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2. CALCULATED BLADE RESPONSE AT HIGH TIP-SPEED RATIOS

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SUMMARY

This paper presents the initial results of a digital computer study of helicopter rotor-blade-motion stability for a broad range of forward speeds encompassing proposed conventional and compound helicopter designs. The analysis treats the general case of nonlinear, coupled flapping and lagging motions of hinged rigid blades. The results of the study to date indicate that blade-motion stability boundaries cannot be specified for a given blade design in terms of a fixed value of rotor tip-speed ratio. The stability boundaries can shift significantly within the desired operational speed range, with the stability limits depending upon the rotor loading, the magnitude of the disturbance encountered by the blade, and the blade position at the instant the external disturbance is encountered. The sample methods suggested for improving blade-motion stability include increasing the effective hinge spring restraint by incorporating pitch-flap coupling or by using hingeless or teetering rotor systems. Reducing rotor loading also has a beneficial effect on the blade-motion stability. The results indicate that methods used to deal with the blade-motion stability problem can be expected to diminish the overall vibration levels of the helicopter rotor system across the entire design speed range.

Author

INTRODUCTION

The rapid advances in helicopter technology in the past few years have considerably expanded the rotor operating envelope. With the introduction of the compound helicopter wherein the low-speed capability of a rotor is coupled with the high-speed performance of a fixed-wing aircraft, this envelope is being further expanded.

The expansion which results from compounding and the more recent interest in stopped rotors have intensified interest in all aspects of the rotor operating environment, including high tip Mach number operation, high tip-speed ratios, and the extreme operating conditions during maneuvers. The purpose of this paper is to discuss some aspects of the blade-motion stability and response characteristics associated with high tip-speed ratio operation as determined from a numerical treatment of the nonlinear, coupled equations of motion of a hinged rotor with flapping and lagging degrees of freedom.

SYMBOLS

R	rotor radius, feet
V	forward velocity, feet per second
$\Delta\alpha$	angle-of-attack increment, degrees
β	blade flapping angle with respect to shaft at particular azimuth position, degrees
δ_3	flap-hinge cant angle, degrees
ζ	blade lead or lag angle at particular azimuth position, degrees
ψ	blade azimuth angle measured from downwind position in direction of rotation, degrees
Ω	rotor angular velocity, radians per second

Subscript:

o	initial

RESULTS AND DISCUSSION

The basic hub geometry of the rotor and the primary angles of interest are illustrated in figure 1. The hub is fully articulated with both flapping and lagging degrees of freedom. The diagram on the left-hand side of the figure simply illustrates the sign convention used to define the azimuth position of the blade.

Variables in the computer program include the blade planform, the blade mass factor, and the offset distance of each hinge point - that is, the distance from the center line of rotation to the respective hinge. The flap-hinge cant angle δ_3 may also be varied, as shown in figure 1. However, the discussion herein is limited to the case of zero δ_3.

Since this discussion is concerned solely with the motions of a blade about the two hinges illustrated in figure 1, it might be well to define the terminology used - in particular, the terms stable and unstable blade motion. As this is a digital computer study, large flapping or lag amplitudes as such are not limiting factors. In other words, the blade-motion amplitudes which may be excessive or intolerable for practical rotor operation are not necessarily unstable; however, in order to place some limit on the amplitudes, transient oscillatory amplitudes which exceed 90° are termed unstable.

Of course, the practical rotor operating limit occurs long before the unstable condition is reached. However, by looking at the extreme condition, it is believed that a better understanding may be gained of the more subtle effects which are present for the conditions at which rotors are currently being operated.

This study indicates that the stability boundaries, as such, are not very rigid in the sense that it is difficult to define a single boundary for the nonlinear system that is valid for all rotor operating conditions, as is illustrated in figure 2. This figure presents regions of stable and unstable blade motion as functions of the blade mass factor and tip-speed ratio for two different initial conditions. Since the mass-factor parameter is inversely proportional to the blade inertia, light blades are at the upper end of the scale and heavy blades are at the lower end. The two boundaries were established by setting an initial flap-angle displacement β_0 of approximately 11° and solving for the transient solution for the unloaded rotor condition. Thus, the stable, steady-state condition expected was one of zero blade flapping and only the forced lead-lag response.

The disturbance was initially introduced at an azimuth angle of 0° - that is, with the blade in the downwind position - and the right-hand boundary shown in figure 2 was developed. The motion is stable or convergent for conditions on the left of this boundary and unstable or divergent for conditions on the right. This boundary is the one generally presented in most studies which use only the nonlinear flapping degree of freedom.

From a study of the various terms in the equations of motion and the blade-motion time histories used to develop this boundary, it became apparent that the unstable moments were developed only in the forward quadrants of an unloaded rotor - primarily in the range of azimuth angles from 90° to 180°. This fact implies that at high tip-speed ratios, the unloaded rotor would be very sensitive to the azimuth position of the blade when it is initially disturbed. As illustrated by the significant shifting of the left-hand boundary shown in figure 2, the unloaded rotor was in fact very sensitive to azimuth position. This boundary was developed by introducing the same initial disturbance at 90° azimuth - that is, on the advancing side of the rotor disk.

The fact that the stability boundary shifts is not unexpected for nonlinear equations; however, the significant shifting which occurs for all but the extremely heavy blade is somewhat surprising. It is significant that there is so much shifting in the boundary for the range of blade mass factors representative of current design practice (i.e., the range from about 1 to 2), for this is the area in which the operating tip-speed ratios are expanding. For example, while pure helicopters operate at tip-speed ratios below 0.5, the experimental compound helicopters have already reached tip-speed ratios slightly in excess of 0.5 and the advanced compounds, such as the advanced aerial fire support system (AAFSS), will operate in the range from 0.5 to about 0.7. Of course, the stopped rotor must go through the entire range of tip-speed ratios.

As mentioned previously, the unstable moments for the unloaded rotor are developed only in the forward quadrants of the rotor disk. Although it is difficult to separate aerodynamic spring and damping forces in a nonlinear analysis, the term which causes the unstable blade motion is what may be considered as the aerodynamic spring term in the equation of flapping motion.

The actual velocity component involved in producing the aerodynamic spring force is illustrated in figure 3. This diagram shows the relative position of the radial component of the forward velocity for a blade in the forward position ($\psi = 180^\circ$) and the rearward position ($\psi = 0^\circ$). It is apparent that the component of this velocity normal to the blade will produce unstable spring forces in the forward quadrants and will produce stabilizing or positive spring forces in the rearward quadrants.

The two stability boundaries shown in figure 2 illustrate the significance of the aerodynamic spring term in the equation of flapping motion. For example, a relatively light blade which is disturbed at an azimuth angle of 0° has both a positive aerodynamic spring force and a positive centrifugal spring force. Thus, the flapping amplitude is reduced considerably by the time the blade reaches an azimuth angle of 90° and the effects of the destabilizing spring forces are minimized. On the other hand, the same blade released at 90° azimuth has a positive centrifugal spring force but encounters a negative or destabilizing aerodynamic spring force and thus becomes unstable at much lower tip-speed ratios.

The boundary for an extremely heavy blade shows very little effect of azimuth angle because of the very low effective damping which is characteristic of a heavy blade. No matter where the blade is disturbed, the motion does not damp out or expand enough in one rotor revolution to alter the boundary significantly.

In order to illustrate the type of response obtained in determining these boundaries and to show the influence of the lagging degree of freedom on the rotor response, blade transient time histories for two flight conditions are shown in figure 4. This figure presents the transient responses of both the flapping and the lagging motion as functions of rotor revolutions for a blade with a mass factor of 1.6. The dashed curves are for a stable condition at a tip-speed ratio of 1.25, which corresponds to a point just to the left of the 90° boundary shown in figure 2. The solid curves are for an unstable condition at a tip-speed ratio of 1.5, which corresponds to a point just to the right of the 90° boundary.

For both β/β_o and ζ/β_o, the time histories for the stable and unstable conditions are very similar during the first two revolutions. The flapping initially increases because of the destabilizing spring moment and then diminishes considerably during the second revolution. The blade initially swings forward or leads because of the Coriolis forces produced by the high flapping velocity. The predominant difference between the curves for stable and unstable conditions is the higher lag angle which exists for the higher tip-speed ratio during the second revolution. It is this large lag amplitude which causes a reduction in the blade flapwise inertia such that even the relatively small flapping displacement which exists at the end of the second revolution is enough to set off a completely divergent oscillation.

While stability boundaries, as such, may appear to be more of a future problem than one of immediate concern, it should be emphasized that the velocity component, which ultimately causes rotor instability, starts building up when the rotor leaves hovering flight. In fact, linearized equations of motion of a flapping blade can be used to show that the total spring constant can become negative in the forward quadrants at tip-speed ratios well below 1. Another point to consider is the effect of rotor loading on the stability boundary. In general, rotor loading produces a destabilizing moment around the whole azimuth and thus a lifting rotor would be expected to experience instabilities earlier than an unloaded rotor when subjected to a disturbance.

Figure 5 presents regions of stable and unstable blade motion as functions of blade mass factor and tip-speed ratio. The major boundary is simply a repeat of the boundary shown in figure 2. The short boundary indicates the point at which blade-motion instability was encountered when a rotor initially carrying a lifting load was subjected to a disturbance - in this case, a vertical gust. As expected, the lifting rotor became unstable sooner than the nonlifting rotor. Of course, it should be noted that the point at which a lifting rotor encounters unstable blade motion is a function of the initial rotor loading and, also, the magnitude of the disturbance.

There are several methods available for extending the stability boundaries. For example, increasing the effective hinge spring restraint by pitch-flap coupling or by the use of a hingeless or teetering rotor will increase the stability limit. Increased damping will also increase the limit. Of course, flapwise damping will be more effective than in-plane damping; however, an in-plane damper will tend to reduce the lag-angle excursions and thus keep the flapping inertia at its maximum value. Both of these methods, increased spring moment and increased damping, are a matter of detail design for the flight conditions anticipated, because of the root moments introduced by any type of hinge restraint. A third method of extending the boundaries is reduced rotor loading. Rotor unloading decreases the sizable destabilizing moment contributed by rotor thrust.

Practical rotor operating is not necessarily limited by so-called stability boundaries at extreme tip-speed ratios, as mentioned previously, but is more likely to be limited by excessive or intolerable blade-motion amplitudes or vibration problems at more conventional tip-speed ratios. As an example, figure 6 presents the flapwise response characteristics of a rotor which is initially carrying a lifting load and then is subjected to an angle-of-attack step input due to a vertical gust. The maximum peak-to-peak flap amplitude which occurred during the transient is plotted as a function of the angle-of-attack increment caused by the vertical gust.

These data indicate that, at a tip-speed ratio of 0.3, the rotor may be subjected to a sizable disturbance without encountering extreme transient amplitudes; however, at a tip-speed ratio of 0.5, relatively mild disturbances cause transient amplitudes equal in magnitude to the amplitude reached only for the severe disturbance at the lower tip-speed ratio. At a tip-speed ratio of 1.0, the response is such that even a very modest disturbance causes extreme transient amplitudes. The dashed portion of this curve was extrapolated merely to indicate that a disturbance of approximately 6° caused complete instability. This point at which instability occurred corresponds to the unstable boundary presented in figure 5 for a lifting rotor. It is apparent that the amplitudes which result from a disturbance at the higher tip-speed ratios place a more critical restriction on the acceptable rotor operating condition than does the concern for stability.

Since the stability boundaries shift so much when the disturbances are introduced at different azimuth angles, blade tracking during a transient gives rise to vibration problems associated with tip-path separation during maneuvers or as the result of gusts. Figure 7 shows a time history of tip-path separation for adjacent blades of a four-blade lifting rotor operating at a tip-speed ratio of 0.5 after a step input due to a vertical gust is imposed. The trace represents the difference between the paths of two blades, which are 90° apart. The large separation which initially occurs certainly indicates a source of vibratory input. Although the amplitude is rapidly damped, it is unlikely that the steady gust such as that used in this example will ever exist in practice. In effect, an actual rotor is in a continual transient in gusty air, and consequently the differences in the tip trace are not likely to damp out as rapidly. It is of interest to note that even at this tip-speed ratio of 0.5, there is evidence of a relative difference in the aerodynamic spring moment just past 90° azimuth, as indicated by the change in slope of the curves in each cycle.

Of course, any efforts to extend the stability boundaries by the methods previously discussed are likely to be accompanied by improvements in rotor characteristics at the more conventional tip-speed ratios in terms of vibratory problems. Vibrations associated with tip-path separation and the excessive flapping response, which limits even stable rotor operation, can be expected to decrease across the entire design speed range.

CONCLUDING REMARKS

Although some of the examples presented in this study are not realistic in terms of practical rotor operation, the limited experimental data available indicate that very real problems exist at high tip-speed ratios. These problems, which may be categorized as tip-path separation, blade-motion amplitude response, and blade-motion stability, are all related in some degree to the dissymmetry of the flow conditions around the azimuth as tip-speed ratio increases.

The significant shifting of the rotor stability limits pointed out herein is certainly discomforting, for this shifting makes it impossible to define a so-called stability boundary which must not be exceeded. This study indicates that the predominant destabilizing factor is the aerodynamic spring force in the flapwise direction and that introduction of the lagging degree of freedom has more of a secondary effect - that is, the lag amplitude tends to reduce the flapwise inertia and this reduction in turn makes the flapping motion more responsive to the driving forces.

The sample methods suggested for improving blade-motion stability include increasing the effective hinge spring moment by incorporating pitch-flap coupling or by using hingeless or teetering rotor systems. Reducing rotor loading also has a beneficial effect on the blade-motion stability. The results indicate that methods used to deal with the blade-motion stability problem can be expected to diminish the overall vibration levels of the helicopter rotor system across the entire design speed range.

BASIC HUB GEOMETRY

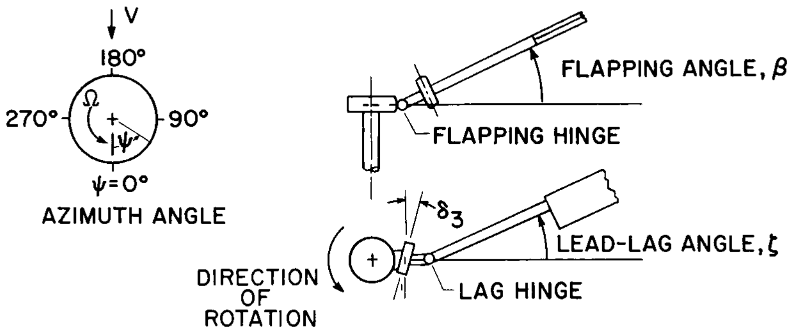

Figure 1

EFFECT OF AZIMUTH ANGLE ON BLADE-MOTION STABILITY BOUNDARY

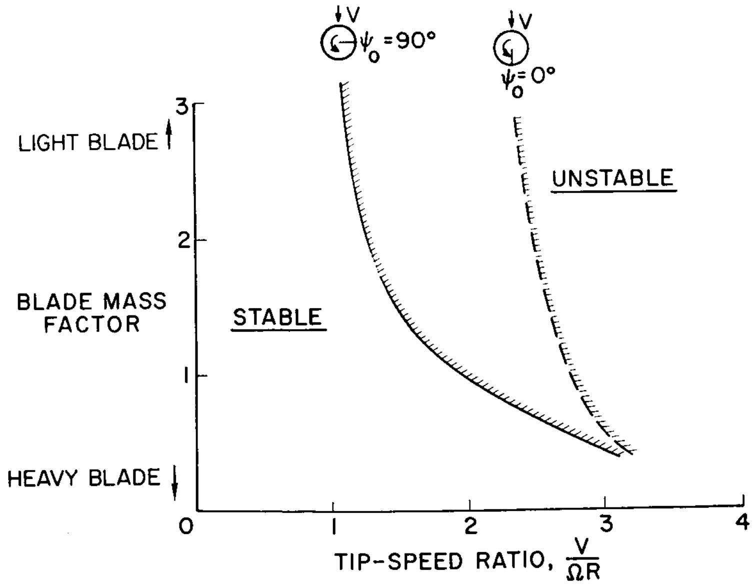

Figure 2

VELOCITY COMPONENT CONTRIBUTING TO AERODYNAMIC SPRING FORCE

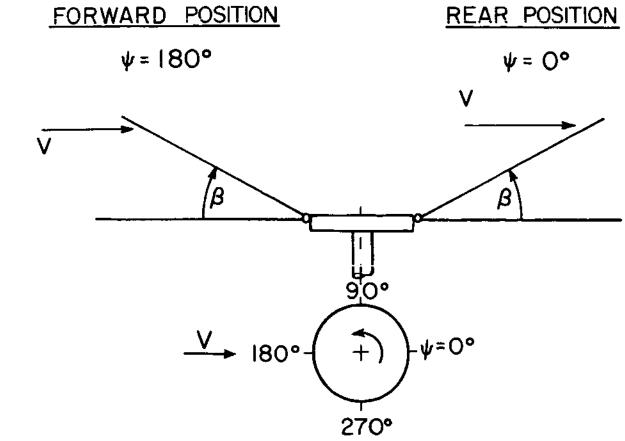

Figure 3

TRANSIENT RESPONSE FOR INITIAL DISPLACEMENT AT $\psi = 90°$

MASS FACTOR = 1.6; $\beta_0 \approx 11°$

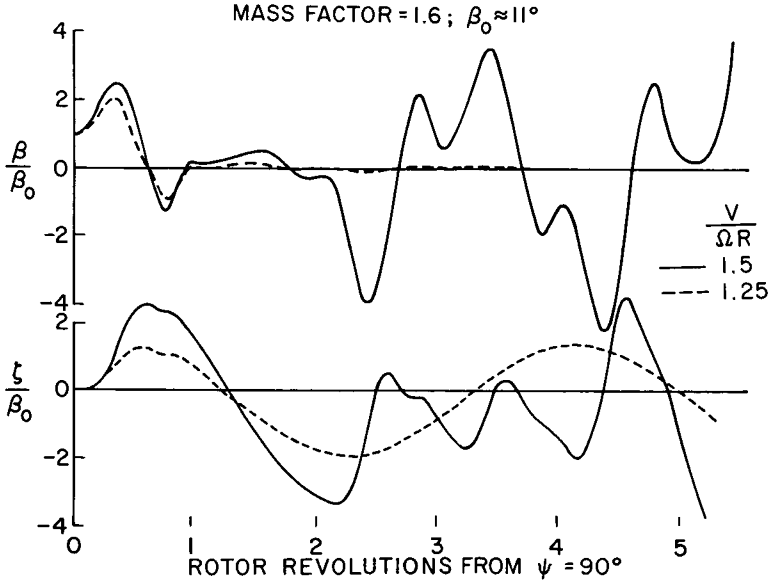

Figure 4

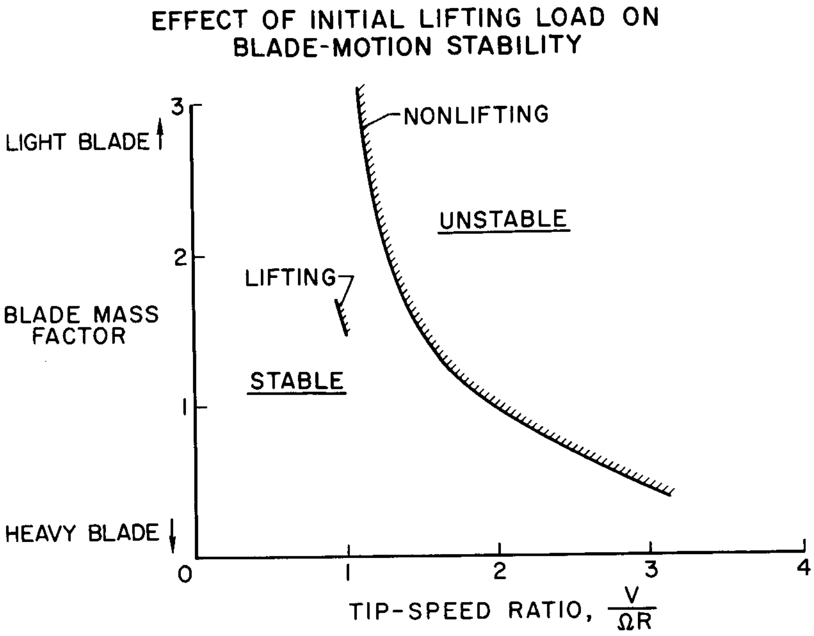

Figure 5

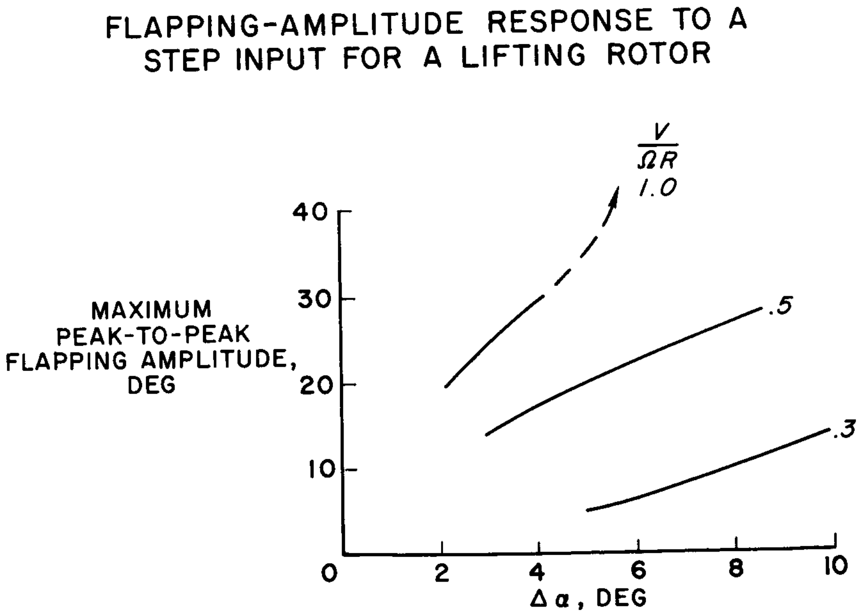

Figure 6

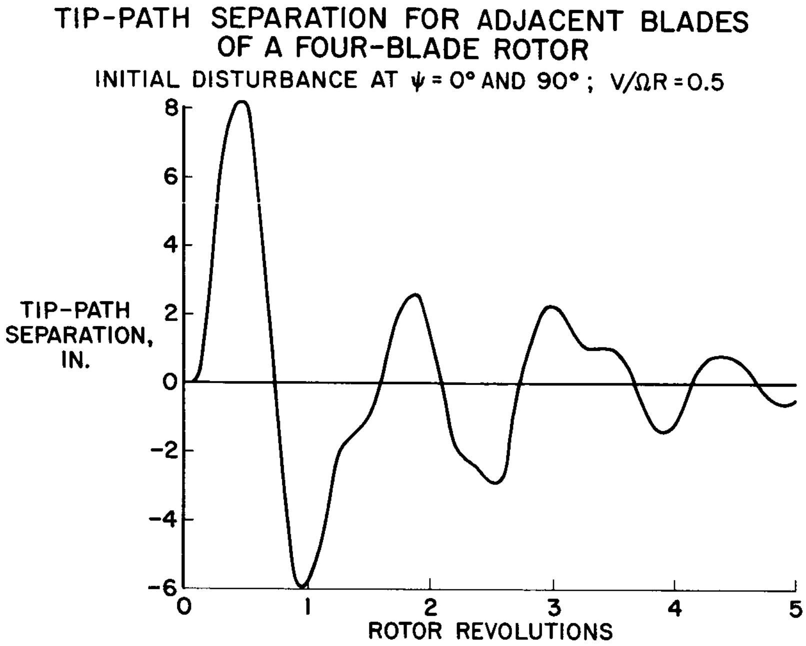
TIP-PATH SEPARATION FOR ADJACENT BLADES
OF A FOUR-BLADE ROTOR
INITIAL DISTURBANCE AT ψ = 0° AND 90°; V/ΩR = 0.5
TIP-PATH
SEPARATION,
IN.
8
6
4
2
0
-2
-4
-6
0
1
2
3
4
5
ROTOR REVOLUTIONS

Figure 7