Paper No. 5

ADVANCED CONTROL SYSTEMS FOR HELICOPTERS

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1. THEME

It is the aim of this paper to illustrate some of the basic control and stability problems that are typical of the present day helicopter,and to indicate the way in which these problems play a part in defining rotor characteristics.

The idea of "DEMAND" types of control systems is introduced as a possible solution to these problems and as a means to releasing some of the present rotor design constraints - particularly in rotor stiffness.

The use of very stiff rotors in a co-axial system is briefly discussed in order to show the possible freedom in helicopter design resulting from the use of such stiff rotors.

2. ROTOR FUNDAMENTALS

The "classical" helicopter rotor has its blades freely hinged at some position close to the centre of rotation,as is shown in Fig.1.The hub moment per unit blade flapping is proportional to the blade flapping inertia (which defines the centrifugal force which is by far the largest force acting on the blade) and the offset of the flapping hinge from the centre of rotation.The addition of a hinge spring would,of course,increase the amount of hub moment per degree flapping.The recent hingeless rotors may be viewed in fact as "classical" hinged rotors with a flapping hinge spring.

Rotor control consists of varying the blade pitch angles in a collective and cyclic manner.In hovering flight collective pitch - applied to all blades equally - defines the rotor thrust and,as each blade flaps up by the same amount,there is no resultant hub moment.Cyclic pitch - varying in a sinusoidal fashion with a frequency of once per rotor revolution - leads to a once-per-revolution flapping motion of the blades which may be considered as a tilt of the rotor disc relative to the shaft.The resultant hub moment is in the same sense as the disc tilt and,of course,proportional to this tilt.Cyclic pitch may be applied in any sense such that the rotor disc can be tilted in any desired direction.

It must also be noted that when the disc tilts the rotor thrust vector remains essentially normal to the disc so that disc tilt brings with it a force normal to the shaft and in the direction of tilt.This force also gives rise to a moment about the aircraft centre of mass.

The total moment about the aircraft centre of mass due to the rotor thus consists of two components - the "stiffness" contribution due to hinge offset and spring-induced hub moment and a "thrust vector tilt" contribution.

The stiffness component can conveniently be described in terms of a "stiffness" number $S=(\lambda^2-1)/n$ - which is a non dimensional number expressing the ratio of "elastic" flapping moments to aerodynamic flapping moments on the blade - without any direct reference to the blade flapping hinge offset or spring.This is because these terms merely define the blade flapping frequency ratio λ .

The upper diagram of Figure 2 shows the relationship between the blade natural flapping frequency ratio λ and inertia number n and the stiffness number S.Classical articulated and present day hingeless rotors lie in the areas indicated. It is immediately seen (making allowance for the log scale) that helicopter main rotors as yet have only made use of a very restricted area of the inertia / stiffness plane.

The amount of flapping produced on a fixed hovering rotor per degree of cyclic pitch is shown as a function of stiffness number in the second diagram, illustrating that articulated and soft hingeless rotors are not too different in this respect.

Moving to the third diagram we see the phase lag between cyclic pitch application and blade flapping and here one sees that present day hingeless rotors differ by some 15 - 20° from articulated rotors.

The bottom diagram is very important as it shows the amount of moment about the aircraft centre of mass per degree of cyclic pitch. At the very low stiffness numbers of articulated rotors the thrust vector tilt is the main component and the stiffness component may, at the most, equal the thrust vector component. It is obvious therefore that the control moment of articulated rotors is highly dependent on rotor thrust level and consequently may vary considerably throughout the flight envelope. (Typical thrust levels have been assumed in the diagram). However the hingeless rotors of today produce control moments primarily by "stiffness" and the total control moment is some 3 to 5 times greater than for articulated rotors. Although the thrust vector tilt component is much the same as for articulated rotors its contribution is only some 20% of the total which results in only a small variation of control power with rotor thrust level. It is interesting to note that even though the modern hingeless rotor has resulted in a quite tremendous increase in control power, it produces less than 50% of the maximum control power possible with very stiff rotors.

In a very crude manner the rotor moment per unit cyclic pitch can be considered to give an indication of the sensitivity of the rotor to aircraft state perturbations as well as to control displacements, whilst the phase lag between cyclic and flapping can (again crudely) be considered as an indication of the cross couplings present in the rotor. A phase lag of 90° - the articulated rotor - indicates a low cross-coupling (although this is not in fact really true as will be discussed later) and a phase lag of 0° can be considered as extremely cross-coupled.

It would be desirable to have the freedom to use a far greater range of rotor characteristics than at present if, by so doing, sensible improvements could be achieved : - for example, if better use could be made of available materials, if increased performance or improved structural features were forthcoming or if the helicopter could be made more cheaply.

However before extending the useable area of the S-n plane (fig.2) it is necessary to resolve any problems which may be introduced. One area of difficulty which is most certainly associated with rotors of higher stiffness numbers is the increased rotor sensitivity and cross-coupling and its effect on helicopter stability and control, which must be overcome if stiff rotors are ever to become realistic. Even the low stiffness numbers typical of today's hingeless rotors have resulted in considerable problems in this area.

3. CONTROL ANGLE REQUIREMENTS

The allowable centre-of-mass range of single rotor helicopters is small and is spread equally about the shaft ($\leq \pm 0,025R$) in order to minimise the magnitude of the rotor moments (ie. disc tilt) required for aircraft trim. A low level of disc tilt relative to the shaft implies a consequent low level of rotor blade root loads in both the flapwise and the lagwise (due to coriolis forces on flapping blades) senses and rotor hub and shaft loads.

The requirement for low levels of disc tilt throughout the flight envelope however entails the use of considerable cyclic pitch control as is illustrated in Figure 3 for level flight. The full line indicates the cyclic control required throughout the speed range for zero flapping of the rotor disc.Cyclic pitch displacement is seen to be pronounced at the higher flight speeds.

Obviously helicopter fuselage and tailplane aerodynamic characteristics and aircraft centre-of-mass position necessitate some disc tilt relative to the shaft (ie.a moment) for trim purposes,and there is also a requirement for control displacements for manoeuvre,and some allowance for coping with emergencies such as some failure in any A.S.E. equipment. The final cyclic pitch requirements for a helicopter tend therefore to appear as indicated by the fuzzy outline.

The corresponding movement of the pilot's cyclic pitch control stick must be fitted into a box of about 30cm square,however,for reasons mainly of pilot arm movement.This defines to a large extent the control sensitivity to the pilot - in degrees cyclic pitch per cm. stick displacement - which is hardly less than about 0,6 degrees / cm in the fore-and-aft sense, regardless of the rotor stiffness.

Though at the higher flight speeds ($\mu > 0,1$) the locus of trim cyclic requirements is predominately in one direction this is definitely not the case at the low speeds around hover.

In the hover to pitch the nose of the aircraft down practically purely θ_{1S} cyclic is required but,as soon as any pitch rate is achieved, some θ_{1C} is required to compensate for the longitudinal / lateral cross coupling brought about by assymetric aerodynamic and gyroscopic forces acting on the blades.Increase of forward speed then imposes further assymetries of airflow which require different θ_{1C} cyclic for compensation. Thus one sees that the control requirements change in a most complex manner during manoeuvres in flight.

The shape of the control requirements shown in the figure may be further distorted by the fact that different stick gearing will probably be arranged in the two cyclic senses.

At this point one possible advanced control system may be introduced. Suppose that the pilot's cyclic control stick acts through a control system which "demands" a tilt of the rotor disc relative to the shaft and proportional to stick displacement.In such a system all the "zero-flapping" points in figure 3 would be concentrated at one point - neutral stick position - and the tear drop shape for control requirements would be transformed into something approaching a circle which could be tailored much more easily to fit cockpit design and control sensitivity requirements.A disc tilt demand system of this type would of course ensure decoupling of the pilot lateral and longitudinal controls which would undoubtedly improve helicopter handling characteristics.

At the bottom of figure 3 is shown the collective pitch variation with forward speed.Even though the thrust throughout the speed range remains essentially constant the collective pitch varies considerably and perhaps one should also ask for a demand system here - ie. pilots control demanding rotor thrust rather than collective pitch.

4. CONTROL CROSS - COUPLING

The helicopter's control problems are compounded by the fact that its controls are cross-coupled to a greater or lesser extent and that the magnitude of the couplings vary with flight condition.

In particular the collective and θ_{1S} cyclic controls are very considerably coupled on modern hingeless rotor helicopters as is shown in fig.4. In the hover ($\mu = 0$) of course they are uncoupled - collective pitch defining rotor thrust and hence vertical acceleration and cyclic pitch defining disc tilt and hence pitch angular acceleration.The coupling becomes very severe at high speeds due to aerodynamic assymetry between the advancing and retreating sides of the rotor disc.In view of the basic unstable characteristics of the helicopter in the pitch sense (to be discussed later) this state of affairs is most undesirable,and hence it is fairly common practice to introduce some compensation between cyclic and collective controls in the mechanical linkage system in order to reduce as much as possible the cross-coupling immediately following control application.

A typical interlinkage is shown in figure 5.

At high speeds (say 60-70% cyclic stick,60-70% collective) the interlinkage is designed to remove the pitch coupling due to collective pitch illustrated in Fig.4.However,in the hover (say 30-40% cyclic stick, 60-70% collective) there is still considerable interlinking although ideally (see Fig.4) we require none,and thus this interlinkage has further compromised the already awkward low speed handling characteristics.Mechanical control linkages do not allow such an interlinkage to be optimised throughout the flight envelope.There is obviously an opening here for electrical signalling techniques which would allow much more flexibility in interlinking scheduling with flight condition,and indeed this is actively being pursued in the electrical signalling work under way at the moment. In fact perfect interlinking would imply that,throughout the flight envelope the initial effect of "collective" and "cyclic" control displacements would be to demand only vertical acceleration (ie.rotor thrust) and pitch acceleration (ie.disc tilt) respectively.Once again the idea of a "demand" control system suggests itself,at least in so far as initial control cross-coupling is reduced to zero or minimised.

5. PILOT WORKLOAD

The topic of handling characteristics and associated pilot workloads is very large and complex and will not be discussed here save for one example which,it is hoped,will give an indication of the workload to which pilots are subjected.

A typical manoeuvre is a rapid deceleration from forward speed to the hover whilst maintaining constant height.Time histories of several aircraft state and control parameters are shown in Fig.6 for such a case.

Note the high fuselage attitudes attained,leading to reduced visibility of the ground coinciding with maximum activity in terms of pitch rate and acceleration.

Inspection of the collective pitch time history shows a very considerable variation especially when the aircraft attitude is approaching its maximum even though the rotor thrust level has changed very little throughout the manoeuvre.The same applies,though to a lesser extent perhaps,to the θ_{1S} cyclic and the longitudinal flapping or disc tilt.

Thus it is obvious that the pilot's workload is at its greatest when the aircraft pitch is large and changing rapidly and his field of vision is curtailed.Returning to Fig.4 it can be seen that if constant height is to be maintained - especially a low height as may well be required in many military situations - then control must be very precise as any error could quickly place the aircraft in a dangerous situation.

Again in this example it would appear that a "demand" control system of the type discussed previously,where the pilots "collective stick" is linked to rotor thrust rather than blade collective pitch and his "cyclic" stick to disc tilt rather than cyclic pitch,would considerably reduce pilot workload and thus improve manoeuvrability.

6. LONGITUDINAL STABILITY CHARACTERISTICS OF PRESENT DAY HELICOPTER.

The reasons for the small allowable centre-of-mass range of single rotor helicopter have already been discussed in section 3.In the fully loaded state most helicopers tend,to have their centre-of-mass behind the rotor shaft to some extent and it is this case,which provides the greatest stability problems,which is considered here.

The helicopter rotor has a pronounced unstable m_w derivative in forward flight because a perturbation in aircraft attitude in the nose-up sense gives rise to :

1) a tilting-back of the rotor disc relative to the shaft and hence a nose-up moment composed of two components :
   a) the stiffness component of magnitude dependant on the stiffness number
   b) the thrust vector tilt component of magnitude proportional to rotor thrust.
2) an increase in rotor thrust giving a nose-up moment for an aft centre-of-mass.

Obviously,as in fixed-wing aircraft,a tailplane with its stable m_w effect can counteract the rotor to some extent,but for many reasons helicopter tailplanes cannot usually be made large enough to provide stability.

The longitudinal unstable root shown in Fig.7 for an aft centre-of-mass position and various blade flapping frequency ratios spanning the usual range illustrates the very considerable instability of helicopter especially at high speeds.

The introduction of hingeless rotors on high speed helicopters is seen to have exacerbated the stability problem at least in the controls-fixed (open loop) case.Of course the hingeless rotor has considerably more control power available and the overall stability characteristics with pilots control reaction included (closed loop) may well be superior to an articulated rotor helicopter.

A movement of the aircraft centre-of-mass forwards does improve the stability situation but the basic helicopter is still in most circumstances an unstable machine and hence automatic stabilisation devices of various levels of sophistication tend nowadays to be standard equipment on all but the smallest aircraft.

7. DEMAND CONTROL SYSTEMS

The preceeding brief survey of helicopter stability control and handling has,it is hoped,illustrated the considerable problems that exist and how they play a not inconsiderable part in limiting the rotor characteristic to the two low stiffness number areas shown indicated in figure 2.

At the same time the concept of "demand" control systems has been introduced as being perhaps a suitable means of providing better control and handling characteristics.By "demand" systems is meant here the pilots' controls demanding particular rotor thrust levels and rotor disc tilts relative to the shaft which are then held invariant whatever the aircraft state unless the pilot demands otherwise.This implies removing direct linkages between the pilots' controls and the blade angles and having some type of feedback control mechanism and sensor system between the pilot and rotor.Such a "black box" would identify the state of the rotor - e.g.thrust, disc attitude - and continuously adjust blade pitch angles (both collective and cyclic) so that the demanded thrust and disc attitudes were maintained. Such a system would of course exclude any cross couplings and in short would endow fixed-wing aircraft handling characteristics to the helicopter.

Such a system may appear very difficult to achieve in practice and extreme care would have to be taken not to react unfavourably with rotor dynamic conditions such as blade flutter,air or ground resonance.

However, before such systems are dismissed as too complicated, or only achievable by the utmost in adaptive, optimal or modal-following techniques let us remember that there is one rotor system which does provide a disc-attitude demand system with purely mechanical control techniques. This is the Lockheed Company's so called gyro-controlled rotor which makes use of "natural" forces acting on a rotor system to produce an uncoupled disc attitude demand system - with inherent pitch and roll rate damping. Undoubtedly this system had its (very severe) problems and nowadays we can pinpoint some unfortunate design faults which led to extraneous signals entering the feedback loop in considerable magnitude but, nevertheless, this system does perhaps provide a suitable point for electronic or other control methods.

Besides improving helicopter control and handling demand control systems would naturally improve stability characteristics quite considerably. The longitudinal stability characteristics for an ideal disc tilt demand rotor system of the Lockheed type is shown in Fig.8. where K signifies the gain in the blade flapping / feathering feedback loop. A considerable improvement in stability compared with a conventional rotor system (Fig.7) is immediately seen, as is the fact that the magnitude of the feedback gain is not of great significance. A most important aspect of such a control system however, is that, as it results in uncoupled behaviour, any stiffness rotor could now be used and, in fact, an increase in stiffness (acting approximately as a decrease in gain K) could even improve stability characteristics to some degree.

If very stiff rotors were used, they would most probably be designed to be capable of sustaining a fairly considerable hub moment in which case it could well be possible to position the whole of the aircraft centre-of-mass range in front of the rotor shaft. This would then allow the contribution of rotor thrust to the derivative m_w to be stabilising and would further improve the stability characteristics - perhaps becoming inherently stable without the use of other automatic stabilisation equipment.

8. STIFF ROTORS

It was implied in the introductory chapter that the use of very stiff rotors would considerably extend the helicopter designer's freedom. Leaving aside stability and control problems for the moment let us look briefly at the sort of helicopter configuration changes that could follow the adoption of very stiff rotors.

Fig.9 illustrates the thrust capability of a rotor (trimmed to zero hub moments) as defined by the retreating and advancing blade aerodynamic limits (in the latter case it has been assumed the retreating blade is not aerodynamically limited). Notice that rotor tip-speed affects very much the advancing blade limited thrust levels whereas the retreating blade limits are essentially unaltered. It can be seen that the thrust capability of a conventional helicopter rotor is determined by the stalling of the retreating blade (at least up to some maximum forward speed) which is reached long before the advancing blade comes up against its aerodynamic limitations - which of course means the loss of considerable potential additional thrust. Furthermore the maximum thrust levels attainable from a rotor decrease as forward speed increases - which leads to the rotor being defined essentially from high speed consideration and having surplus capacity at low speed. It is this inherent rotor thrust characteristic that has led to the use of ever increasing tip-speeds - nowadays rarely below 215 m/s (700 ft/sec) - and has spurred the search for better aerofoil sections as a means of improving rotor performance.

However if blades were made very stiff and strong so that they were capable of carrying a large flapping moment without too much deflection then it would be possible, by accepting a large rolling moment on the rotor, to utilize the lifting potential of both advancing and retreating blades to the maximum.The use of such rotors in contra-rotating pairs (eg.coaxial) would allow advantage to be taken of the increased rotor thrust capability whilst cancelling the undesired rolling moments.Such a rotor pair may be termed a "maximum-thrust rotor" system,also dubbed the "advancing-blade concept" (ABC) rotor by the Sikorsky Company.The appropriate thrust limit for a 152 m/s (500 ft/sec) tip-speed maximum-thrust rotor is also shown in the upper diagram of Figure 9 whilst the corresponding rolling moment on each individual rotor is shown below.

A considerable improvement in rotor thrust capability is evident, and a comparison between conventional and maximum-thrust rotors for a helicopter in the Lynx class is shown in Figure 10.The higher load factor possible with the maximum-thrust rotor at the higher speeds means a quite considerable increase in manoeuvrablility and agility at these speeds compared to the conventional rotor.In fact,unlike the conventional rotor,the variation of load factor with forward speed for the maximum-thrust rotor corresponds quite closely to the power-limited thrust variation and hence it may be suggested that the maximum-thrust rotor system would provide a more balanced helicopter design.

For the case considered here it is interesting to note that the coaxial rotor system power and torque requirements in the hover flight condition are only some 15-20% higher than for the conventional rotor but, of course,this penalty is considerably reduced as the tail rotor for torque compensation and yaw control would not be necessary.

Noise calculations for the two rotors indicate a level some 3-5dBA lower for the maximum thrust rotor system in the hover even through no attempt at optimisàtion was made in this respect.Reduction could well be more if this was a design aim.

We know however that very stiff rotors of the type necessary for a maximum-thrust rotor configuration are very cross coupled.To some extent the pairing of such rotors in a co-axial arrangement removes much of this cross coupling and it is interesting to consider the longitudinal stability of a helicopter equiped with coaxial stiff rotors.Figure 11 shows the unstable behaviour at a tip speed ratio of $\mu=0{,}4$ for an aircraft with neutral centre-of-mass position (i.e.on the shaft axis).Note that maximum instability occurs at those stiffness numbers associated with propellers which are also comparable to the Sikorsky ABC rotor.If very high stiffnesses were possible then the aircraft may become essentially stable.But,as mentioned before,very stiff rotors are capable of carrying considerable moments and thus it may well be possible (as indeed Sikorsky have suggested) to have the whole aircraft centre-of-mass range in front of the rotor shaft thus increasing aircraft stability beyond that shown in Fig.11.

The cross coupling characteristics of maximum-thrust rotors are unfortunately by no means completely eliminated,especially in the control sense,and it is likely that a quite sophisticated control system will be required.In view of the large moments existing on this type of rotor system it would seem appropriate to control rotor moments directly rather than through the medium of blade pitch control.In fact the disc tilt demand system (which is in other words a rotor moment demand system) suggested previous -ly would seem to be appropriate - perhaps with some automatic scheduling of individual rotor rolling moment with flight state in the manner shown in figure 10.

9. CONCLUDING REMARKS

To borrow a phrase which is topical in fixed-wing aircraft circles, the helicopter is a control-configured vehicle in that its rotor provides all the lift,propulsion and control functions.However,the inherent characteristics of the conventional rotor and control system lead to a number of performance,stability,control and handling problems and it is hoped that this paper has managed to illustrate these aspects and the way in which they play a part in defining helicopter rotor parameters.

The idea of "demand" control systems - in which pilots' controls demand rotor thrust and disc attitude rather than being directly linked to blade pitch - has been introduced as a possible solution to some of the rotor problems and thereby being of benefit to the conventional helicopter.

Further it has been suggested that demand control systems release the constraints on rotor stiffness which could lead to much greater freedom in helicopter design, such as the use of coaxial stiff rotors to provide a 'maximum thrust rotor' which could lead to a more balanced aircraft with improvements in performance; size and noise.

In short it appears that the helicopter can gain greatly from the introduction of advanced control systems.

ACKNOWLEDGEMENTS

This paper is presented with the permission of Westland Helicopters Ltd. but the views expressed are entirely personal and do not reflect official policies.

NOTATION

- a   blade lift-curve slope,
- c   blade chord,
- C   centrifugal force on a blade,
- C_m rotor moment $\div \rho \Omega R^2 \pi R^2 s R$
- C_t rotor thrust $\div \frac{1}{2}\rho \Omega R^2 \pi R^2$
- e   flapping hinge offset,
- I   blade flapping inertia,
- K   flapping/feathering feedback gain,
- m_w pitch static stability derivative,
- M   hub moment,
- n   blade flap inertia no. $= \rho c a R^4/8I$
- R   rotor radius,
- s   rotor solidity = blade area $\div \pi R^2$
- S   blade stiffness no. $= (\lambda^2-1)/n$
- T   rotor thrust,
- X_{cg} position of aircraft centre-of-mass relative to rotor shaft : R (+ve forwards)
- β $=\beta_0+\beta_{1s}\sin\psi+\beta_{1c}\cos\psi$, blade flapping angle (+ve upwards)
- λ blade natural flap frequency ratio, nondimensionalised by Ω.
- μ tip-speed ratio = forward speed $\div$ tip-speed
- θ $=\theta_0+\theta_{1s}\sin\psi+\theta_{1c}\cos\psi$, blade pitch angle (+ve nose up)
- ψ azimuthal position of blade, zero at rear of disc.
- ρ air density,
- Ω rotor angular velocity.

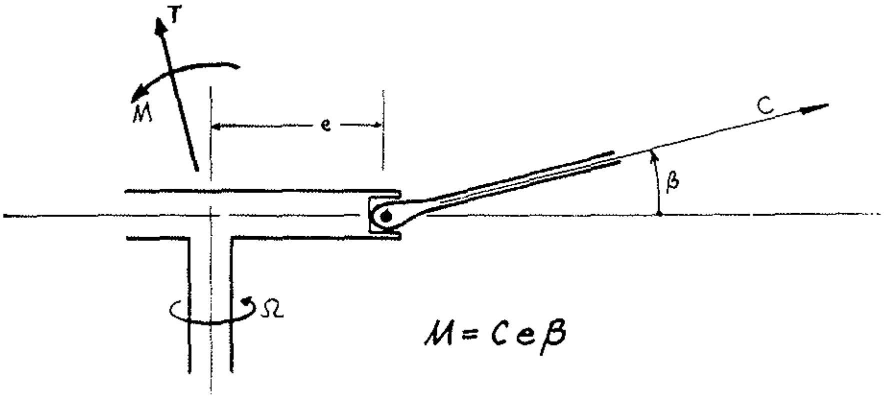

FIG.1 THE ARTICULATED ROTOR

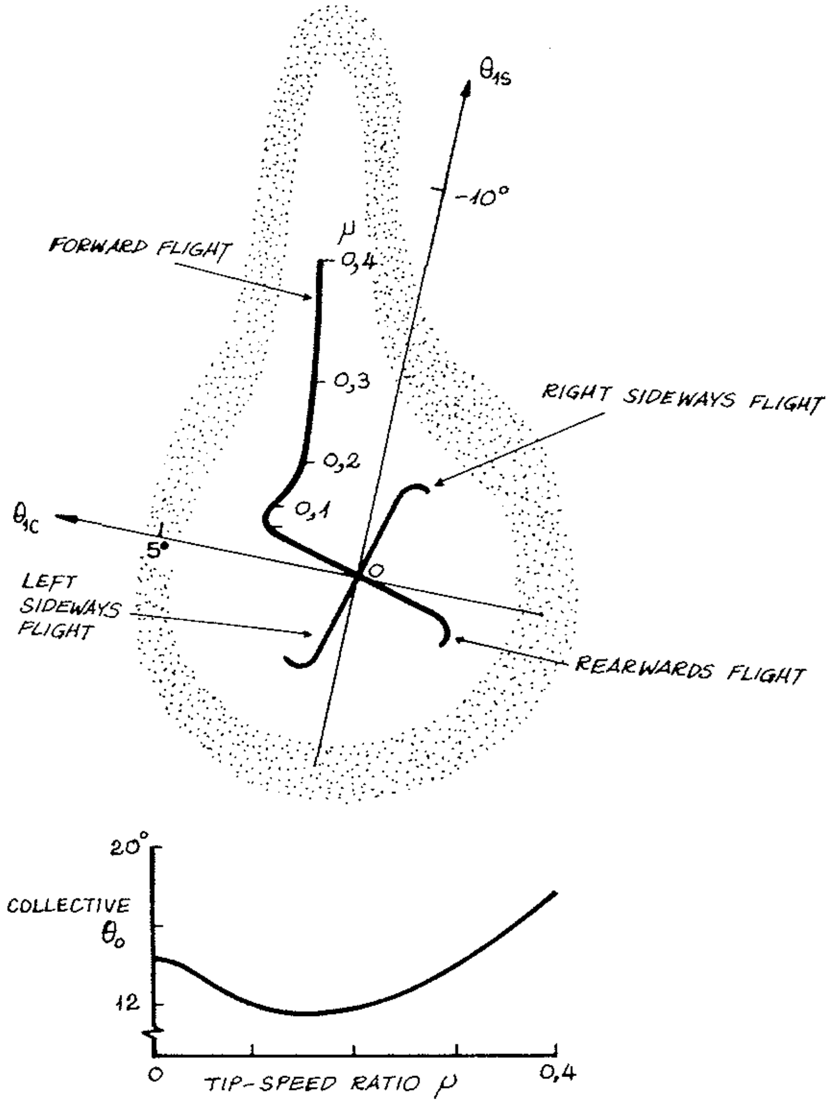

FIG. 3 ROTOR CONTROL REQUIREMENTS

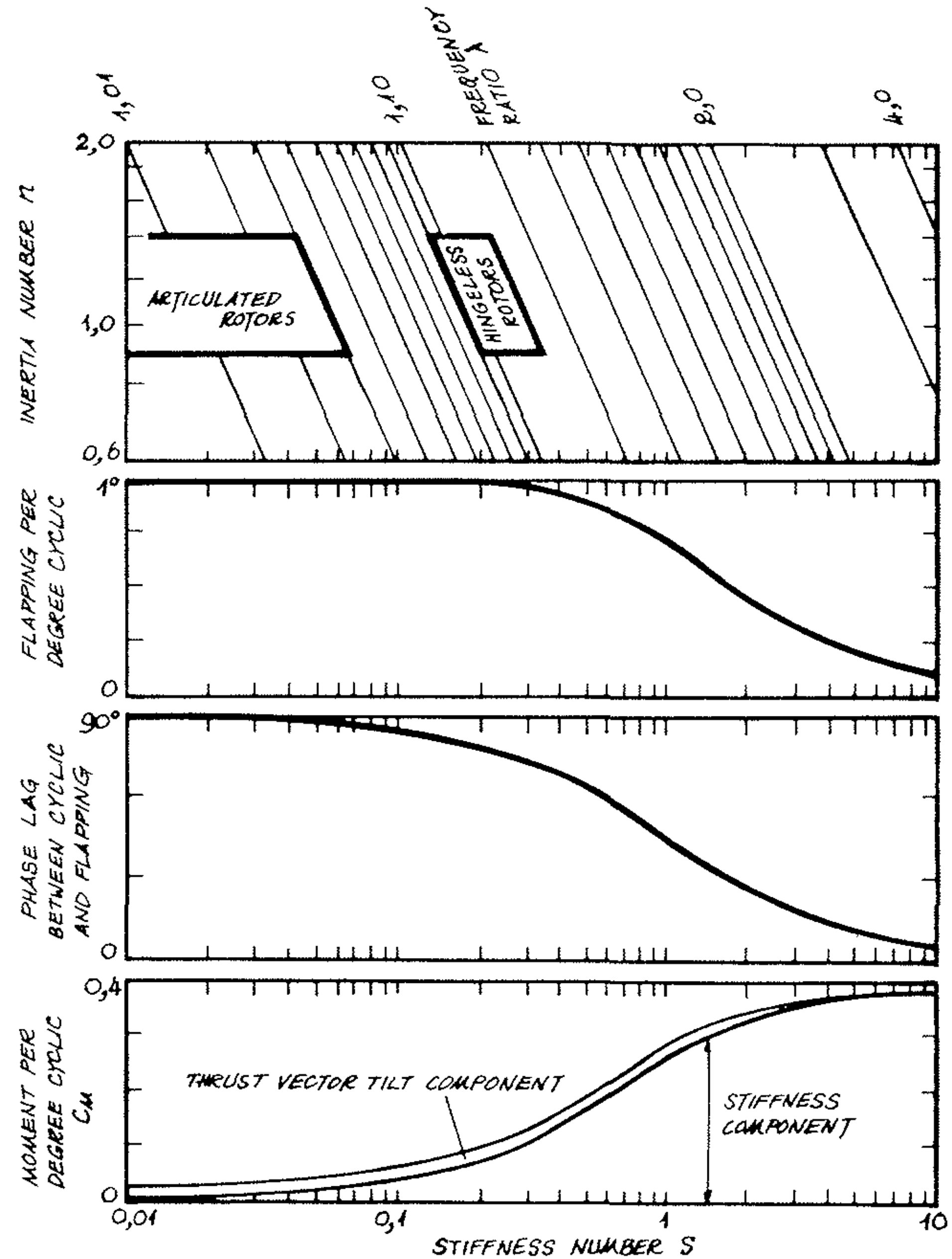

FIG. 2 HELICOPTER ROTOR CHARACTERISTICS

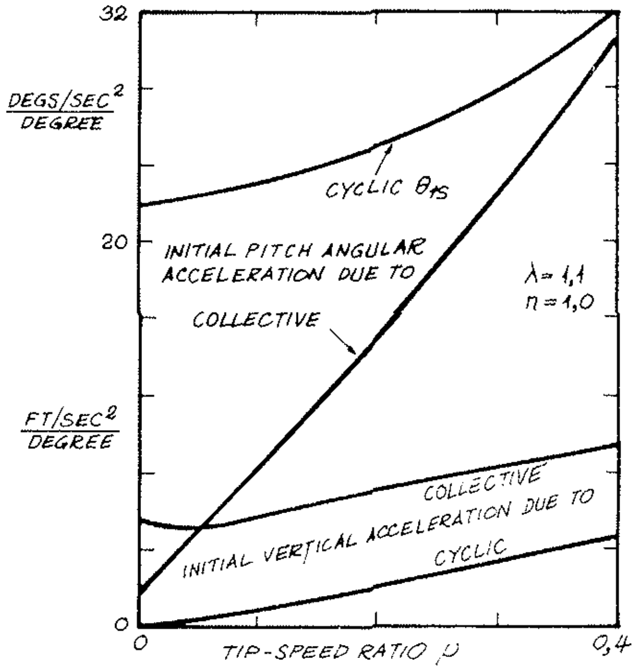

FIG. 4 ROTOR CONTROL COUPLING

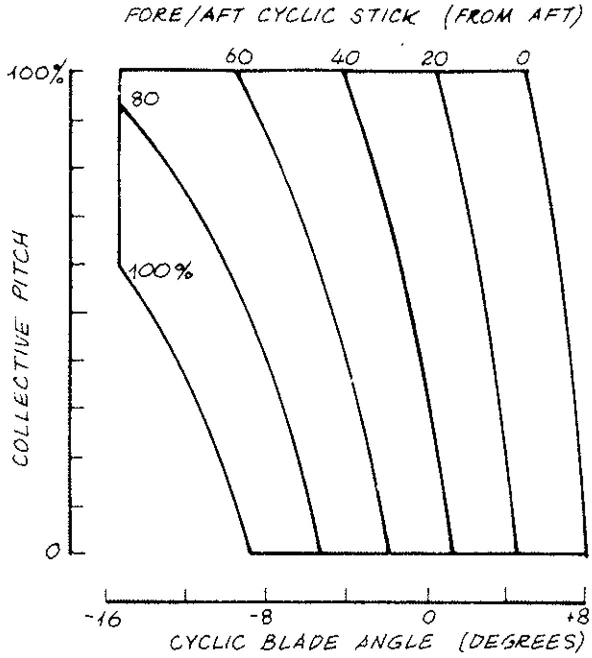

FIG. 5 TYPICAL COLLECTIVE/CYCLIC CONTROL INTERLINKAGE

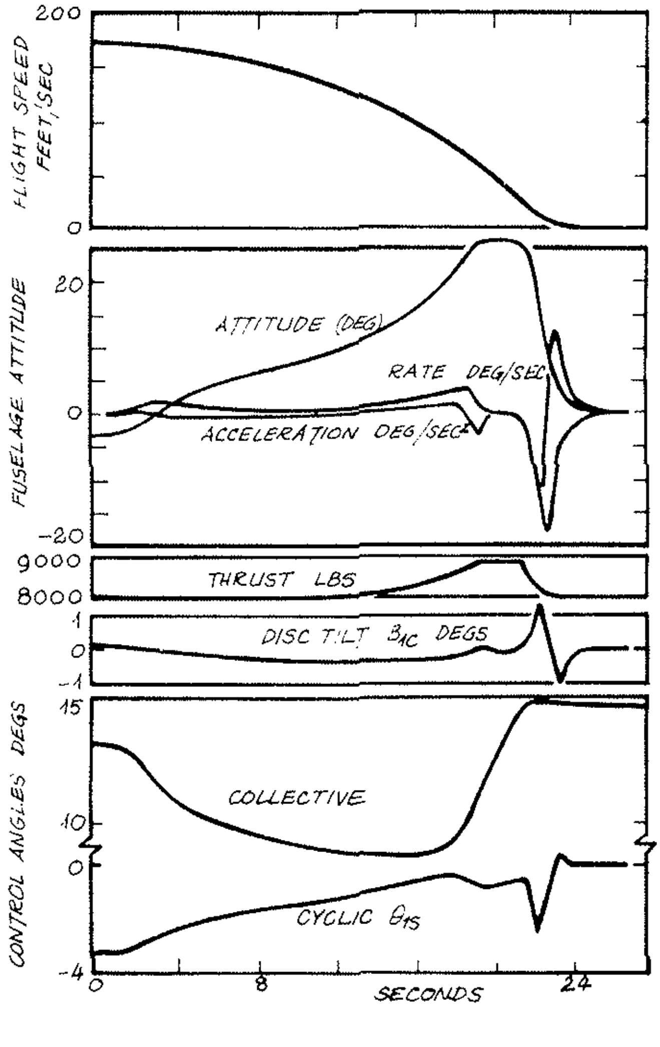

FIG. 6 A DECELERATION MANOEUVRE TIME HISTORY

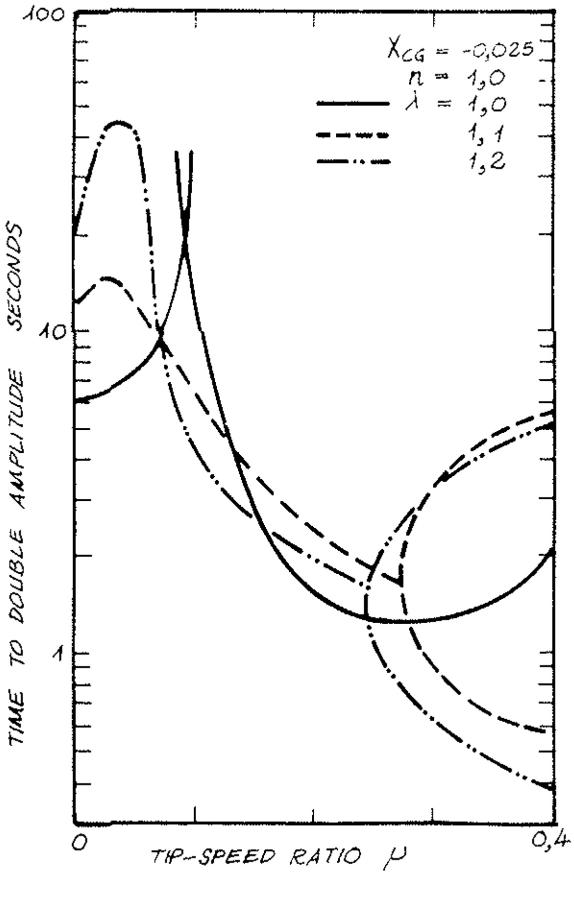

FIG. 7 HELICOPTER STABILITY

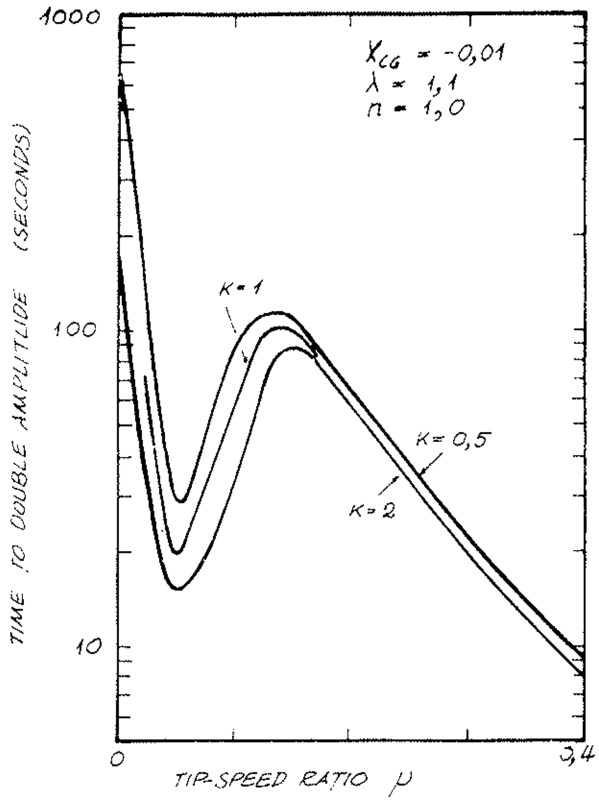

FIG. 8 STABILITY WITH A DISC-TILT DEMAND CONTROL SYSTEM

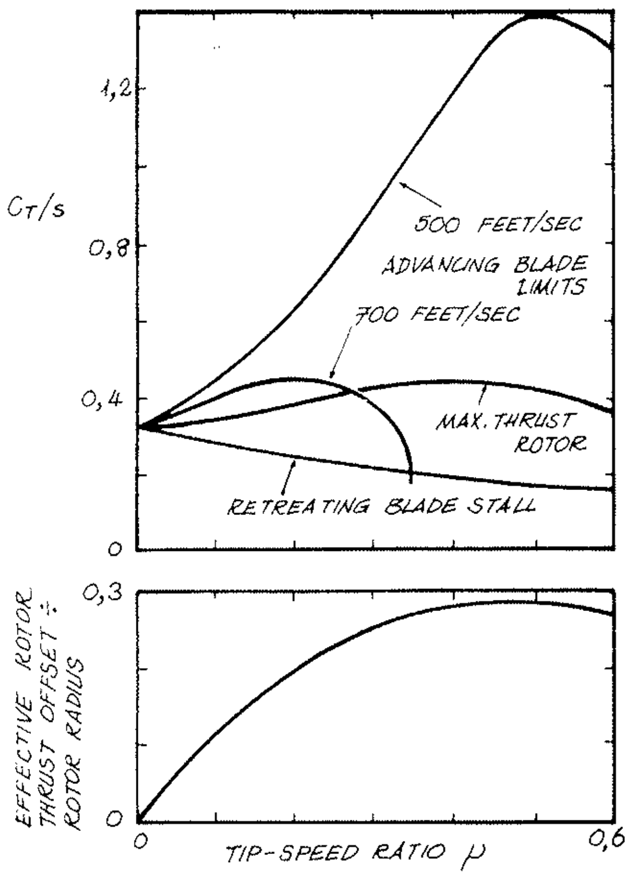

FIG. 9 ROTOR THRUST LIMITS

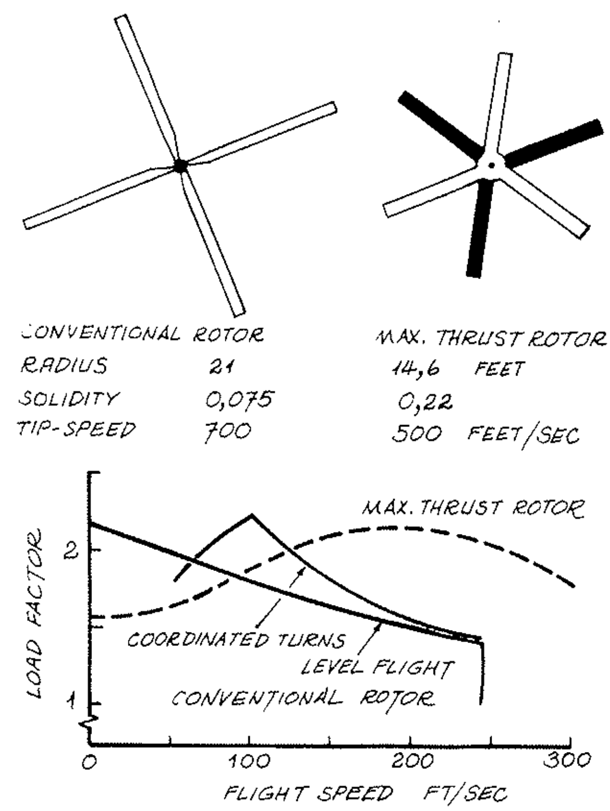

FIG. 10 COMPARISON OF CONVENTIONAL AND MAXIMUM-THRUST ROTORS

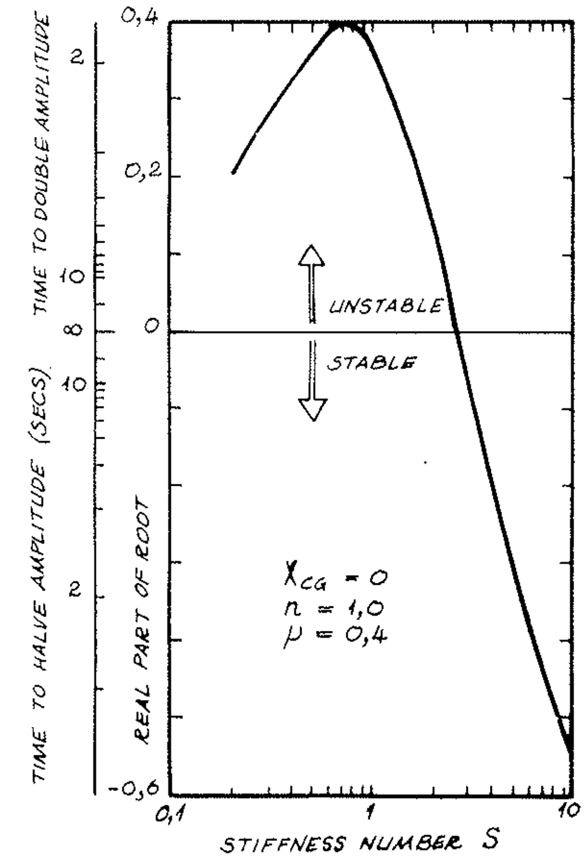

FIG. 11 EFFECT OF HIGH STIFFNESS ON HELICOPTER STABILITY