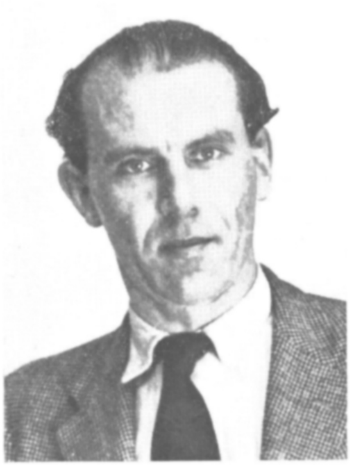


THIRD LECTURE, 1948

Some Technical Aspects of W 9 Development

By J S SHAPIRO, A F R Ae S

A lecture illustrated with slides and delivered before the Helicopter Association of Great Britain on Saturday, 3rd April, 1948, at Manson House, 26 Portland Place, London, W 1

H A MARSH, A F C , A F R Ae S , IN THE CHAIR

It is regretted that owing to lack of space the lecture could not be published in full and as there was insufficient time for the lecture to be rewritten the following is published as " EXTRACTS FROM THE TEXT "

INTRODUCTION BY THE CHAIRMAN

LADIES AND GENTLEMEN,—A number of you may not know our lecturer of this afternoon and I am glad to be able to tell you something of his past experience by way of an introduction

Mr SHAPIRO has had several years of engineering experience and his first aircraft appointment was in France working on the design of gyroscopic instruments, which post was rudely terminated by happenings in 1940 He came to this country and joined Power Jets, working on jet propulsion and then had a further period on aircraft instruments design This was followed by work on electric assister units for aircraft before he joined the Cierva Autogiro Company in 1943 as Senior Technical Officer

Mr SHAPIRO is a Founder Member of our Association, an A F R Ae S and holds an engineering diploma of the Federal Polytechnic in Zurich

It was intended that he should tell us something of the problems of multi rotor design, and it is due to circumstances beyond his control that the subject had to be changed at a late date and he will now talk instead on " Some Aspects of W 9 Development "

It is again a pleasure to welcome our guests today on behalf of the Association

MR J S SHAPIRO

MR CHAIRMAN, LADIES AND GENTLEMEN

I am going to report this afternoon on some experiences with an experimental helicopter Considering the rapid progress in this art, I may call them early experiences Some of the conclusions which you will hear to-day have been generally accepted, others are controversial, but all must be judged in their context, having regard to time and circumstances

THE TORQUE EQUILIBRIUM OF SINGLE-ROTOR HELICOPTERS AND THE CONTROL FORCES IN TILTING HUBS

Static Equilibrium of a Helicopter

Figures 1 and 2 show a hovering helicopter and illustrate the principal forces acting on it The torque reaction, being, together with the lift, the resultant of all aerodynamic forces acting on the rotor, is represented by the moment vector Q_R This vector is a free vector and defines direction and magnitude only and not a line of action It is, therefore, depicted along an arbitrary line *normal* to the tip path plane of the rotor

For the sake of simplicity it could be taken, to start with, that flapping hinge off-sets are absent, and we are, therefore, entitled to assume that the resultant rotor thrust goes through the centre of rotation As regards the precise direction of the thrust vector, we can again make assumptions identical with those relating to the resultant torque vector

Static equilibrium of a hovering single-rotor helicopter, as that of every free body, requires the fulfilment of six equilibrium conditions expressing the absence of resultant force and moment components

Most of these conditions are trivial but some deserve mention For simplicity, minor inaccuracies are covered up by the following, somewhat loose, terminology—

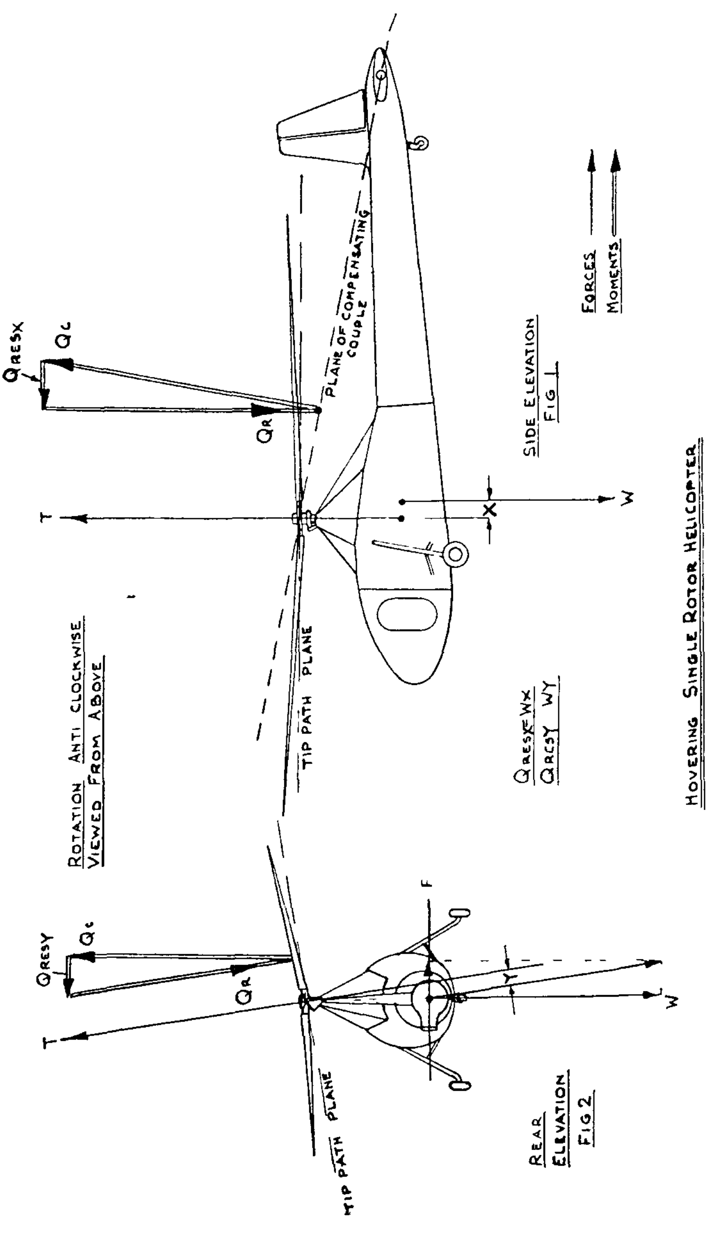
As easily seen in Figs 1 and 2, rotor thrust balances the weight of the aircraft The thrust is vertical in the pitching plane (Fig 1), but in the rolling plane (Fig 2) a lateral thrust component has to balance the tail thrust F Whilst this tail thrust is represented as being generated by a reaction jet, this is by no means an essential feature of the present argument

Moment equilibrium is established as follows Q_R is the rotor torque reaction The moment vector Q_C, representing the couple between tail force and lateral thrust component, which, again, is a free vector, is shown along a line intersecting the line of the moment vector representing torque reaction, and the direction of the compensating moment is at right angles to the plane defined by the line joining the rotor centre with the centre of the tail thrust and by direction of the tail thrust itself

The main thesis of this chapter is a fact of elementary simplicity, but too often overlooked, that the compensating couple can only fully balance the rotor torque reaction when their two lines of action are parallel and that, consequently, if an angularity exists between the two lines of action, an unbalanced moment is present which we have termed ‘residual torque’ and which may have pitching and rolling components

It is clear that since the direction of the rotor torque reaction depends on the tip path plane and the direction of the compensating moment depends on a plane defined by the aircraft, the residual torque is varied whenever the tip path plane is displaced with regard to the aircraft

Furthermore, any increment of residual torque, caused by an angular displacement of the tip path plane, acts about an axis at right angles to the



SIDE ELEVATION
FIG 1

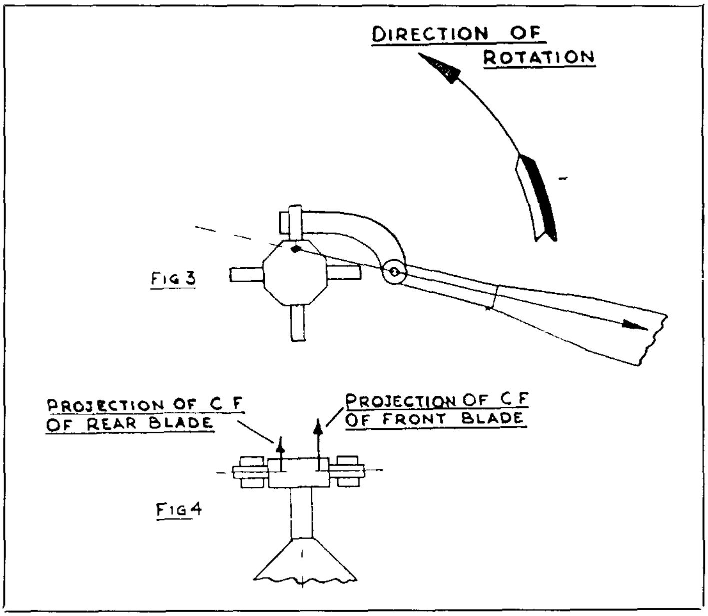
REAR
ELEVATION
FIG 2

HOVERING SINGLE ROTOR HELICOPTER

axis about which the inclination of the tip path plane takes place These relationships are quite fundamental and entirely independent of the control system of the rotor provided only that direct control is applied, *i e*, the rotor is displaced relatively to the aircraft Residual torque components in pitching and rolling must be compensated by pitching or rolling couples if equilibrium is to be maintained These can only be generated by off-sets between the line of action of gravity applied at the c g of the aircraft and the line of action of the rotor thrust applied at the rotor centre (See Figs 1 and 2)

Forces in Direct Rotor Controls

To examine the influence of these relationships on control forces it is now assumed that in a certain position which may correspond to the neutral stick position, the hovering helicopter is in equilibrium and, for the sake of generality, it may be assumed that this equilibrium is associated with pitching and rolling moments balanced by the above off-sets We now proceed to incline the rotor by application of control in the pitching sense and it follows from the above that, before motion sets in, apart from an unbalanced pitching moment which is the primary purpose for applying pitch control, a rolling moment is also generated Whilst the pitching moment is proportional to the thrust and the change of tilt in pitching, the rolling moment is proportional to the torque and equally, to the change of tilt in pitching Up to this point we have ascertained that the rolling moment always finally acts on the aircraft but it depends on the control system in what way this rolling moment is transmitted



It is further concluded that in a cyclic pitch controlled rotor this rolling moment increment is transmitted entirely through the mechanical axis of the rotor and through its bearings to the aircraft However, when the rotor is controlled by tilting, the rolling moment increment, arising as a consequence of pitching inclination of the rotor tip path plane, is transmitted partly through the mechanical axis and partly through the control mechanism itself

The former statement can be very easily illustrated by representing the rotor by the centrifugal forces of the blades acting along their longitudinal axes, this being a very useful pictorial simplification adequate in most instances Inclination of the tip path plane is identical with first oder flapping which causes the longitudinal axes of the blades to have different vertical components on both sides of the rotor Since these components act at an off-set from the axis of rotor due to the torque, the presence of a lateral or rolling moment is immediately visible when fore and aft flapping takes place (Figs 3 and 4)

To find the proportion in which residual torque increments are transmitted directly to the aircraft or indirectly through the control mechanism in a tilting rotor, we have to examine the torque transmission mechanism of the rotor In the first place, we examine a constant velocity joint in which torque is transmitted through pressure elements always maintained along the line bisecting the angle between the input and output shafts of the joint It is clearly seen from the diagram in Fig 5 that half the residual torque is transmitted through bending of the input shaft and the other half appears as a lateral tilting moment acting on the output shaft, and therefore, loading the control mechanism

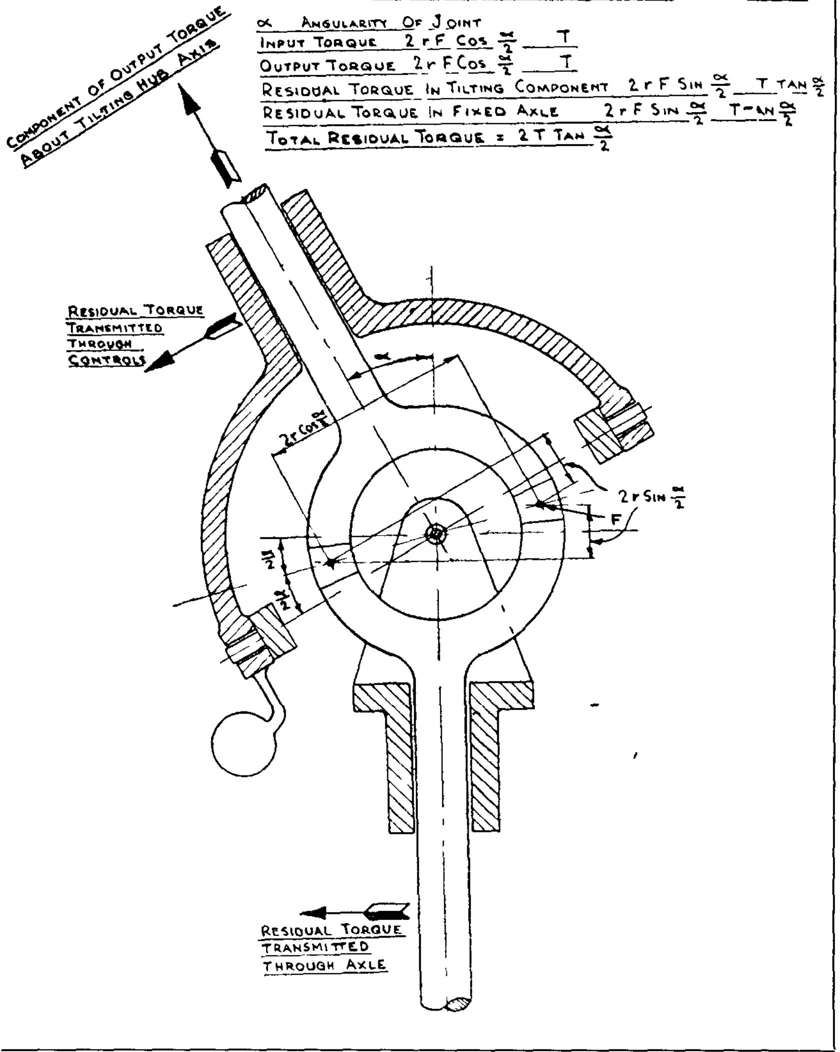
If, instead of a constant velocity joint, an ordinary Hook's joint is used, the proportion of the two moments varies periodically between two extremes in one of which the entire residual torque is transmitted as bending of the input shaft and in the other the entire residual torque is transmitted as a lateral tilting moment on the tilting hub and hence as a control force

Among various arrangements examined is one in which the rotor is tilted together with the main speed-reducing gear box , in such a case the only forces arising from the drive are those associated with high speed torque and these are only of secondary importance It can then be demonstrated, however, by examining the gimbal mechanism on which the rotor with its gear box is suspended, that, on the average, half the residual torque will still be transmitted through the control linkage

It ought to be emphasised that since the total travel of a control column is a constant determined by the pilot's convenience, maximum stick load is proportional to the square of the angular range associated with maximum stick travel In view of this quadratic relationship, it is impossible to predict the forces in a tilting control without precise knowledge of the required range of tilt, which can only be found by experience or comparison with other helicopters

From the pilot's point of view the transmission of part of the residual torque through the control mechanism is felt as a control force at right angles to the stick movement Though the control force as such can be eliminated in an irreversible mechanism, an unbalanced resistance to the application of control remains For instance, whilst a certain amount of fore and aft control is maintained, an application of control to port has to

CONSTANT VELOCITY JOINT FIG 5



overcome the control force due to residual torque, whilst an application of control to starboard is aided by residual torque

Powered Control Systems

Given the range found necessary to control the W 9 machine, the control forces due to residual torque can be shown to exceed the permissible level for precise and comfortable response by the pilot They represent the only aspect in which a tilting power driven rotor is fundamentally different from a similar autogiro rotor

Among other causes responsible for control forces, there is friction which, in some autogiros having plain bearings for flapping hinges, has been responsible for excessive control forces This is not the case with rolling bearings and the needle bearings provided in the W 9 are quite adequate for this duty However, in a rotor with flapping hinge off-set the presence of flapping, such as in forward flight conditions, causes a biasing moment transmitted through the control linkage in a tilting control This biasing moment, in contrast to that arising from residual torque, is partly in phase with the control displacement It can be used to provide a measure of " stick free " static stability Its neutral position and characteristics can be, to a large extent, controlled by selection of the tilting hinge of the rotor The stability aspect was not intended in the W 9 machine It could not be used because of the large forces involved and originally also because of the out of phase component of biasing moment

At that stage the order of magnitude of control moments was investigated on reasonable assumptions under adverse conditions, mainly high speed forward flight, and it was found that moments of the order of 200 or 300 lb ft occurred due to residual torque and moments of the order of 400 to 500 lb ft occurred due to flapping hinge off-set, the latter moment, originally found to exist in equal measure in both rolling and pitching could, later on, with the introduction of the compound back coupling linkage, be confined to pitching moments only

By suitable positioning of the rotor centre against the c g of the aircraft and suitable arrangement of initial angularity of the drive, maximum moments could be reduced to half the above value It is clear, however, that moments of this magnitude are beyond the power of a human pilot

It was decided to apply a powerised control system installation which had been contemplated from the beginning Upon examination it became evident that the most elegant solution, from the mechanical point of view, was a hydraulic assister unit on the follow-up principle and the unit chosen was a pair of Lockheed " Servo-dyne " jacks which are hydraulic servo motors characterised by the following features —

(*a*) Positional correspondence is ensured by placing the follow-up valve on the moving part of the servo motor and arranging the pressure and return lines through flexible hose connections

(*b*) Double action is obtained by arranging different effective piston areas for the two senses of motion and maintaining continuous pressure on the smaller area, whilst controlling, on and off, the larger area

(*c*) The " Selector " or follow-up valve is of the poppet type and the fluid pressure is counteracted by spring loading of the valve elements

This last feature is responsible for an extremely small lost motion (of the order of 3 thou) but calls for a comparatively large input force to control the " selector " valve

Though in the course of flight testing there have been many modifications to mechanical details such as lever ratios, selector valve spring loading, and ratio between pitching and rolling control, the assister unit installation can be regarded as a complete success In spite of initial " sales " resistance the test pilot became accustomed to the feel, or rather lack of feel, of an assisted control mechanism of this type and the control force could be adjusted to suit the pilot's convenience After several dozens of hours of flight and operations on the ground involving an estimated number of control movements running into several 10,000's, no mechanical trouble of any kind has been experienced with the installation

TORQUE COMPENSATION BY TAIL JET USING ENGINE WASTE HEAT RESPONSE TO YAWING CONTROL

The basic conception of a tail jet is simple and no different fundamentally from the tail airscrew Physically, both forms of thrust generating devices embody the reaction principle and are subject to the law that thrust is proportional to the square of the velocity of the reaction jet and the power expended to generate the thrust is proportional to the cube of that velocity and it is, therefore, more advantageous to work with low velocities Hence, to attain a given thrust, both mass flow and area of jet must be as large as possible One difference between airscrew and jet is that the effective area of the jet may be equal to that of a (well designed) orifice, whereas the area of the airscrew slip stream is only half the disc area of the airscrew

It follows from this simple consideration that, given equal conditions, an airscrew will be more efficient as it is quite impossible to design jet orifices even approaching half the size of a reasonable airscrew disc area Conditions, however, are not equal in several respects

1 The required magnitude of thrust for torque compensation naturally depends on the distance of its line of action from the axis of the rotor It is quite conceivable that an orifice may be placed further out for an equal weight of tail structure as compared with an airscrew involving a concentrated weight and giving rise to vibrations

2 It is possible to improve jet performance by the addition of waste heat from the engine Although the amount of heat is large, the benefit from the addition of heat depends entirely on the pressure level at which it is added The highest pressure level can only be equal to the dynamic head of the reaction jet It is clear, therefore, that a larger, and therefore more efficient orifice, leads to a reduced benefit from the addition of heat

3 The very size of the tail airscrew makes it necessary to raise its axis, mainly to enable the helicopter to carry out certain manoeuvres near the ground which require a tail-down attitude Such raising of the airscrew axis is accompanied by additional weight, which is equivalent to additional power

The jet reaction system was mainly proposed for reasons other than performance considerations, principally for the sake of avoiding vibrations in forward flight and for safety near the ground The latter feature undoubtedly remains a valid argument in favour of a jet, but it is felt that, in the meantime, designers of tail airscrews have succeeded in eliminating vibrations peculiar to that source and it can no longer be regarded as an argument against the tail airscrew The original opinion that a jet offers less drag in forward flight is totally wrong Although a jet installation lends itself more easily to the arrangement of a fin which can furnish all the torque reaction required at and above cruising speed for approximately 2—2½% of total power, with due refinement a tail airscrew may furnish the equivalent of 1 or 2% in the form of thrust It is seen, therefore, that this aspect is altogether marginal

Summarising, it can be said that the jet system, when properly laid out, is marginally inferior in performance, but offers safety to personnel on the ground

It is, however, in the *control* of the tail jet which constitutes the yawing control of the aircraft that the greatest difficulties arose The original design was arranged to provide a throttling control on blower intake by moving shutters This proved to be a problem in mechanical design which could only be satisfactorily solved by the addition of considerable weight It was also realised that any type of throttling control, whether applied to blower inlet or orifice outlet, would require a continuous power input to the blower corresponding to the highest value of thrust required at any time during the application of the yawing control Experience showed that the variation of thrust for yawing control comparable to control by tail airscrew required an increase in tail thrust of the order of half the average value for torque compensation in hovering The power increase is even greater than the percentage of thrust increase and 50% of increase in thrust would amount to 84% increase in power, which, in the circumstances, was not acceptable

These considerations led to the construction of a variable pitch fan of all metal design which was fitted to the machine Although a mechanical solution for controlling the torque reaction jet was thereby fully achieved, the method of jet control " at the source " proved to be inadequate in comparison with the yawing control provided by a variable pitch tail airscrew

The disadvantages attributed to this form of control are as follows —

1 The control is sluggish, that is, its effect is felt after an appreciable lapse of time following the application of control In view of lack of measurements, it is difficult to state in terms of physical magnitudes what precisely is the meaning and magnitude of the time lag and whether the sensation of angular acceleration or the observation of the change of position is predominant but, for what it is worth, the pilot states that the delay in control effect is of the order of 1 to 2 secs The cause of this delay is believed to be due to the compressibility of the air and must depend on the cubic capacity of the tail which acts as a pressure vessel In fact, were the air incompressible, an increase in blade pitch would produce an immediate rise in pressure throughout the tail and the jet would commence accelerating immediately until the jet velocity acquires a new equilibrium value The period of acceleration already constitutes increased thrust It is clear that the chief weakness of the W 9 installation, in having the blower mounted very far forward, was a feature greatly contributing to this particular disadvantage of yawing control by jet reaction

2 Whilst the continuous expenditure of power by jet torque reaction may, as mentioned previously, be justified on performance grounds alone when everything is taken into consideration, such an increased expenditure of power per unit of torque causes large power variations to accompany an application of yawing control The effect is inseparable from any type of torque compensation involving the expenditure of power unless special interlinkage mechanisms are used The magnitude of the effect may make it irksome to the pilot, especially if he is used to a different level of variation

Undoubtedly, the combination of the two disadvantages is an added difficulty for the pilot because, in the attempt to reduce the control lag, he increases the amount of control unnecessarily and thereby aggravates the interference with rotor power

HOVERING STABILITY OF HELICOPTERS WITH ROTORS HAVING PRONOUNCED FLAPPING/PITCH COUPLING

At the time when the following investigations were made, hovering stability of helicopters was known in its application to machines with counter-rotating rotors of the superimposed or side-by-side types Such machines offer, in principle, a substantial simplification of analysis due to the fact that hovering stability can be examined separately in the two principal planes of the machine, namely the pitching and rolling planes A further simplification is made if blade flapping or, what amounts to the same, the inclination of the tip path plane is not considered a separate degree of freedom Hovering stability then involves only two degrees of freedom, namely fore and aft movement and tilting in pitch of the whole aircraft, and leads to characteristic equations of the cubic type which can be solved with very little labour

The elimination of flapping as a degree of freedom implies that the tip path plane adjusts itself to the general motion within a time interval of negligible length in comparison with the natural period of the general motion Flapping, therefore, enters the picture only in its effect on the derivatives of the rotor force and moment with regard to motion in the two degrees of freedom

In actual fact, in a single-rotor helicopter, there is no inherent reason to separate the pitching and rolling planes There is, in fact, a side force generated by forward motion and vice-versa In what follows it will be seen that these " cross " forces and moments are of decisive importance in a single-rotor helicopter from the point of view of control and the development of the " compound back coupled " rotor can, from the point of view of stability and control, be simply expressed as the elimination of coupling between the pitching and rolling planes of motion (or any other two planes through the vertical axis of the machine normal to each other)

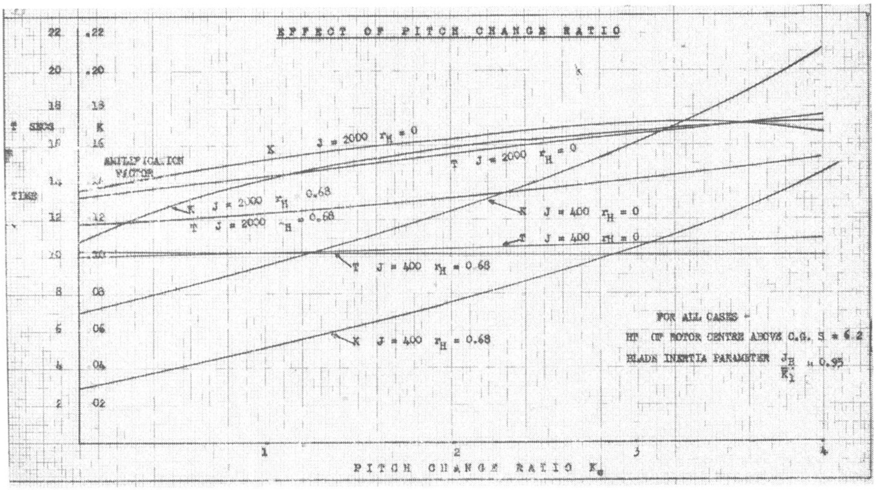
In the first place, a considerable amount of work was done whilst *disregarding* the coupling terms in an endeavour to establish stability and control features derived from the " flat tracking " properties of the rotor irrespective of phase relationships It was subsequently found that the conclusions reached from such investigations can be applied, without modification, in principle, to a practical rotor in which the coupling is *eliminated* instead of being *disregarded* We shall, therefore, regard the results as applying to a " flat " tracking rotor of any description, that is a rotor in which the flapping is automatically substantially reduced as compared with a freely flapping rotor

As is well-known now, single-rotor helicopters are generally unstable in hovering in the sense that, when left to themselves after a disturbance, they carry out an oscillating movement involving both tilting and fore and aft translation which motion is self-excited and has a natural period measured in seconds and a rate of amplification which depends to a large extent on the design parameters

The investigation was concerned with the influence of important design parameters on the amplification factor and the natural period of the free motion of the machine Most of the conclusions are to-day well-known and have been verified by various investigators so that emphasis is put here on the effect of " flat tracking "

Before dealing with the influence of " flat tracking," we must point out, however, one feature which is usually surprising to designers, namely that high inertia of a machine has a destabilising effect in the sense of increasing the amplification factor Although high machine inertia also increases somewhat the natural period and makes it, therefore, easier to deal with instability, beyond a certain machine inertia all other design parameters become of decreasing importance Expressed in practical terms, there is likely to be less difference between single-rotor helicopters in the pitching plane than in the rolling plane

W 9 Stability in Hovering

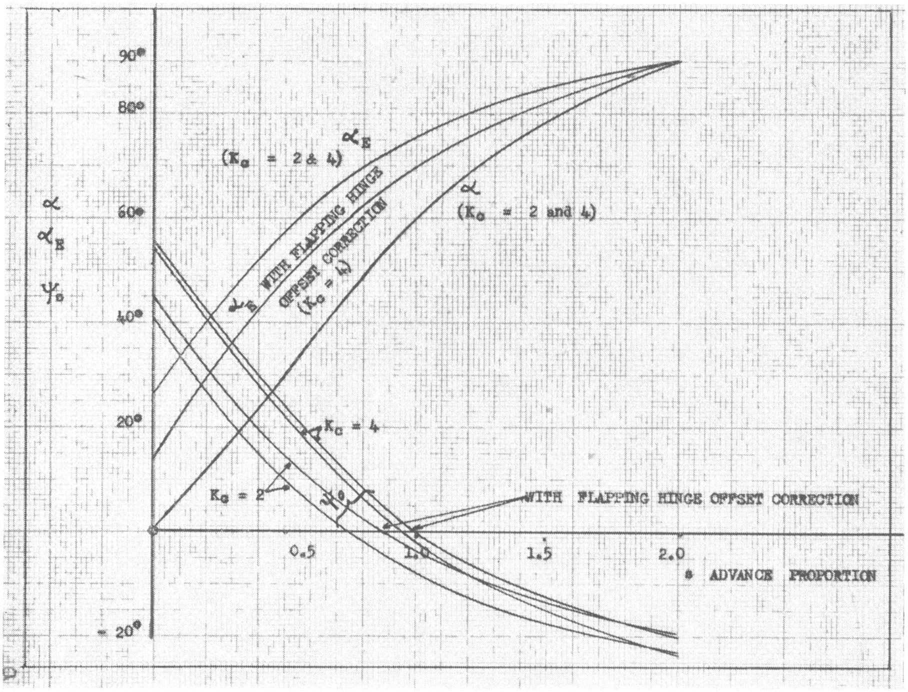


The main result of this investigation is the destabilising effect of " flat tracking " expressed in a linear increase of the amplification factor with the pitch change ratio, whilst the natural period remains almost unaffected This is particularly visible with low machine inertia (rolling) The result is surprising in a sense, and emphasises the importance of investigating the machine as a whole rather than the rotor itself In visual terms, it points to the completely misleading nature of observations made on a model when the hub is rigidly mounted   In such a model a high negative pitch change ratio, by making the rotor more " flat tracking " and reducing the oscillations of the tip path plane caused by casual disturbances in the wind tunnel, produces the impression of stability   It is this apparent stability which has led to the expression " gust stability," and whilst it is true that in a rotor with a high pitch change ratio the rotor plane is less disturbed in relation to the hub, this does not mean stability of the machine as a whole, but the very opposite

Related to more systematic investigations leading to explicit expressions for the amplification factor, it can be said that the moment derivative of tilting motion and the force derivative of translational motion have a stabilising effect whereas the moment derivatives of translational motion and the force derivatives of tilting motion have a destabilising effect   Numerically, both moment derivatives are the more important ones   Roughly speaking, the main effect of a negative pitch change ratio is to reduce both moment derivatives   It has, therefore, both a stabilising and a destabilising effect   However, in a first approximation the amplification factor is proportional to the moment derivative of translational motion and inversely proportional to the square of the moment derivative of the tilting motion   The nett effect of a negative pitch change ratio is, therefore, destabilising

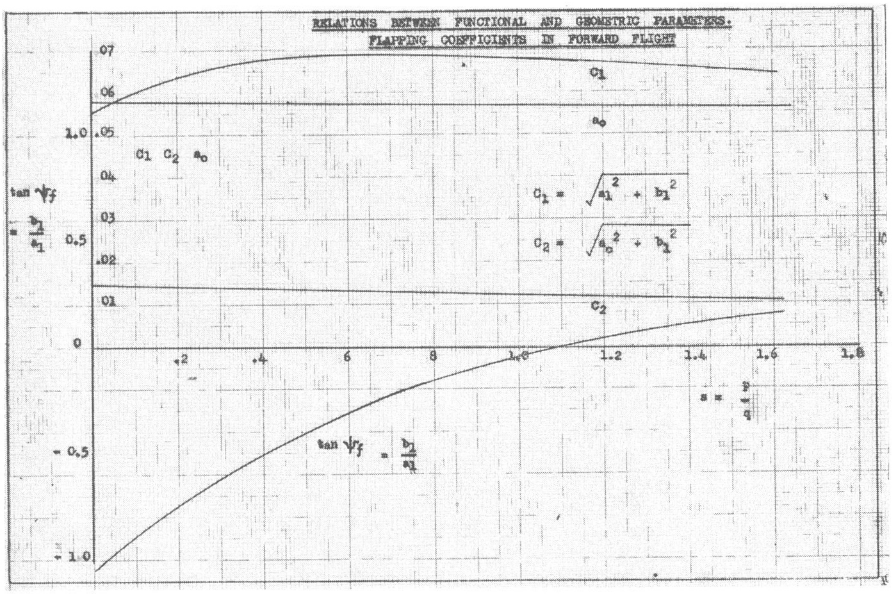
W 9 Compound Back-Coupled Rotor

Relations between Functional and Geometric Parameters



It is known that these investigations were based on several approximations It has already been mentioned that flapping as a separate degree of freedom was eliminated The vertical and yawing degrees of freedom were also neglected Both these approximations are amply justified Furthermore, the resultant rotor force was assumed to be normal to the tip path plane and, moreover, in the tilting motion no dissymetry of the slip stream was considered Both approximations are unjustified, and have been corrected by a more exact treatment The results suggest that numerical values are sufficiently modified to make it desirable to avoid the last two approximations wherever the actual magnitudes are of importance, but neither of these approximations is responsible for a shift of emphasis in the general conclusions reached

W 9 Compound Back-Coupled Rotor



However, the disregarding of coupling between the pitching and rolling planes, in the presence of a high negative pitch change ratio which produces considerable out of phase flapping in rotational and translational motion appeared to be totally unfounded and an investigation was carried out taking into account all four degrees of freedom The equations of motion led to four simultaneous differential equations, the characteristic equation of which was of the sixth degree Numerical values were introduced and applied to the W 9 machine, but, for the sake of generality, the method of flapping reduction remained unspecified and was merely introduced by a coefficient expressing a reduction of flapping in phase with the direction of motion to 1/3 of the freely flapping rotor The out of phase component of flapping was given values beginning with 0 and ending with a component of equal magnitude to the in-phase component The coefficients of the sextic were plotted against the ratio of the derivatives in the two phases and most coefficients found to be symmetrical about the zero value The numerical solution of the sextic was carried out by the Mathematics Division of the N P L and the results showed that no critical increase in instability was introduced through the coupling between the rolling and pitching planes On the contrary, the highest amplification factors were reduced by the existence of the coupling which signified, as it were, that the lower instability in the rolling plane and the higher instability in the pitching plane are mixed into an intermediate instability when the two planes are cross-coupled

RESPONSE TO AZIMUTH CONTROL OF HELICOPTER WITH TILTING ROTOR AND PRONOUNCED FLAPPING-PITCH COUPLING

The investigations summarised under this heading are concerned with the behaviour of a helicopter arbitrarily constrained to tilt about an axis through its c g This axis can coincide with the pitching or rolling axis and, to be specific, the pitching axis was chosen In this instance, the flapping of the blades expressed by the inclination of the tip path plane was considered a separate degree of freedom The motion, therefore, consists of two degrees of freedom, viz , rotation of the machine about a horizontal axis through its c g and inclination of the tip path plane relative to a chosen reference plane fixed in the machine

Viewed in this light, it is immaterial whether out of phase flapping exists and the investigation does not reveal its effect Consequently, results reported here are the same whether we disregard the out of phase flapping or eliminate it through a compound linkage

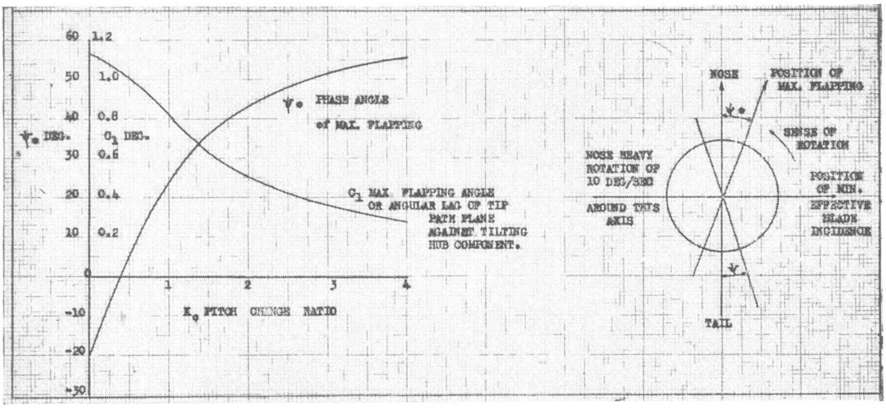
Apart from the existence of cross coupling between the pitching and rolling planes, these calculations also exclude the translational motions to which the real machine is subject once the hovering equilibrium is disturbed by the application of control Furthermore, the calculation assumes that a control displacement is completed instantaneously

At the time, the calculations were carried out to crystallize the influence of control parameters in the comparison between hovering helicopters of various types It is believed that the results do, in fact, reveal significant features and measure magnitudes of real value in judging the control of a helicopter The reason is that control displacement can be applied within time intervals which are negligible compared with the duration of motions here considered and that the first few seconds of the motion of the machine initiated by a control displacement are unaffected by the interaction between the translational and rotational degrees of freedom On the other hand, the existence of out of phase force and moment components has proved to be a decisive feature causing inability of the pilot to control the W 9 machine in hovering until these out of phase forces and moments were substantially eliminated This aspect will be discussed fully in the next chapter

Perhaps it is profitable to proceed from the physical aspect It would seem that the essential difference between control by cyclic pitch change and hub tilting, when both are associated with flapping hinge off-set, is that, in the cyclic pitch controlled rotor, the tip path plane is tilted first, and as soon as the tip path plane is inclined, the centrifugal force of the blade exercises a so-called T bar effect on the hub, producing a powerful moment in the same direction as the moment of the resultant rotor thrust about the c g of the aircraft When the aircraft attains a certain rate of pitch this rate causes a backward inclination of the tip path plane and angular acceleration ceases when the backward inclination restores the tip path plane to a position where the moment about the c g vanishes

W 9 Rotor System

Flapping Coefficients during 10 deg /sec Tilting Motion

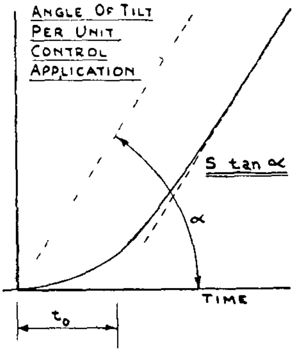


When, on the other hand, the hub is tilted, during the initial period, the tip path plane has not moved yet the " T bar effect " works the opposite way and the machine actually experiences a reverse acceleration to start with In the next phase, the tip path plane has followed the hub and exercises a moment by virtue of the inclination of the left vector but without T bar effect Finally, equilibrium sets in when the same condition is fulfilled as above

The main object of these calculations was to establish whether the initial period of acceleration is responsible for a difference in behaviour which is likely to affect control from the pilot's point of view The result of the calculations can be expressed numerically in a very simple way A given amount of control displacement corresponds to a steady rate of tilt to which the machine settles down, asymptotically A line, representing

MACHINE CONSTRAINED TO ROTATE ABOUT PITCHING AXIS THROUGH C G

HINGE OFFSET r_H	FLAPPING REDUCTION K_c	TILTING		CYCLIC	
		S	t_0	S	t_0
0	0	8 92	1 60	8 92	1 60
0 68	0	4 31	0 965	8 92	0 81
0 68	2	9 3	1 71	19 25	1 67



this rate of tilt in a graph giving the angle of tilt upon time, cuts the time axis at a point which can be taken to represent the initial delay between the instant of application of control displacement and its effect on the machine An illustration shows initial delay and rate of tilt almost identical in the R 4 and W 9 machines and gives an idea of influence of flapping hinge off-set and pitch change ratio It is seen, for instance, that an increase in flapping hinge off-set reduces the rate of tilt in the tilting hub controlled machine but has no effect on the rate of tilt in a cyclic pitch controlled machine A pronounced negative pitch change ratio increases both the rate of tilt and the initial delay in a tilting hub controlled machine and has the same effect on a cyclic pitch controlled machine The latter combination, incidentally, represents a hypothetical rotor not attained by any known blade articulation

These investigations showed further, when compared with the calculation of instability, that in a W 9 type of hub, all parameters which reduce instability, such as larger hinge off-set, lower pitch change ratio and higher blade inertia, also slow down control response, in the sense of reducing the rate of tilt But rotor height (above c g) when increased up to a certain limit marginally reduces instability and quickens control Machine inertia whose increase makes instability worse, has no effect on control rate of tilt but increases the initial delay following the application of a control displacement These results apply to a tilting hub With cyclic pitch control an increase in flapping hinge off-set both reduces instability and quickens the control response

COMPOUND BACK COUPLING LINKAGE

In this context the relevant aspect of this linkage is its functional purpose This can simply be described as a mechanism ensuring the absence of out of phase components of forces and moments in the motion of the rotor following the application of control It can equally well be described as the elimination of " cross " derivatives in free rotor motion, for example, translational movement of the rotor in a direction X produces forces and moments on the machine substantially only in the plane containing the rotor axis and the direction X A simple flapping rotor without coupling between pitch change and flapping fulfills this condition, though not accurately, but to an acceptable degree

In view of many misconceptions encountered since the introduction of this linkage it is desired to emphasise that it differs from the simple pitch/flapping coupling only in the presence of rotor motion Once that motion ceases, or if no such motion can take place, both the simple pitch flapping coupling and the compound linkage produce the identical result—namely, that upon the application of a control displacement, the rotor, after a very brief transient, but highly stable motion, settles down to a new position in strict sympathy with the control displacement in magnitude and direction It is clear, therefore, that the difference could hardly be discovered by merely observing the manner in which a model rotor, mounted on a rigid base, follows the application of tilting control

Further, the effect of out of phase forces is clearly a matter of degree No rotor system can eliminate all " cross " components under all conditions and the degree to which such rotors have been flown successfully shows that " cross " components, up to a certain magnitude, are acceptable This aspect emphasises the importance of a practical flight test since in involves the translation of human reactions, in a manner not hitherto generally explored or summarised, into physical magnitudes It is clear, therefore, that had attention been concentrated from the start on the phase aspect of rotor response to motion and control, there would be no means of telling whether " cross " components were excessive or not except by a practical flight test in full scale

In fact, to some extent, calculation would have been misleading as analysis would have to concentrate on the instability which, as was proved later, does not deteriorate in the presence of " cross " derivatives

The choice of means for the elimination of " cross " components was dictated by mechanical considerations, having regard to the design of the existing hub The " compound back coupling linkage " constitutes one such method which has the advantage that, from the mechanical aspect, it is no more complicated than the simple pitch/flapping coupling The essence of the mechanism is that the pitch angle of each blade depends uniquely, and in the simplest case linearly, upon the sum of two terms being constant multiples of the flapping angle of the blade itself and that of the preceding blade respectively

This definition, although it fully characterises the adopted mechanism, does not represent the most general expression of the fundamental requirements This must be expressed in terms of the following magnitudes —

1 Ratio between maximum amplitudes of pitch variation and flapping oscillation—d

2 Non-dimensional blade inertia about flapping hinge expressed by J/K

3 The azimuth angle (α) between the phase of maximum flapping and the phases of maximum pitch amplitudes of any blade moving through a revolution This phase difference can be registered in a variety of ways, none of which is a direct materialisation of its fundamental definition since, of course, no blade can be in two places at the same time In reality the phase displacement can be introduced in one of the following ways —

  (*a*) By making use of a neighbouring blade

  (*b*) By introducing a datum expressing the steady motion of all blades

(*a*) was the method actually used, of which only the mechanical design is new The idea of coupling between neighbouring blades was first conceived by Oemichen and a combination between such interconnection and a direct pitch change linkage was already mentioned by Young, though in an apposite sense and without realising its limitations

Method (*b*) has not been previously proposed or used

Although the two methods are equivalent in fulfilling the basic requirement of phasing, they are different in their response to motions involving higher harmonics of flapping than the first

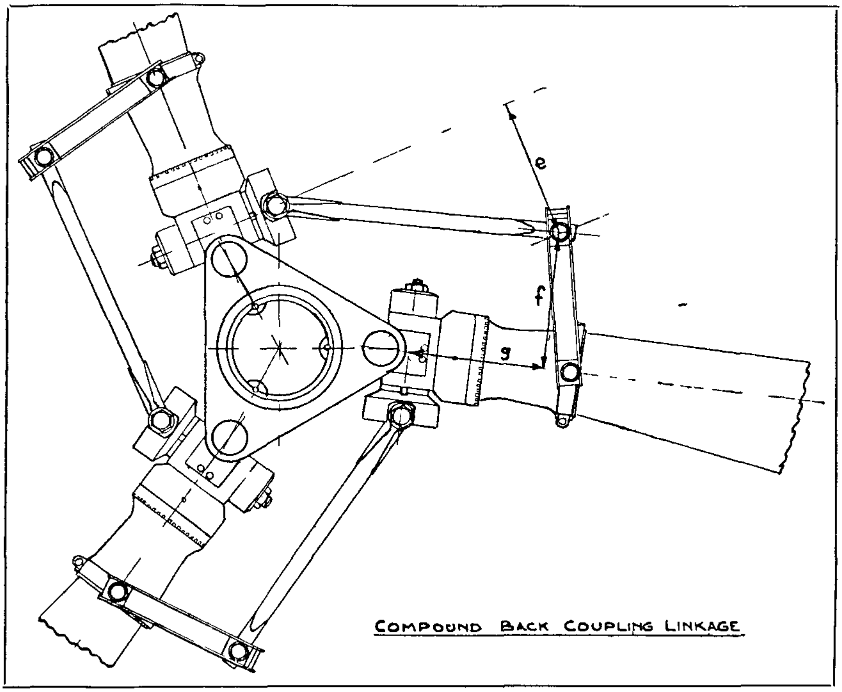
The fundamental requirement refers to specific elementary motions of the rotor It is fortunate that the two basic types of rotor motion, namely tilting and translational motion, do not lead to contradictory requirements and tilting motion can be taken as the determining condition, being much easier to handle analytically in view of the absence of inherent second harmonics of flapping

We can now express the fundamental requirements in the following form —

$$\tan\alpha + \frac{1}{d}\,\frac{1}{\cos\alpha} = 2\,\frac{J}{K}$$

It can be easily verified that for any reasonable values of J/K and a value of d around 2, the fundamental requirement cannot be fulfilled by either a direct pitch/flapping linkage or a pure " backed coupled " linkage and must, therefore, be met by a compound linkage except in a six-bladed rotor where a pure " back coupled " linkage is possible

Leaving the generalised expression we concentrate on the actual mechanism incorporated in the W 9 rotor A drawing shows the mechanism The essential dimensions of this drawing are e, g and f, their effective



COMPOUND BACK COUPLING LINKAGE

ratios are — p = g/f, q = c/f, referred to as the direct and advanced pitch change ratios These two form the coefficients in the expression for the blade pitch, where θ_2 is the representative geometric pitch of blade No 2 θ_0 is the pitch setting at zero coning β_2 the flapping angle of blade No 2, β_1 the flapping angle of the preceding blade No 1

$$\theta_2 = \theta_0 - p\beta_2 - q\beta$$

To characterise this rotor system quantitatively, the most significant *built-in* geometry parameters are the following combinations of the above ratios p and q —

1 The coning ratio $k_c = p + q$

2 The advance proportion $s = \frac{q}{p}$

The coning ratio is important on its own as it determines the behaviour of the rotor in all symmetrical flight conditions such as vertical climb and descent, and, in this respect, is the equivalent to the pitch change ratio in a simple linkage

However, the operationally significant magnitudes are the ratio d_E of maximum effective pitch variation to the maximum flapping amplitude and the angle α_E between the phase of maximum flapping and the phase of maximum effective pitch variation Effective pitch is the sum of geometric pitch and the first harmonic of flapping, which sum, in conjunction with a given slip stream velocity, determines the incidence and hence lift of the blade These operational parameters can be expressed in terms of geometry parameters

The importance of d_E and α_E derives from the fact that they are simply connected with the magnitude of flapping c_0 during a steady rate of tilt and with the azimuth angle ψ_0 between the phase of maximum flapping amplitude and the normal to the axis of tilt

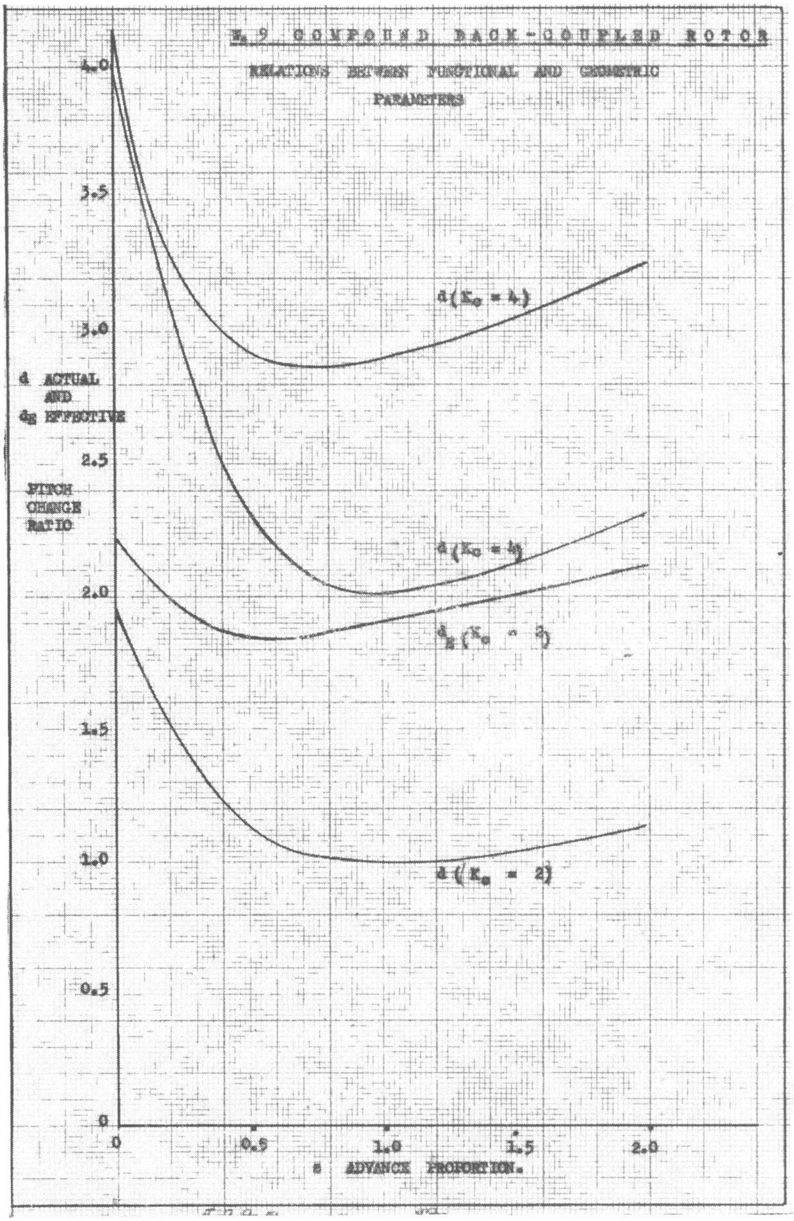
In numerical terms relations are given in graph form which is self-explanatory It is seen that with coning ratios k_c between two and four, the advance proportion to achieve flapping in phase with the normal to the axis of tilt ($\psi_0 = 0$) is around unity and this advance proportion was actually adopted in the W 9 machine whilst the coning ratio was maintained at 2 A graph shows d_E as a function of p for equal k_c

It is to be noted that numerical relations are not greatly affected by flapping hinge off-set and its elimination means a great simplification in the formulae

Blade flapping motion in forward flight was investigated by setting up equations of motion incorporating the two first harmonics of flapping and solving 5 simultaneous differential equations for various advance proportions to obtain the unknown flapping coefficients Calculations were carried out for a coning ratio of two and the results are presented showing the maximum amplitudes of first and second harmonics of flapping C_1 and C_2, the tangent of the out of phase azimuth angle b_1/a_1, and the coning angle as, at a tip speed ratio of $M = 35$ and a through-flow ratio λ corresponding approximately to level flight with a given forward drag It is seen that the maximum amplitudes of flapping vary but little over the whole range of advance proportions but the phase angle alters considerably, going through zero around an advance proportion of unity

These investigations also show that with a coning ratio of zero, there is some out of phase component of flapping which can be eliminated by introducing a direct pitch/flapping coupling of 4

The behaviour of a machine equipped with a compound back coupling linkage in regard to performance, control and hovering stability has already been referred to under the appropriate headings Summarising, the *elimination* of out of phase components of flapping leads to a behaviour as


F. 9 COMPOUND BACK-COUPLED ROTOR
RELATIONS BETWEEN FUNCTIONAL AND GEOMETRIC PARAMETERS
d ACTUAL AND d_E EFFECTIVE
PITCH CHANGE RATIO
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
d (K_0 = 4)
d (K_0 = 4)
d_E (K_0 = 3)
d (K_0 = 2)
0
0.5
1.0
1.5
2.0
s ADVANCE PROPORTION.

predicted in a machine in which the out of phase component is *disregarded*, provided d_E has the same value On the basis of equal coning ratio, the compound linkage is slightly more effective In performance computations it is presumed that the coning ratio alone is of any consequence and influences r p m requirements at a given setting angle throughout the forward speed range

When the W 9 machine was equipped with the compound linkage, it became at once controllable in hovering and it must be concluded, therefore, that out of phase components of flapping approaching in magnitude the in-phase components during the application of control are unacceptable to the helicopter pilot and make it impossible for him to control the machine

Several hours of flying were logged with this set up in its final form, incorporating several adjustments of lever ratios, etc Anticipating further findings, it can be said broadly that " azimuth " control was successful and, after some adjustments, could be considered as equivalent to the Sikorsky R 4 machine in flying qualities

The above account is necessarily incomplete, but it is believed that the selected topics represent those aspects of the many phases of W 9 development which are of general interest from the technical point of view

It has been said that experience consists in learning from other people's mistakes The Cierva Autogiro Co , it's Chief Designer, Mr C G Pullin, and my colleagues had to learn from their own mistakes In view of the record of the Company and it's associates in the development of Rotating Wing Aircraft, they can afford to be candid in the assessment of past experience true to the motto of Francis Bacon " Truth emerges more easily from error than from confusion " It is this spirit which enables us to look confidently into the future and await the unfolding of subsequent developments representing the materialisation of years of experience in practical machines for practical users

References from which general information has been extracted are too numerous to be listed I have to acknowledge gratefully the help of my colleagues on the Staff of the Cierva Autogiro Co , and wish to express my appreciation of the company's permission to disclose the information given in this paper It gives me particular pleasure to acknowledge the continued support given to our work by the Ministry of Supply and, in particular, by Captain R N Liptrot, D D R D Helicopters I thank you, Ladies and Gentlemen, for being a patient and attentive audience