague idea of the effectiveness of certain devices developed for this purpose in the United States, and this afternoon DR SISSINGH has undertaken to clarify the position and to tell us exactly what can be expected of automatic stabilisers in the future

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DR G J SISSINGH

Mr Chairman, Ladies and Gentlemen

Before I proceed to deliver my paper, I would like to acknowledge that I am greatly indebted to the Ministry of Supply, and to Group Captain LIPTROT in particular, for permission to do so, and also for having given me the opportunity and facilities for continuing my work on this subject I wish also to express my thanks to the Council of the H licopter Association for the great honour done me by allowing me to address you this afternoon

My lecture today deals with the automatic stabilisation of the helicopter in hovering flight and is mainly concerned with the Sikorsky configuration You all know that this configuration is inherently dynamically unstable in the low speed range and that after a disturbance an increasing oscillation builds up Therefore, an automatic control device is very desirable It would not only be a help to the pilot but would also be a very great advantage for night and blind flying operations, which at present are only possible under " contact conditions " or with the use of instruments

During recent years some American firms such as Bell and Hiller have already made an encouraging beginning with automatic control We know that the results still leave something to be desired, but it is at least a start We shall try to find out how these control devices work and what is still wrong with them

I want to avoid going into the mathematical complexities of the problem, in order to make the main points as clear as possible Any of my listeners who wish to go into the theoretical side more thoroughly are referred to various R A E. reports on this subject which are to be published in the near future

FUNDAMENTALS OF CONTROL DISPLACEMENTS NECESSARY TO GOVERN AN UNSTABLE HELICOPTER

At first sight the problem of automatic control and stabilisation looks very complex But it becomes much simpler if we tackle it in a roundabout way by first investigating the effect of given periodic control displacements on the dynamic stability

The investigations have shown that it is sufficient if we restrict ourselves to control displacements which are proportional to and in phase with

(1) the attitude of the helicopter, and
(2) the angular velocity of the helicopter,

and a combination of these two types The former corresponds to a kind of static stability and the latter to a kind of damping The control displacements mentioned above are illustrated in Fig 1 for a disturbed longitudinal motion (1a being a sketch of the angle in pitch against time) The curves of 1b and 1c show the attitude and the angular velocity of the helicopter and the broken lines give the corresponding control displacements, where a negative control displacement means the lift vector of the rotor is tilted forward

At present it does not matter how these control displacements are brought about As an example we can imagine that we have installed an ideal autopilot which carries out the desired displacements without any time lag

We shall now investigate the effect of our hypothetical autopilot by means of stability charts These charts are calculated from the frequency

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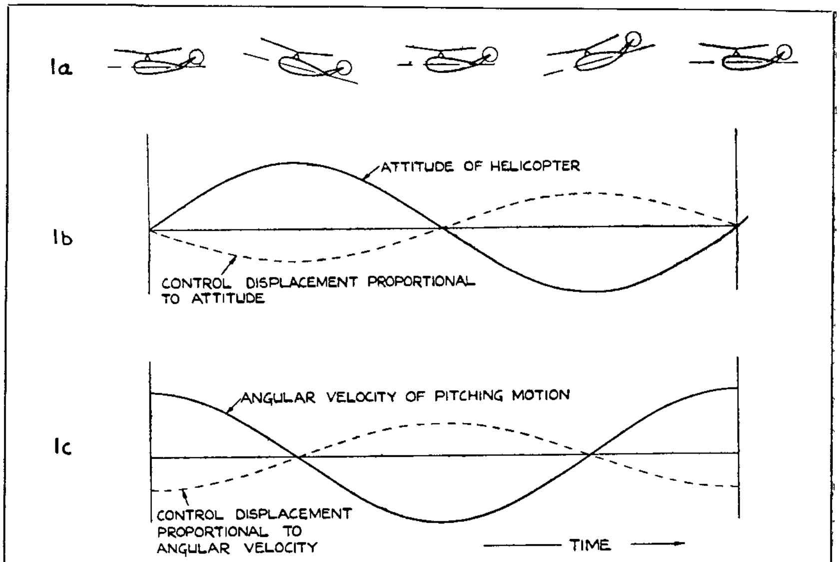

ATTITUDE DIAGRAM

FIG 1

equation, which (if we consider the flapping motion of the blades as a sequence of steady motions) is of the 3rd order and may be written as

$$\lambda^3 + A_2\lambda^2 + A_1 \lambda + A_0 = 0$$

where for the Sikorsky configuration with the controls fixed $A_1 = 0$ I do not wish to trouble you with the calculation of the coefficients A_0, A_1, A_2, but would like to point out that they depend on the layout of the helicopter and can only be varied within certain limits for a given design It can be proved that periodic control displacements effect a change of the coefficients For the Sikorsky configuration it follows that

A_0 is not affected by control displacements,

A_1 is proportional to control displacements in phase with the attitude of the helicopter, and

A_2 increases with control displacements proportional to and in phase with the angular velocity of the helicopter

Routh's stability criterion requires that A_1 must be greater than A_0/A_2, therefore we cannot achieve dynamic stability in the Sikorsky configuration without control displacements in phase with the attitude

We will now go into this problem more thoroughly with the help of the stability charts mentioned previously, in which the dynamic stability of the helicopter is characterised by the oscillation period T_0 and the times T_D, T_H, in which the amplitude is doubled or halved, as the case may be Let us take the single rotor helicopter as an example, because the conditions for this type are particularly simple, but of course similar calculations can be made for any other configuration

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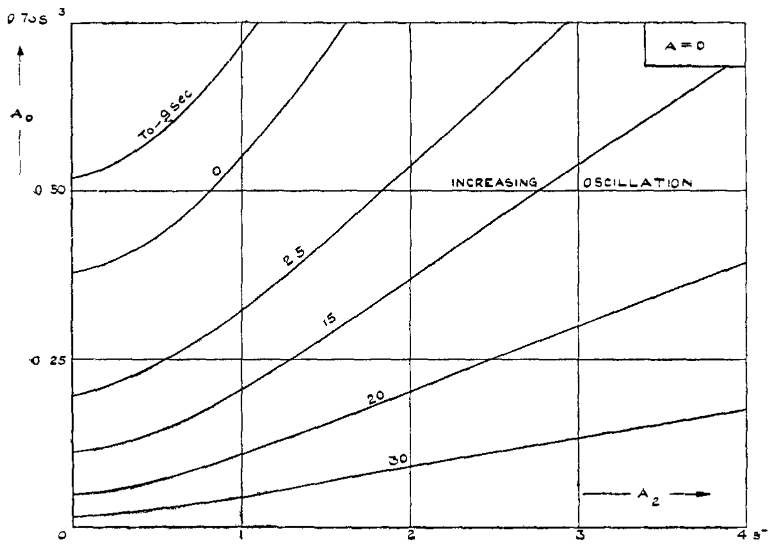
For the longitudinal motion of the Sikorsky R-4B with the controls fixed,

$$A_0 = 0\ 1 \text{ sec}^{-3} \text{ (approx)}$$
$$A_2 = 0\ 2 \text{ sec}^{1} \text{ (approx)}$$

and thus we obtain from Figs 2 and 3

$$T_0 = 16 \text{ sec and } T_D = 5 \text{ sec}$$

or, in other words, the helicopter is unstable and has a period of 16 sec The amplitude of a disturbance is doubled in 5 sec As already mentioned, the control displacements proportional to and in phase with the angular velocity of the helicopter have the effect of an apparent increase in the quantity A_2 It follows from Figs 2 and 3 that both the period of oscillation T_0 and the time T_D become greater The helicopter certainly becomes less unstable, but still remains unstable In this respect the control displacements in phase with the angular velocity have the same effect as an increase of the blade masses In the most favourable case (infinite control displacements) the oscillation becomes neutral The reason for this perhaps astonishing fact is that we cannot apply pure moments about the longitudinal or lateral axis of the helicopter With the present types of rotor control (tilting of the lift vector) the moments are always coupled with horizontal forces



PERIOD OF OSCILLATION FOR $A_1=0$

FIG 2

If we have periodic control displacements in phase with the attitude, the stability chart is divided into a stable and unstable range, where the stability boundary is given by a straight line with the slope A_1 passing through the origin The range above this boundary line corresponds to an unstable helicopter and below it to a stable one In the stability charts of Figs 4 and 5, $A_1 = 0\ 5$ For the Sikorsky R-4B it means that the control displacements in phase with the attitude amount to approximately 10% of the attitude

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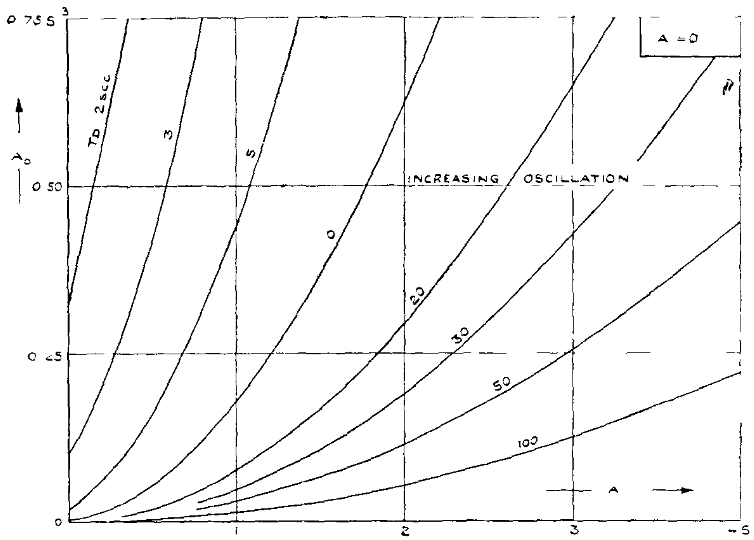
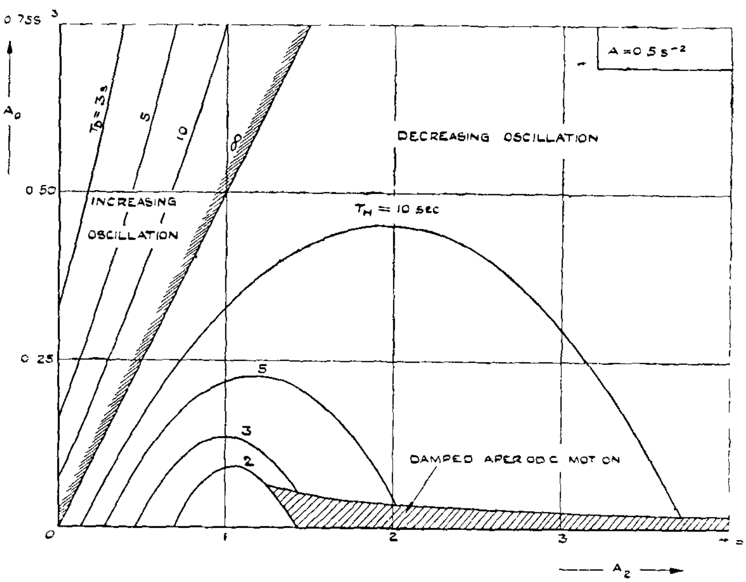


TIME TO DOUBLE AMPLITUDE FOR A_1= O

FIG 3



TIME TO DOUBLE (HALF) AMPLITUDE FOR A_1= O 5 s^{-2}

FIG 4

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According to the investigations made up to the present this range appears to be the most promising for obtaining the best results

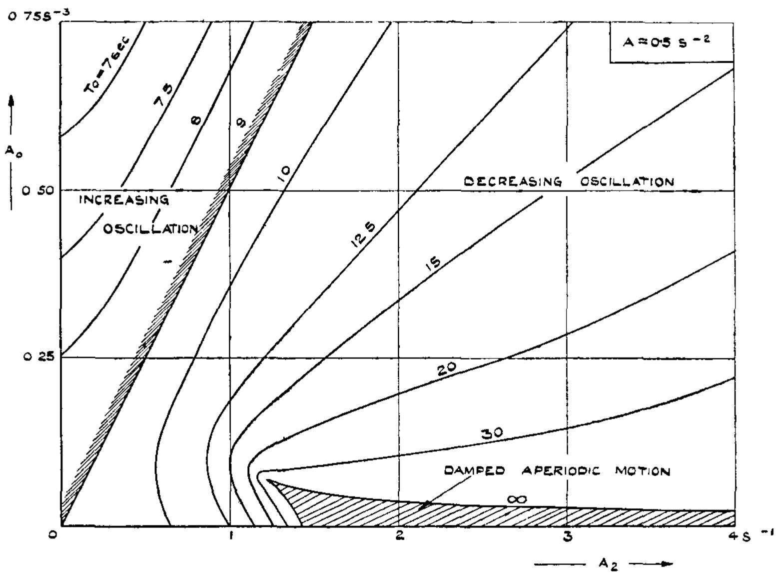
If we apply Figs 4 and 5 to the Sikorsky R-4B we obtain for $A_0 = 0\ 1$ and $A_2 = 0\ 2$ a period of oscillation of 9 sec As the above figures lie just on the boundary line, the helicopter is neutral However, the dynamic stability can be considerably improved, if we apply additional control displacements in phase with the angular velocity, *i e*, if we increase the quantity A_2

$$\text{For } A_0 = 0\ 1 \text{ sec}^{3}$$
$$A_1 = 0\ 5 \text{ sec}^{2}$$
$$A_2 = 0\ 7 \text{ sec}^{-1}$$

we obtain, for instance, from Figs 4 and 5

$$T_0 = 11 \text{ sec and } T_H = 3 \text{ sec}$$

This means that a disturbance is halved in 3 sec and we have a very effective automatic stabilisation



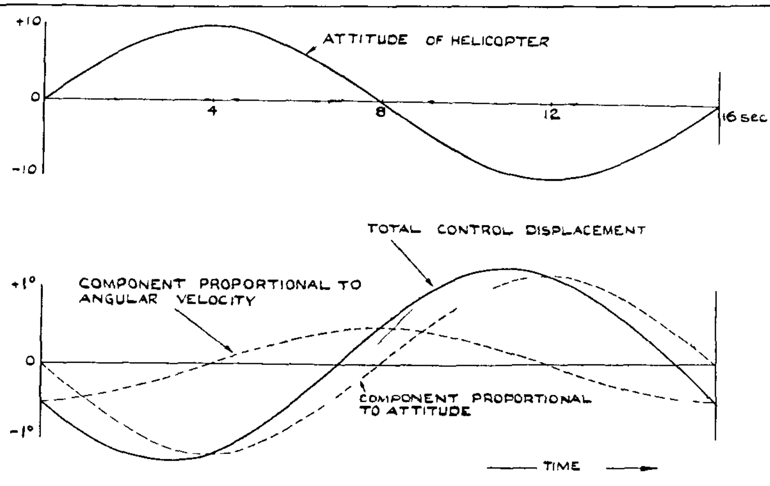
PERIOD OF OSCILLATION FOR $A_1 = 0\ 5\ s^{-2}$

FIG 5

It can be shown that the apparent change of the coefficients A_0, A_1, A_2 of the Sikorsky R-4B from $A_0 = 0\ 1 \quad A_1 = 0 \quad A_2 = 0\ 2$ to $A_0 = 0\ 1 \quad A_1 = 0\ 5 \quad A_2 = 0\ 7$ requires an autopilot, the control displacements of which are approximately

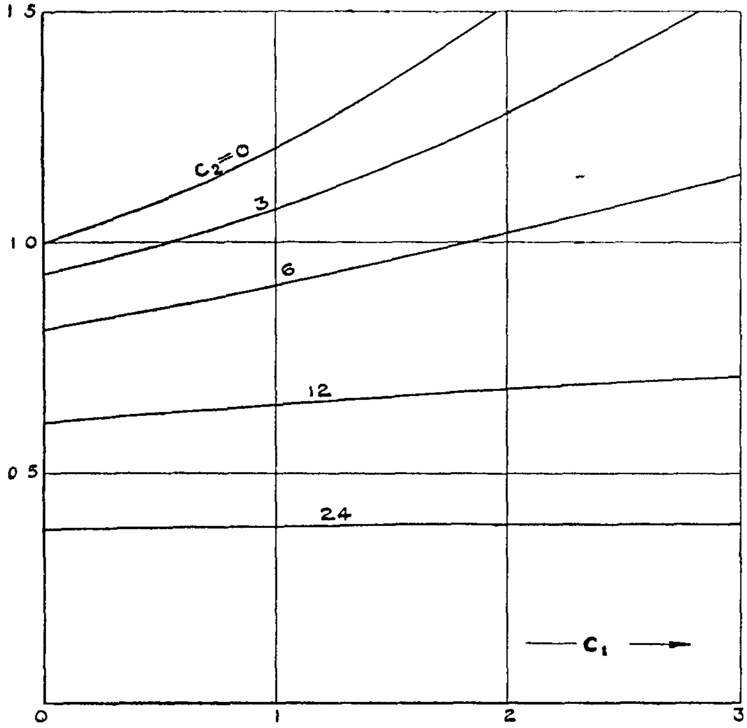
$$-(0\ 12\alpha + 3\ 25\ \frac{\dot{\alpha}}{\Omega}) \text{ rad}$$

where α, $\dot{\alpha}$ denote the attitude and angular velocity of the helicopter, and Ω the angular velocity of the rotor With an amplitude of $\alpha = \pm 10°$ and a rotor velocity of $\Omega = 25$ rad /sec this hypothetical autopilot would apply the control displacements as given in Fig 6



CONTROL DISPLACEMENT DIAGRAM (C_1 = 0 12, C_2 = 3 25)

FIG 6



CONTROL EFFECTIVENESS

FIG 7

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I would like to refer to two important facts at this point Fig 5 shows that the stability again decreases if the control displacement proportional to and in phase with the angular velocity of the helicopter becomes too large We shall see later that the unsatisfactory stabilisation of the Bell and Hiller systems are probably due to this kind of " overcontrol " which is always coupled with long oscillation periods

The other point is the control sensitivity, or, more accurately expressed, the response of the automatically stabilised helicopter to the pilot's control According to J STUART[2] we assume that the pilot applies manual periodic control displacement with a period of 4 sec These manual control displacements impose on the helicopter forced oscillations of the same frequency, and the control sensitivity is defined as the ratio of the amplitude of forced oscillation of the helicopter to the amplitude of manual control displacement For simplicity we will also assume that the helicopter is pivoted at its C G , which means that only angular oscillations can occur Our hypothetical autopilot may achieve automatic control displacements such as

$$-(C_1\alpha + C_2\frac{\alpha}{\Omega}) \text{ rad}$$

and we wish to know the effect of the quantities C_1, C_2 on the control sensitivity The answer (for the longitudinal motion of the Sikorsky R-4B) is given in Fig 7 The curves show the ratio of the amplitude of the helicopter with autopilot to the amplitude of the helicopter without autopilot, and thus give an idea of the effect of the automatic stabilisation on the control sensitivity It follows that within the range of practical significance, C_1 has only a small influence Large values of C_2, however, decrease the sensitivity This means that too large automatic control displacements in phase with the angular velocity of the helicopter spoil both the dynamic stability and the control sensitivity

Bell's Stabiliser and Hiller's Servo Control

I assume that the stabiliser of the Bell helicopter is fairly well-known to my listeners , therefore I shall confine myself to a brief summary of this device (Fig 8)

The lifting rotor has two blades which are rigidly connected with each other and are attached to the rotor shaft by means of a universal joint The feature of the Bell stabiliser is a bar with a mass on each end which rotates with the rotor The bar is joined to the rotor shaft in such a way that it may pivot up and down , this see-saw motion is provided with viscous damping By means of a lever the bar is mechanically linked to the rotor in such a way that the displacement of the bar changes the pitch setting of the main blades If, for instance, mass I rises, the pitch angle of blade I increases As the two rotor blades are rigidly connected with each other, the pitch setting of blade II simultaneously decreases

How does this device work ? In the undisturbed condition the centrifugal forces tend to keep the bar in its equilibrium position (plane perpendicular to the rotor axis) in which the pitch setting of the rotor is not affected

If, however, the hovering condition is disturbed, *i e*, if a pitching or rolling motion occurs, the bar oscillates with the rotor frequency about its pivot These oscillations are excited by the gyroscopic couple of the masses of the bar The oscillations impose on the blades a cyclical pitch which means that an automatic control is applied Automatic stabilisation can be achieved by using a proper layout The main parameters in this respect are the viscous damping of the bar and the linkage ratio between the bar and the main rotor

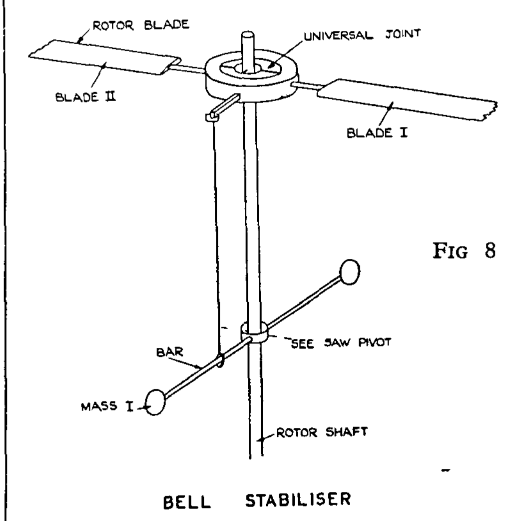


FIG 8

Another automatic control device appeared recently This is the control system of the Hiller helicopter The fundamental idea is the same automatic control by means of the gyroscopic couple and the restraining moment of centrifugal forces of masses rotating with the rotor The most striking difference is that the bar has been replaced by servo blades, *i e*, the viscous damping has been replaced by the damping of the airforces Another feature of the Hiller system is that the flapping motion of the main blades may be coupled with the pitch setting of the servo blades It can be proved that this " feedback " has the effect of

(1) an apparent change of the damping of the servo-blades and

(2) an apparent increase of the disturbance of the helicopter

The latter effect is almost identical with an apparent change of the linkage ratio between servo blade and rotor This means that the two control devices are very similar with respect to the *automatic* control and may therefore be dealt with together For simplicity we investigate the Bell stabiliser, the basic results, however, can also be applied directly to the Hiller servo control

Before going into the control device in connection with the stability of the helicopter, we first investigate the control displacements which occur if a rotor with Bell stabiliser is subjected to an angular oscillation with constant amplitude Mathematically expressed, we will try to make a statement on the magnitude of the quantities C_1 and C_2 for a given period of oscillation The answer is given in Fig 9 where, following B KELLEY[1], the amount of viscous damping is expressed as the " following time " T_f, in which a displacement of the bar is reduced to a tenth of its initial value T_f is inversely proportional to the damping, and it means that a large value of T_f corresponds to a small damping and *vice versa* The curves of Fig 9 show the quantities C_1 (full lines) and C_2 (broken lines) for the linkage ratio n (= 1 0) and a rotor angular velocity of $\Omega = 25$ rad /sec against damping with the period of the enforced oscillation T_0 as parameter The graphs have been plotted for $T_0 = 10$, 20 and 40 sec , they allow the following statements, which have a general application —

(1) $C_1 = 1$ for zero damping ($T_f = \infty$) and decreases rapidly with increased damping

(2) $C_2 = 0$ for zero damping and has a maximum at $T_f = 0\ 366 T_0$ In the range of greater damping (*i e* , $T_f < 1$ *sec*) C_2 is independent of the period of oscillation T_0

(3) In the medium range, where both C_1 and C_2 occur, the control characteristics depend to a great extent on the period of oscillation C_1 decreases and C_2 increases with increased period of oscillation T_0 and *vice versa*

The automatic stabilisation of the helicopter requires both control displacements in phase with the attitude and in phase with the angular velocity of the helicopter , we are therefore forced to choose a small damping of the bar In this range C_1 and C_2 are greatly affected by the period of oscillation We have seen previously (Fig 4) that large control displacements in phase with the angular velocity of the helicopter increase the period of oscillation On the other hand, Fig 9 shows that long periods of oscillation increase the control displacements in phase with the angular velocity of the helicopter It must therefore be suspected that the Bell stabiliser tends to increase the period of oscillation to such an extent that only an unsatisfactory stabilistion is achieved and such proves to be the case in actual fact (Fig 10) The curves are calculated for the longitudinal motion of the Sikorsky R-4B fitted with a Bell stabiliser, where, according to B KELLEY, a following time of $T_f = 3$ sec has been assumed The graphs are plotted against the linkage ratio

n = (change of pitch setting of main blade)/(displacement of the bar)

and show that in the most favourable case ($n = 0\ 3$) a very slightly damped oscillation with a period of 26 5 sec occurs The amplitude is halved in 37 sec , which means that the longitudinal motion is almost neutral When $n < 0\ 16$ the helicopter becomes unstable, *i e* , in the stability charts (Figs 4 and 5) the helicopter goes over from the stable to the unstable range when the A_2 value is too small Summing up, we can say that the Bell stabiliser counteracts the inherent instability of the helicopter, but the results are not yet up to expectations

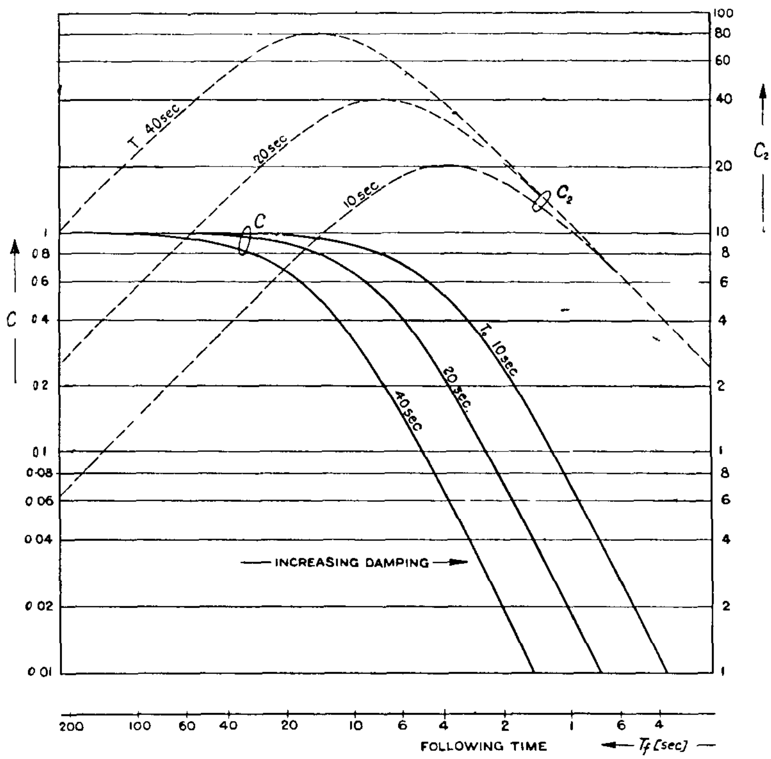
I would like to mention that the curves of Fig 9 may also be applied directly to the flapping motion of the rotor blade for the case in which the rotor is subjected to oscillations with constant amplitude The " following time " T_f of the rotor blade is given by

$$T_f = \frac{40}{\gamma\Omega} \text{ sec}$$

where γ denotes the inertia number of the blade and Ω the angular velocity of the rotor It can be shown that the coefficients a_1, b_1 of the flapping angle β ($\beta = a_0 - a_1 \cos\psi - b_1 \sin\psi$) can be divided into components in phase with the attitude, and with the angular velocity of the helicopter The coefficient a_1, for instance, may be expressed as

$$a_1 = -(C_1 \alpha + C_2 \frac{\alpha}{\Omega})$$

For the blade of the Sikorsky R-4B the following time T_f amounts to approx 0 13 sec The graphs of Fig 9 (the curves may also be applied in approxi-



CONTROL DISPLACEMENTS OF BELL STABILISER

FIG 9

mation to an increasing or decreasing oscillation) show that for this degree of damping, $C_1 = 0$, which means that the flapping motion is proportional to the angular velocity of the helicopter and may therefore be considered as a sequence of steady conditions However, the flapping motion in phase

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with the attitude of the helicopter can no longer be neglected if short oscillation periods occur The basic parameter in this respect is the frequency ratio, (circular frequency of the oscillation of the helicopter) / (angular velocity of the rotor) It can be proved that the stabilising effect credited to the downwash lag (Strahlablenkungs-Effekt) is partly due to the static stability caused by the flapping motion in phase with the attitude of the helicopter Therefore, the results of model tests with oscillating rotors may only be applied to the full scale helicopter if the frequency ratio just mentioned is the same

How Can the Present Control Devices be Improved?

To be able to improve the Bell and Hiller systems we must first know what is still wrong with them Our example has shown that with a following time of $T_f = 3$ sec , a disturbance of the longitudinal motion of the Sikorsky R-4B is, in the most favourable case ($n = 0\ 3$) halved in 37 sec , where a period of oscillation $T_0 = 26\ 5$ sec occurs It can be seen from Fig 9 that for $T_f = 3$ sec $T_0 = 26\ 5$ sec and $n = 0\ 3$, $C_1 = 0\ 03$ and $C_2 = 9$, which means that the Bell stabiliser in this case has about the same effect as a hypothetical autopilot, the control displacements of which are

$$-(0\ 03\alpha + 9\frac{\alpha}{\Omega}) \text{ rad}$$

We have previously seen that an autopilot with the control characteristics $C_1 = 0\ 12$ and $C_2 = 3\ 25$ results in a very effective stabilisation (Table 1) By comparison of the two pairs of values, C_1 and C_2, it follows that

(1) the quantity C_1 of the Bell stabiliser is too small and must therefore be increased, and

(2) the quantity C_2 is too large and must therefore be decreased

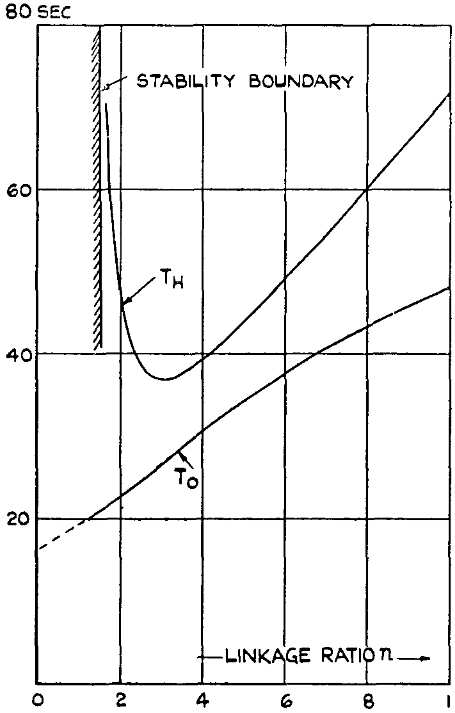
How can it be managed? Fig 9 shows that the desired changes occur if the period of oscillation decreases On the other hand, we see from Fig 4 that this decrease of the period of oscillation can be attained by a decrease of the coefficient A_2 of the frequency equation, *i e*, by counteracting control

Table I

LONGITUDINAL MOTION OF SIKORSKY R–4B

	Without control device	*With autopilot*	*With Bell Stabiliser* $T_f = 3$ sec , $n = 0\ 3$
	UNSTABLE	STABLE	NEUTRALLY STABLE
C_1	0	0 12	0 03
C	0	3 25	9 0
T_0	16 sec	11 sec	26 5 sec
T_D, T_H	$T_D = 5$ sec	$T_H = 3$ sec	$T_H = 37$ sec

displacements in phase with the angular velocity, or, more generally expressed, by a decrease of the damping of the helicopter This can be done by various means It could, for instance, be accomplished by a counteracting second bar (*Provisional Specification 14988/48 of 3 6 1948*) which has such a degree of damping that only control displacements in phase with the angular velocity



INFLUENCE OF BELL STABILISER ON SIKORSKY R 4B

FIG 10

of the helicopter occur The basic idea is illustrated in Fig 11 The two differently damped bars rotate with the rotor and are connected to the rotor by a system of linkages in such a way that the change of pitch-setting of the rotor blades is

$$n_1\delta_1 + n_2\delta_2$$

where n_1, n_2 denote the linkage ratios and δ_1, δ_2 the angular displacements of the two bars In our example the quantities n_1, n_2 must have opposite signs, which means that the heavily damped second bar counteracts the excessive control displacements in phase with the angular velocity of the helicopter achieved by the slightly-damped first bar

As an example, calculations for the longitudinal motion of a Sikorsky R-4B fitted with a double bar stabiliser have been carried out (Fig 12) The curves are plotted against the linkage ratio n_2 of the second bar and show for the two modes of oscillation, the times T_H in which a disturbance of the automatically stabilised helicopter is halved In this example

First bar	*Second bar*
$T_{f1} = 3$ sec	$T_{f2} = 0\ 46$ sec
$n_1 = 0\ 25$	

This means that the first bar has the same degree of damping as in the

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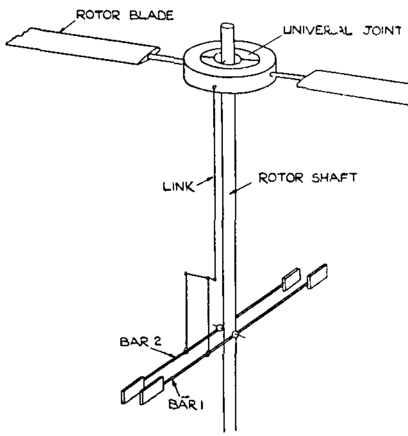
previous example of the Bell stabiliser If $n_2 = 0$ the second bar is put out of action and, in agreement with the previous investigation, a disturbance is halved in approx 40 sec Besides this mode of oscillation, a heavily damped short period oscillation occurs , this mode of oscillation generally has very little practical significance and has therefore not been mentioned until now It can be seen from Fig 12 that the second bar affects the two modes of oscillation in such a way that

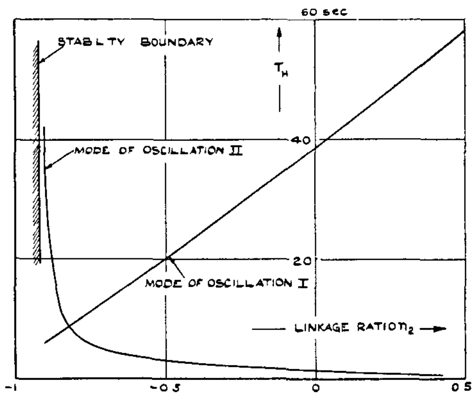
(1) the originally slightly damped oscillation becomes more stable, and
(2) the originally heavily damped oscillation becomes less stable



DOUBLE BAR STABILISER

FIG 11

FIG 12



INFLUENCE OF DOUBLE BAR STABILISER ON SIKORSKY R-4B

The stability boundary is given by $n_2 = —0\ 92$ The optimum lies at or near the point of intersection of the two curves ($n_2 = —0\ 82$) where the amplitude of both modes of oscillation is halved in approx 8 sec The optimum value found for the Bell stabiliser was 37 sec We thus attain a considerable improvement in stability, which in theory can be improved still further by using other combinations of the damping of the two bars

However, I would like to make it perfectly clear that at present we are dealing with purely theoretical investigations, and that their accuracy and practical applications have still to be confirmed by tests

Conclusions

In conclusion I wish to summarise the essential facts once again The control displacements necessary to govern an unstable helicopter may be divided into displacements which are proportional to and in phase with the attitude and the angular velocity of the helicopter respectively The former correspond to a kind of static stability and the latter to a damping of the pitching or rolling motion It appears that any helicopter can be stabilised by a proper combination of these two types of control displacements

For the Sikorsky configuration some noteworthy statements can be made In the ideal case where there is no time lag in the control device and in the flapping motion of the blades, control displacements proportional to and in phase with the angular velocity of the helicopter alone are not sufficient to stabilise the single rotor helicopter The reason for this perhaps astonishing fact is that we cannot impose a pure pitching or rolling moment With the present systems of rotor control (tilt of the lift vector) the moments are always coupled with horizontal forces Effective stabilisation of the Sikorsky configuration requires a certain combination of the two types of control displacements The stability again decreases if too large control displacements in phase with the angular velocity of the helicopter are applied

Contrary to fixed-wing aircraft where the automatic control and stabilisation require the installation of a special gyroscope, the helicopter can make use of its rotor, which is in itself a gyroscope Examples of this group are the Bell stabiliser and the Hiller servo rotor It is obvious that automatic stabilisation can be achieved by using a proper layout The results, however, are not yet up to expectations The present gyratory stabilising systems require a compromise which is usually such that the control displacements in phase with the angular velocity of the helicopter are too large in relation to those in phase with the attitude This kind of automatic " overcontrol " spoils both the dynamic stability and the response to the pilot's control It is to be expected that within the next few years some more control devices will appear and that the present state of automatic stabilisation will be considerably improved

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DISCUSSION

Mr J S Shapiro (Founder Member) There are many people who doubt the necessity for developing a stable helicopter and I would like to hear the views of the department for which Dr Sissingh works, on the subject Personally, I have no doubt at all, that a stable helicopter is essential for widespread private ownership, and a great help for commercial operation

Stability is measured by two parameters, being the natural period and the damping factor of the oscillation of the machine I would like to know, whether, in the light of the department's flying experience, they have specific views on desirable values for either parameter and whether they know to which of the two the Pilot is more sensitive

In the paper Dr Sissingh mentions a criterion of control sensitivity, being a ratio of machine amplitude to control amplitude in forced oscillatory motions of the helicopter , our own method of judging control sensitivity is by means of the ratio between the moment produced by unit displacement of control to the moment of inertia of the machine, in other words, the angular acceleration imposed by unit displacement of control I am wondering whether the lecturer's criterion is more significant than our own, especially as it is bound to be a function of frequency of oscillation

I would also like to add another question referring to the hypothetical ' autopilot ' namely, the effectiveness of automatic control displacements proportional to the angular acceleration of the machine

Mr R Hafner (Member) I believe that there is a need for positive stability in forward flight, but one might perhaps be satisfied in hovering with only a neutrally stable rotor I would like to point out that the stability cubic in Dr Sissingh's paper applied to two dimensional movement and the coupling between the longitudinal and lateral motion has been ignored

I would also like to point out that the lack of stability in a hovering helicopter can be clearly recognised even during very small displacements of the aircraft It is quite clear, however, that the minute translational velocities caused by such movements are much too small to produce a significant flapping motion of the blade, if indeed friction in the flapping hinges and similar marginal factors do not entirely overshadow this effect I am of the opinion therefore, that some of the fundamental reasoning in conventional stability calculations breaks down in practice for very small movements and the instability observed then is symptomatic not so much of the mechanical features of the rotor (blade flapping, etc) as of an aerodynamic feature connected with the slipstream We know that a fast climbing rotor or auto-rotating rotor is more stable than a hovering rotor or indeed one operating in the vortex ring state I had hoped to learn more about this aerodynamic derivative In fact, what is the stability of an actuator disc carrying a weight underneath ?

Dr J A J Bennett (Founder Member) It would appear that the helicopter is dynamically unstable so long as the tip-path plane oscillates in phase with, and with the same amplitude as, the body of the aircraft We have two extreme cases to consider, therefore The case of the tip-path plane oscillating with the same amplitude as the body of the aircraft is more or less typical of existing helicopters and, if the rotor were subject to complete gyroscopic control, the tip-path plane would remain stationary as the body of the aircraft oscillates The stabilising device must control the tip-path so that its oscillation is only partly suppressed

Although in his analysis DR SISSINGH has assumed that the rolling and pitching oscillations of the helicopter are independent, has he considered the cases in which the undamped natural frequency of the flapping motion is not equal to the angular speed of the rotor, *i e*, the effect of " delta three " or flapping hinge offset If an offset of the flapping hinge can give dynamic stability, are the best results obtained with a positive or negative offset ?

MR A McCLEMENTS (Founder Member) The lecturer has today considered the case of the single rotor helicopter In view of the possibility of multi-rotor machines becoming available, I would like to enquire if DR SISSINGH can advise us if the stability of the multi-rotor configuration is likely to present less of a stability problem than the single rotor machine Also, is anything known about which multi-rotor arrangement is best from the stability viewpoint ?

MR D R GARRAWAY (Member) The amount of damping applied to the stabilising bar can be adjusted to give the best response to lateral oscillation, but since the inertia of the helicopter is less in roll than pitch, the stability characteristics in a lateral sense will not be as satisfactory as if the damping were selected for optimum lateral stability In a typical aircraft having optimum longitudinal characteristics how do the resulting lateral characteristics compare with the optimum ones ?

DR THURSTON (Member) I would like to point out that from experiments which I have made it is possible to stabilise blades in a similar way to ordinary aircraft, and that the problem of stability of helicopters is very similar to the problem in fullsize aircraft, and its solution appears to be following on the same lines

Many years ago I constructed helicopter blades which were stabilised by elevators and fins, and I feel that a great deal of experimental work could be done with the use of models in this respect

MR W STEWART (Member) I would like to offer a few comments in reply to several speakers, who have raised questions on the wider implications of DR SISSINGH's lecture and on possible alternative solutions

As Mr Shapiro has pointed out, the stability characteristics of the helicopter—as of the fixed-wing aeroplane—go beyond the stick-fixed motion discussed by DR SISSINGH In fact, it can be divided into four classes, *viz* the static and dynamic stability under stick fixed and stick free conditions, the lecturer having dealt with only one of these The pilots' impressions of the flying characteristics are a combination of these together with control response and effectiveness It is agreed that the most important influence is the stick-free conditions However, to consider the desirable handling qualities of a helicopter would require a complete lecture on this subject

Dr Sissingh's work has shown the control displacements required to stabilise the helicopter motion and has indicated the influence of automatic devices applying these displacements under stick-fixed conditions Nevertheless, the work could be applied in a different form to stick-free considerations An important point—perhaps not sufficiently emphasised by Dr Sissingh—is that most automatic devices improve stability at the cost of loss in the pilot's control effectiveness Dr Sissingh's method involves only a small loss of control effectiveness for the stability gain

The control sensitivity used by Dr Sissingh, *i e*, the control displacements to produce a constant amplitude oscillation of a given frequency, is not a good handling criterion but it constitutes a very good method of mathematical treatment It is fully appreciated—and I thoroughly agree with Mr Shapiro—that neither this method not the more usual response to unit control method are satisfactory, but I have no better criterion to offer as yet

Mr Fitzwilliams has mentioned the possible solution advocated by Professor Miller This is sound in theory but would be difficult to design in practice It would be exceptionally difficult to arrange for the appropriate twisting of the blades to provide the cyclic changes required The use of stiff blades with a spring support may well give rise to undesirable blade oscillations and may even lead to flutter

I agree with Mr Hafner that the double bar is a considerable complication to ask of the designer The simple offset hinge does affect stability but the improvements possible are very small For most blades a negative hinge offset is required but for very heavy blades positive offsets can give a little improvement Again, vibration must be considered

In reply to Dr Thurston, the use of auxiliary aerofoils to stabilise each of the blades (and to control them) has been tried The Landgraf system could be considered as a step in this direction but there is a system with the auxiliary blades several chord lengths behind the main blades However, while it would appear that this stabilises the blade motion and to a much lesser extent the helicopter, very little information is available Vibration trouble due to possible dissymetry between each blade system should be considered

Dr Sissingh's reply to the Discussion

In reply to Mr Shapiro In the future the helicopter will probably be engaged in a silent but tough fight for general recognition by the public In my opinion an effective automatic control device which stabilizes the helicopter without too much loss of control sensitivity would be a very valuable contribution towards making the public helicopter-minded and increasing the applications of helicopters I fully agree with Mr Shapiro that dynamic stability is one of the essentials for widespread private ownership From the point of view of stability an aperiodic subsidence of the disturbance would probably be desirable However, this requires such a degree of damping in pitch and roll that the response to the pilot's control becomes insufficient This means that a compromise must be found, the final decision is left to the pilot, but owing to lack of practical experience it is not yet possible to make any forecasts in this respect It may be assumed, however, that very short oscillation periods are undesirable, and it is my personal belief that with present knowledge the solution of the stick-fixed stability is easier than that of the stick-free stability

As already stated by Mr STEWART, the criterion for control effectiveness mentioned in my paper is characterized by a simple mathematical treatment The control period of 4 secs is taken from the paper by J STUART and corresponds to average practical conditions I admit that this criterion is by no means ideal, and if, in spite of this, I have mentioned that criterion, it has been done to show in a simple way that the loss in control sensitivity is mainly caused by the control displacements proportional to the rate of change of attitude The criterion mentioned by Mr SHAPIRO only covers the initial acceleration Actually, what we want to know is how quickly, to what extent, and in what way (with or without overshoot) the helicopter responds to the control Unfortunately, neither of these criteria can give the answer to these questions I would like to take this opportunity of referring to a paper by R H MILLER (*Journal of the Aeronautical Sciences*, August, 1948) dealing with automatic control and response of the automatically stabilized helicopter to the pilot's control, which appeared after I had completed my manuscript

With regard to the control displacements proportional to the angular acceleration, it should be noted that, although the vector of the angular acceleration in an undamped oscillation has a phase difference of 180° in comparison with the attitude vector, the effect of these control displacements is quite different from that of the control displacements proportional to the attitude If we apply control displacements proportional to the angular acceleration in the Sikorsky configuration, then it is only the factor of λ^3 which is changed in the frequency equation of the 3rd order , the other coefficients remain unchanged Particular attention should be paid to the fact that the coefficient of λ remains zero, *i e* , dynamic stability cannot be obtained in this way In the most favourable case the coefficient of λ^3 becomes zero, which means that the helicopter is neutral The control displacements proportional to the angular acceleration have a certain similarity to an apparent change of the moment of inertia of the helicopter The difference lies in the fact that a change of the moment of inertia only affects the equilibrium of the moments, while the control displacements proportional to the angular acceleration also affect the equilibrium of the horizontal forces as well

In view of Prof MILLER's suggested solution I should like to add the following remarks on the statement by Mr STEWART I presume that Prof MILLER's arrangement corresponds to a hypothetical autopilot which responds with a small time lag to the angular velocity of the helicopter This time lag has the effect that one component of the control displacement is in phase with the attitude, *i e* , automatic stabilization is possible under certain conditions However, here again we probably have the disadvantage that the control displacements proportional to the rate of change of attitude are too large in comparison with those proportional to the attitude This would mean that very slightly damped oscillations with long periods of oscillation occur

I agree with Mr HAFNER that for the Sikorsky configuration the coupling between the longitudinal and lateral motion is very important For simplicity, this coupling has been neglected in my paper, and this means I have assumed that the hypothetical autopilot

(1) applies the required longitudinal control displacements, and
(2) compensates the lateral tilt of the lift vector of the rotor at all times

The investigations have shown that these effects can to a certain extent be accomplished by various means, so that in the first approximation the simplification is justified

If the hovering state is disturbed, we have a flapping motion of the blades due to both the angular and linear velocity of the helicopter Theoretically, the two components are approximately of the same order of magnitude As measurements on the flapping motion in the disturbed hovering state are not known, it is very difficult to make any statements on the influence of the friction in the flapping hinges I personally believe that this effect may be neglected As far as I know, the theoretical investigations on the hovering stability compare fairly well with flight measurements The main causes of discrepancies are probably the twisting of the blade, play in the controls and—if the stick is not actually clamped—the involuntary control displacements of the pilot

It is known that in the hovering state near the ground and in vertical descent, the slipstream changes the rotor derivatives and, through this, greatly affects the stability Unfortunately, the existing measurements are not adequate to make further detailed statements in this respect With regard to the stability of an actuator disc carrying a weight underneath , if the actuator disc is defined as a hypothetical device, the resulting force of which is always perpendicular to the disc and passes through the centre, the motion is neutral

In reply to Dr Bennett If we neglect the flapping of the blade due to the linear and angular velocity of the helicopter, the tip path plane of a helicopter with the controls fixed oscillates in phase, and with the same amplitude as the body of the aircraft If the control displacement is equal to the attitude ($C_1 = 1$), the lift vector of the rotor always remains approximately vertical In the case of an automatically stabilized helicopter the tip path plane oscillates with a time lag and with a smaller amplitude when compared with the oscillation of the fuselage

Take the case where the undamped natural frequency of the flapping motion is not equal to the angular speed of the rotor if a helicopter is subjected to pitching oscillations we have an oscillation of the lift vector in two directions, longitudinal and lateral Both modes of oscillation can split up into components in phase with the attitude and the angular velocity of the pitching motion Any device or arrangement which influences the undamped natural frequency of the blade effects a change of the oscillations of the lift vector By using a proper layout this effect can be employed to decouple the longitudinal and lateral motion of the single rotor helicopter to a considerable extent

Regarding the effect of the offset of the flapping hinges, I would like to add the following statement to the remarks by Mr Stewart For the Sikorsky configuration with the controls fixed it follows that a positive hinge offset has approximately the same effect as an increase of the distance of the rotor above the C G of the helicopter and *vice-versa* This means that the coefficients A_0, A_2 of the frequency equation are multiplied by a factor

>1 in the case of a positive hinge offset and by a factor <1 in the case of a negative hinge offset In the stability charts (Figs 2, 3), this change of the hinge offset has the effect of moving along a straight line passing through the origin with the slope A_0/A_2 An increasing positive hinge offset means that we move to the right and an increasing negative offset means a move to the left It follows that the stability is improved by a positive offset if the slope of the T_D—curve in Fig 3 is larger than A_0/A_2, and by a negative offset if the slope is smaller than this figure However, as the coefficient A_1 remains zero, the motion always remains unstable

Replying to Mr McClements Due to increased damping multi-rotor helicopters are generally less unstable than single rotor helicopters With a proper layout it is possible to fulfil Routh's stability criterion under certain conditions, but even in this case the damping of the disturbed longitudinal or lateral motion is generally very small A main parameter in this respect is the mutual inclination of the rotor axes If we take the hovering stability of a tandem rotor helicopter as an example, it follows that the longitudinal motion has a certain similarity to an over-controlled single rotor helicopter, which means that slightly damped oscillations with long periods of oscillation occur The lateral motion (if we neglect the coupling between these two motions) does not differ in principle from that of a single rotor helicopter

At present very little is known about the interference of the different rotors in multi-rotor helicopters in forward flight Therefore I am not in a position to formulate any statements about the best multi-rotor arrangement

In reply to Mr Garraway With regard to the comparison of the longitudinal stability with the lateral stability, it can be stated that a decrease of the moment of inertia of the helicopter improves the stability In the case of the Sikorsky configuration fitted with a hypothetical autopilot the coefficients A_0, A_1, A_2 of the frequency equation are inversely proportional to the moment of inertia For the Sikorsky R-4B the moment of inertia in roll is about eight times less than that in pitch, which means that in the example in my paper (Sikorsky R-4B fitted with autopilot) the amplitude of the lateral motion is halved in 1 7 sec instead of 3 sec for the longitudinal motion A similar improvement appears in the case of the Sikorsky R-4B fitted with a Bell stabilizer It is seen that the longitudinal stability of a single rotor helicopter in hovering flight is a stronger criterion than the lateral stability and we do not need to worry about the rolling motion if the pitching motion is sufficiently damped

In conclusion, and in reply to Dr Thurston To stabilize a helicopter we need certain control displacements proportional to the attitude and to the rate of change of attitude, or the corresponding flapping motion of the blades It does not matter how this effect is brought about Generally it will be done, directly or indirectly, by the gyroscopic couple of rotating masses This mass may be a gyro, Bell stabilizer, Hiller servo blade, an auxiliary aerofoil attached to the blade or, as in the proposal of Prof Miller, the blade itself All devices mentioned above respond mainly to the angular velocity of the helicopter The stability problem is solved if we succeed in producing a sufficient time lag, which means that a proper component of the control displacement (or of the flapping motion of the blades) proceeds in phase with the attitude of the helicopter

Mr Raoul Hafner's Vote of Thanks to Dr Sissingh

Mr Chairman, Ladies and Gentlemen

It is my pleasant task to express the appreciation of the members and guests of the Helicopter Association to Dr Sissingh for having given us such an excellent paper, a paper which has helped his audience, to understand, without the aid of complicated mathematics, a most difficult problem For myself, I believe that the two factors mainly involved in the stability of the helicopter are control displacements proportional to the attitude and control displacements proportional to the rate of change of attitude Most schemes evolved for achieving stability do involve the use of these two separate variables but unfortunately do not permit fully their independent use and so have met with only partial success I express the hope that the double bar system will bring us the stability for which everyone is seeking

Finally I should like to congratulate Dr Sissingh for without doubt one of the most excellent papers ever read before our Association, and propose a hearty vote of thanks to him, a vote of thanks which I am sure has the support of everyone here today

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London—Paris Helicopter Link

As most members are probably aware a demonstration to prove the feasibility of the use of helicopters in restricted spaces was staged on the 30th September, 1948, by carrying a letter from the Lord Mayor of London to the President of the Conseil Municipal of Paris by air from city centre to city centre Aircraft taking part in the demonstration were the 171 Helicopter (Bristol Aeroplane Company) from St Paul's, London, to Biggin Hill Aerodrome , the Meteor 7 (Gloster Aircraft Company), from Biggin Hill to Orly Aerodrome , and the S 51 Helicopter (Westland Aircraft Company), from Orly Aerodrome to the Place des Invalides, Paris

An Air Mail cover commemorating this occasion has been presented to the Association by Mr N J G Hill

Acknowledgements

The Council wish to record, on behalf of the Association, their very sincere appreciation of recent presentations in respect of the new office and library These presentations are more than welcome to a young body such as ours

In the first instance, thanks are due to one of our founder members, MR NEIL MORRIS From his Glasgow factory, which specializes in woodwork and rotor blades, he has presented the Association with a very handsome oak bookcase and cabinet It is now in the office, housing the Association's technical and semi-technical library A suitably inscribed plate is being prepared to record the presentation

Appropriately enough we also have to acknowledge the presentation of a number of books to the library by another member, MR C C COOPER, on his return to this country from a visit to the U S A The library is now being reorganised and a list of the books available will be sent out to members in due course MR COOPER at the same time has also kindly presented the Association with a film he has taken of the latest Helicopter developments in the U S A which it is hoped to show to members after the next meeting

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The World's Largest Helicopter

THE CIERVA " AIR HORSE," photographed during its first free flight on the 8th December, 1948, at Southampton, piloted by H A MARSH, A F C