OPEN AND CLOSED LOOP STABILITY OF HINGELESS ROTOR HELICOPTER AIR AND GROUND RESONANCE

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Abstract

The air and ground resonance instabilities of hingeless rotor helicopters are examined on a relatively broad parametric basis including the effects of blade tuning, virtual hinge locations, and blade hysteresis damping, as well as size and scale effects in the gross weight range from 5,000 to 48,000 pounds. A special case of a 72,000 pound helicopter air resonance instability is also included. An evolutionary approach to closed loop stabilization of both the air and ground resonance instabilities is considered by utilizing a conventional helicopter swashplate-blade cyclic pitch control system in conjunction with roll, roll rate, pitch and pitch rate sensing and control action. The study shows that nominal to moderate and readily achieved levels of blade internal hysteresis damping in conjunction with a variety of tuning and/or feedback conditions are highly effective in dealing with these instabilities. Tip weights and reductions in pre-coning angles are also shown to be effective means for improving the air resonance instability.

Notation

C_e	=	landing gear equivalent viscous damping coefficient, lb/ft/sec
C_s	=	pneumatic shock strut viscous damping coefficient, lb/ft/sec
C_t	=	tire viscous damping coefficient, lb/ft/sec
CG	=	helicopter center of gravity
I_x	=	moment of inertia about x axis, slug-ft^2
K_e	=	landing gear equivalent spring rate, lb/ft
K_s	=	non-linear, pneumatic shock strut spring rate, lb/ft
K_t	=	tire spring rate, lb/ft
M	=	mass of helicopter
M_1	=	control moment acting in lateral swashplate equation of motion, ft-lb
M_2	=	control moment acting in longitudinal swashplate equation of motion, ft-lb
N	=	number of blades
T/W	=	thrust to weight ratio
XYZ	=	inertial coordinate system
db	=	decibels
e_1	=	offset of virtual flapping hinge, ft
e_2	=	offset of virtual lead-lag hinge, ft
h	=	distance between center of mass of helicopter and coordinate system axis, ft
t	=	lateral and roll coupling parameter
x, y, z	=	helicopter longitudinal, lateral and vertical displacements, ft
α_1, α_2	=	helicopter pitch and roll angular displacements, rad
$\dot{\alpha}_1, \dot{\alpha}_2$	=	helicopter pitch and roll rate, rad/sec
β_K	=	flapping angular displacement of k^{th} blade, rad
γ_k	=	lead-lag angular displacement of k^{th} blade, rad
δ	=	logarithmic decrement
ζ_1	=	non-dimensionalized (by rotor radius) displacement of virtual flapping hinge from rotor center of rotation, ft/ft
η_j	=	generalized fuselage and rotor system degrees of freedom
θ_i	=	constrained swashplate-blade pitch degrees of freedom
$\lambda_{\alpha 2}$	=	percent of uncoupled critical roll damping
$\lambda_{\ell\ell}$	=	percent of uncoupled blade lead-lag damping
Ψ_k	=	azimuthal coordinate of the k^{th} blade, rad
ω_β	=	out-of-plane or flapping frequency ratio, cycles/revolution
$\omega_{\ell\ell}$	=	in-plane or lead-lag frequency ratio, cycles/revolution

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Introduction

In recent years an intensive research and development effort within government and industry has focused on hingeless rotor helicopters with a view towards mechanical simplification, improved flying qualities and greater aerodynamic cleanness. The approach being employed capitalizes on modern structural materials and technology which, in principle, permit the hingeless rotor blades to flap and lead-lag by flexing elastically, rather than by the use of mechanical hinges. In order to keep cyclic bending fatigue stress and blade weight within bounds, the in-plane or lead-lag hingeless blade fundamental natural frequency ratio, as a practical matter, inevitably falls within the range .6-.9 cycles per revolution, although frequency ratios as small as .5 or as great as 1.2 are possible. As a consequence of this .6-.9 range of frequency ratios, both ground and air resonance instabilities can still occur which stem from this frequency ratio being less than unity.

There arises the added concern that slight amounts of internal blade structural damping to be expected in hingeless rotor blades can cause such instabilities to be much more severe and difficult to control than in an articulated rotor case, where mechanical lead-lag dampers would be a standard design feature. On the other hand, the elastic flapping of hingeless rotor blades and the presence of large blade structural moments which are aeroelastically coupled to the fuselage oscillations both in hovering and on its landing gear, and the aforementioned relatively high frequency ratio of hingeless blade lead-lag oscillations compared to those of conventional articulated rotors (.2-.4 cycles per revolution), present the favorable possibility of significant alterations in the ground and air resonance stability characteristics. This is in contrast to centrally hinged, articulated rotors, where flapping motion would be expected to have negligible effect on such instabilities. Several recent investigations[1,2,3] have contributed to increased understanding of hingeless rotor helicopter ground and air resonance characteristics, but in each case were directed principally at design and development of a particular machine with its unique size, structural and operational characteristics, rather than at broad development of parametric trends and general principles, as well as the possibilities for enhancing system stability by application of modern control engineering techniques in conjunction with existing, conventional blade pitch control systems.

In this study, the effects of the various design and operating parameters which traditionally influence the ground and air resonance instabilities of articulated rotor helicopters have been considered, but with the addition of the unique hingeless rotor helicopter parameters such as blade internal damping and virtual hinge locations. The effect of scale on stability is investigated by considering aerodynamically similar designs which range in gross weight from 5,120 pounds to 48,000 pounds by keeping tip speed and mean rotor lift coefficient constant. Several other cases of general interest are also considered, such as off-loading, rpm reduction, increasing blade number, etc. In view of the enormous control power available with a hingeless rotor due to its structural characteristics and the possible need for or desirability of full artificial stabilization or stability augmentation of certain design configurations or operating conditions, a closed loop stabilization approach is also investigated. It is viewed as an evolutionary approach which would employ a conventional helicopter swashplate type of control system of blade collective and cyclic pitch. A variety of output variables and their derivatives are examined as possible sources of closed loop feedback information for control actuation. The roll and the roll rate variables are seen to be highly effective. The dynamics of cyclic and collective pitch change are also examined[4] as part of such a closed loop stabilization system for ground and air resonance where the control process is seen to be that of a multiple input-multiple output, interacting control system[5].

Detailed parametric studies of the ground and air resonance stability boundaries are carried out using a standard eigenvalue routine. The parameter combinations which can result in the instabilities are examined with a view towards comparing designs with inherent stability with those that are a result of artificial stabilization. Finally those combinations of design, operating and stability augmentation parameters yielding hingeless rotor type aircraft free of the ground and air resonance instabilities are obtained.

Analysis

The analysis is carried out with the objective of developing a broad understanding of the influence of the principal design and operating parameters on both the system air and ground resonance instabilities. Consequently the degrees of freedom chosen for the analytical model are those which can be expected to be common to all hingeless rotor helicopter designs in hovering and on the ground, irrespective of size and gross weight, operational requirements or specific structural design approaches.

The fuselage body degrees of freedom are taken as those which would represent both the hovering and ground oscillations of a single rotor helicopter either in the air or on a three point, conventional oleo-shock strut type of landing gear. These then follow as the lateral, longitudinal and vertical translational degrees of freedom and the angular roll and pitch degrees of freedom. A yawing degree of freedom is not included, since it is deemed an unnecessary and unproductive complication of marginal significance. This follows from the large yawing inertia of the body, the close proximity of the aircraft center of gravity to the two main landing gear and the rotor thrust line, the net effect of which is to virtually decouple the yawing freedom from the others, and thereby effectively eliminates its influence on the air and ground resonance instabilities.

The landing gear type and arrangement used in the analysis of ground resonance are viewed as typical, but by no means universal. However, the effective spring and viscous damping restraints which are arrived at in the landing gear analysis are sufficiently broad in character to be representative of the many different landing gear systems currently in use. The two most prevalent systems are the skid type, and pneumatic shock strut and tire type configurations. Since the skid-type landing gear represents a speccial case of the more general shock strut and tire formulation, an analytic model of the latter has been employed. This formulation has the added advantage of permitting various effects, such as the shock strut damping, the non-linear pneumatic spring rate and the combined spring rate of the tire and landing surface to be more easily studied and is developed in detail in Reference 6.

The hingeless rotor blades are flexible, cantilever structures which flap elastically in oscillations normal to the plane of rotation and lead-lag elastically in the plane of rotation. A generalized coordinate, normal mode type of analysis could be employed effectively for the structural dynamic aspects. However this does not lend itself well to a simple determination of the aerodynamic forces and moments which play a central role in the stabilization process because of the blade bending curvature during the oscillations. Consequently the concept of virtual springs and hinges[7,8] for the flapping and lead-lag oscillations of the blade is used, where quasi-rigid body blade motions are introduced to replace the continuous, elastic bending deformations of the real blades. These degrees of freedom are illustrated in Figure 1. An isometric view of the body degrees of freedom is also shown.

The blade pitch changes are treated as constrained degrees of freedom in the stability analysis. That is the blade pitch can be changed collectively or cyclically by displacement or tilting of a swashplate mechanism. In the open loop case this is done by the pilot displacing the collective or cyclic pitch control sticks. This results in a transient response of the aircraft either about its initial hovering state or on its landing gear by altering the aerodynamic forces and moments produced by the hingeless rotor. Since it takes the form of a reference input or external disturbance, it has no effect on the system stability as long as these disturbances are reasonably small. In the general closed loop case the aircraft roll position, roll rate, pitch position and pitch rate are sensed and used to drive a system of swashplate actuators with a view towards employing the enormous control power inherent in the cantilever blade design of hingeless rotor systems. This can yield full stabilization, if required, or it can augment the inherent stability of the system when design and operating conditions permit. The swashplate-blade pitch change arrangement and the system block diagram are shown schematically in Figure 2. More sophisticated closed loop control system arrangements offer the possibility of enhanced performance and optimization of the system at the expense of complexity or possible reduction in reliability. For example an inner control loop on rotor blade bending deflections by strain gage techniques, as well as sensing of body translational displacements and velocities offer interesting possibilities which are considered in Reference 9. Needless to say, departure of blade pitch from the settings called for by the control system complicates and may degrade the stability and controllability of the system. For example blade torsion which is not included in this study is an important factor considered in Reference 16.

The combination of the fuselage, landing gear (when applicable) and the rotor blade systems yields 5+3N freedoms in the closed loop case and 5+2N freedoms in the open loop case where the blade number N is at least four. The minimum number of four blades follows from the possibilities of a dynamic instability unique to two-blade systems[10] and resonant amplification of three blade aerodynamic loadings in the case of three blades[11] which must be avoided by using a minimum of four blades in a hingeless rotor system.

The number of blade freedoms is reduced by introduction of quasi-normal coordinates to describe the rotor motions[12,13]. This approach reduces the complexity of the analysis by eliminating all blade motions which do not couple with the body in a coherent manner during open and closed loop oscillations. These coordinates describe the various significant patterns of blade motion by five degrees of freedom in the open loop case. These are the rotor cone vertex angle, the lateral and longitudinal tilt of the rotor cone, and the lateral and longitudinal displacements of the blade system center of gravity with respect to the geometric center of the rotor (due to lead-lag motion in the rotating frame of reference). In the closed loop case three freedoms are added through the displacements of the swashplate for blade collective pitch changes and by the angular tilting of the swashplate for blade lateral and longitudinal cyclic pitch changes.

The analysis proceeds assuming that the rotor system has four blades. The single exception to this is the consideration of a very heavy helicopter (72,000 lbs.) air resonance behaviour. In this case a six blade design obtained by adding two blades to a four blade, 48,000 lb. design is examined. This leads to a final quasi-normal coordinate model which has ten degrees of freedom for the open loop case and thirteen for the closed loop case. These equations of motion are then reduced to a canonical form suitable for application of a standard digital computer routine for determining the complex eigenvalues and eigenvectors of the system. In effect twice the number of first order, linear differential equations with constant coefficients result. This is a twenty-sixth order system in the closed loop case, if ideal actuators are assumed. As more realistic models of the control hardware are employed (due to leakage across hydraulic seals, imperfect relays, amplifier frequency response characteristics, etc.) the order of the system would increase further. This is deemed to be a specialized design problem which needs attention on an *ad hoc* basis.

Discussion of Numerical Results

The discussion of the numerical results begins with the open loop stability or stability boundary characteristics of the hingeless rotor helicopter ground resonance problem and is then followed by an examination of the potential influence of closed loop, feedback control in system stability. This approach is then repeated for the air resonance problem. The discussion closes with an overview of the potential of closed loop control for both of these hingeless rotor helicopter instabilities.

Ground Resonance

In order to develop insight into the nature of the ground resonance instability as it might occur for a typical helicopter employing a hingeless rotor, a 12,000 pound reference case based on the S-58 helicopter[14] is considered first. The rotor is modelled as one with four hingeless blades with a flapping frequency ratio of 1.15 cycles per revolution, and a lead-lag frequency ratio of .70 cycles per revolution at a rotor tip speed of 650 ft/sec. The wheels are first assumed to be locked, preventing the aircraft from rolling freely in a longitudinal direction. The uncoupled lateral and longitudinal translation modes of the aircraft are assumed to have five percent and three percent of critical damping, respectively, as a result of tire hysteresis losses. As the thrust to weight ratio is varied from zero to unity the vertical loading on the landing gear decreases. The stability of the small, coupled oscillations about a series of initial steady states determined by the thrust to weight ratio (T/W) is then studied as a function of oleo-shock strut damping for several small, but typical values of blade hysteresis lead-lag damping. Both damping parameters are expressed in terms of percent of equivalent viscous critical damping.

The unstable mode of oscillation is found in all cases to be dominantly a fuselage rolling mode with a small amount of lateral translation coupling, and still lesser amounts of pitching and longitudinal motion. Release of the brakes, permitting the aircraft to move freely longitudinally, has a slightly stabilizing effect, but of minor importance compared to the influence of oleo-shock strut damping and blade internal damping. The numerical results of the study with brakes on are presented in Figure 3. Equivalent viscous damping of the uncoupled rolling mode expressed in percent of critical damping is taken as the abscissa, while thrust to weight ratio is the ordinate. The horizontal dash line at T/W = .9 is a visual reminder that this is an unrealistic condition and that the stability data beyond this value is probably unreliable, since the analytical modelling of the landing gear depends on the questionable assumption of an initial steady state for thrust to weight ratios greater than nine tenths. The aircraft is, of course, in the transient condition of landing or take-off.

It is seen that if blade hysteresis damping should be equivalent to one percent of critical lead-lag damping, then slight amounts of oleo-damping of the rolling mode produce stable oscillations. If the blade internal damping is as little as one quarter of a percent of critical, stability can still be achieved for all thrust to weight ratios, if roll damping is equivalent to fourteen percent of critical damping. Internal blade damping of one percent or greater is found to eliminate the instability entirely, if only slight amounts of landing gear damping are available, for example from tire hysteresis. Thus the ground resonance instability for the reference case is found to be quite mild and easily eliminated with the moderate amounts of blade and landing gear damping normally present.

In order to understand the influence of the tuning of a hingeless rotor on this desirable result, the lead-lag frequency ratio is varied about reference frequency ratio of .7 cycles per revolution as the flapping frequency ratio is held constant at 1.15 cycles per revolution. Blade damping is taken at one-half percent of critical while roll damping is held fixed at eight percent of critical. Figure 4 shows the effect of this tuning on the unstable mode by plotting the log decrement of this mode versus thrust to weight ratio. It is seen that increasing the lead-lag frequency ratio above .7 makes the system stable, while decreasing it below this reference value makes it progressively more unstable. Figure 5 considers the effect of the offset of the virtual flapping hinge and tuning of the flapping frequency ratio on the instability with respect to the reference case. It is seen that a flapping frequency ratio of 1.0 corresponding to a conventional, articulated rotor is considerably more unstable than the reference case. It is seen that increasing the offset and frequency ratio to progressively higher values is beneficial and stabilizing although tending to reach a point of diminishing returns at a flapping frequency ratio of 1.20 cycles per revolution.

Size and scale effects are investigated by considering the coupling of the lateral and rolling motion as the distance between the rotor hub and the center of gravity of the aircraft is varied with respect to the reference case, where it was assumed to be at a distance of seven feet. As this distance is decreased to five feet, the instability is observed to change in relationship to the thrust to weight ratio, but not in general character. On the other hand as the coupling increases by increasing the distance to nine feet, there is a stabilizing effect. This is illustrated in Figure 6. This result can be understood in terms of the coupled rolling natural frequency, which tends to decrease as this distance increases. Thus if the lead-lag natural frequency ratio is held fixed at .7, stability can be improved by detuning the fuselage coupled rolling mode to a lower frequency. This result is typical of all helicopter ground resonance instabilities.

The influence of large size and scale changes is considered by studying the stability of two additional hingeless rotor helicopters of 5,120 and 48,000 pounds, respectively, which are obtained from the reference case by aerodynamic scaling. That is the rotor diameter and overall proportions of the aircraft were altered to accomodate the gross weight changes at the same mean rotor lift coefficient and tip speed. It is seen in Figure 7 that aircraft smaller than the reference case of 12,000 pounds tend toward inherent stability with the blade tuning and nominal amounts of damping assumed. On the other hand the relatively heavy machines tend to a more severe instability at slightly higher thrust to weight ratios than the reference case, but still well within the range of achieving inherent stability with moderate amounts of blade hysteresis damping and oleo-shock strut damping of the unstable, coupled rolling mode.

Ground Resonance with Feedback

As an alternative or as a supplement to parameter selection which results in stable oscillations, closed loop feedback control is considered. Since proportional control action (at least qualitatively) alters the frequency of oscillation of simple systems by adding or subtracting a virtual spring effect, depending on whether feedback is negative or positive, the reference case was used as a basis for investigating this possibility. Figure 8 shows the effect of proportional roll feedback and control action (in this case positive feedback is actually employed) in detuning an unstable coupling by depressing the critical fuselage roll mode frequency. It is seen that this is very effective in stabilizing the system. It should be noted that in the case of other design reference parameters, proportional feedback and control action of opposite sign might be beneficial, if the detuning of the critical fuselage roll frequency required increasing, rather than decreasing. The application of this control action is deemed beneficial, but is best decided on an *ad hoc* basis.

A more conventional use of feedback control is considered in Figure 9 which shows the effect of negative feedback with derivative or rate control action. This tends to augment the damping of the critical fuselage rolling mode. This is seen to be highly effective also, and, at least to a first approximation, is interchangeable with oleo-shock strut damping of the unstable roll mode.

A logical extension of the foregoing application of feedback control to the stability of ground resonance is the blending of both proportional and derivative control action. In this case the critical roll mode can be both detuned and damped to approach an optimum. This is shown to be the case in Figure 10. Here the system is made progressively more stable over the entire range of thrust to weight ratios. It is not the intention here to optimize the stability boundary, but to show that this is possible even with small values of blade internal hysteresis damping and the normal amounts of landing gear damping of the reference case. In view of the relatively unimportant influence of the pitching, and longitudinal degrees of freedom for the reference case, pitch rate feedback and control action was not deemed effective. However, this remains a potentially useful and important tool in the event that special design or operational requirements modify the open loop system.

Air Resonance

The basic reference helicopter of 12,000 pounds gross weight is examined for its air resonance stability as a function of lead-lag frequency ratio for several values of flapping frequency ratio. It is seen in Figure 11 that lead-lag frequency ratios of .70 or less result in instability over the structurally feasible range of flapping frequency ratios between 1.10 and 1.20. It is also to be noted that in the neighborhood of neutral stability (for the assumed blade equivalent viscous internal damping of 1/2%), increasing flapping frequency ratio is stabilizing. This interaction effect between these two key blade natural frequency ratios is further illuminated in Figure 15. It can also be seen that the lighter blades (i.e. an overall mass fraction of 4½% rather than 6½%) require higher frequencies for neutral stability. It is shown in Reference 12 that in the stable range of lead-lag frequency ratios, an increasing helicopter blade mass fraction improves stability further. On the other hand, it is also shown that for an unstable configuration, increasing blade mass fractions can further degrade stability.

The critical effect of internal damping of the blade lead-lag motion is presented in Figure 13 for the reference case with a flapping frequency ratio of 1.10 (comparable results were obtained at frequency ratios of 1.15 and 1.20). It is seen that increased internal damping enhances air resonance stability and internal damping levels of 1% of critical virtually eliminate the air resonance instability for a lead-lag frequency ratio of .75 or greater (since hingeless rotor flapping frequency rates greater than 1.10 improve stability further).

Although the frequency ratios for lead-lag and flapping motions of hingeless rotor blades have a fundamental effect on the air resonance stability boundaries, design differences in structure, materials, and proportioning of such blades can result in differences in the virtual hinge locations and stiffness with important modifications in the stability boundaries. These effects are presented in Figure 14, which show that more outboard location of the virtual hinges for lead-lag motion tends to stabilize, although not by a substantial degree. This effect is believed to stem from a decrease in the relative energy level of the blade in-plane motion, just as in classical ground resonance.

Size effects as distinguished from gross weight are presented in Figure 15. It is seen that the reference helicopter air resonance stability is virtually unaffected by large changes in the body pitch and roll moments of inertia, provided that the lead-lag frequency ratio is sufficiently large for stability ($\omega_{\ell\ell} \geq .75$). However relatively large machines are seen to be less unstable, if an air resonance instability exists. The influence of gross weight changes through aerodynamic scaling is presented in Figure 16 for 5120, 12,000 and 48,000 pound machines which operate at the same mean rotor lift coefficient and tip speed. It is seen that very large increases in gross weight tend to be stabilizing with respect to the minimum lead-lag frequency ratio required for neutral stability, although gross weight effects for machines in the 5,000 to 12,000 pound class are not clear-cut because of the greater sensitivity to all the other system parameters. In fact, it may be difficult to obtain a rational trend when blade mass fraction is held constant, when in reality the very small machines will tend toward larger blade mass fractions. In contrast to this, if the gross weight of the reference machine is decreased by off-loading (cargo, for example), there is a clear-cut improvement in the air resonance stability. This is shown in Figure 17 and stems from the reduction in blade initial coning. The effect of coning is discussed further below.

Built-in pre-coning angles are normal in the design of hingeless rotors; to minimize steady bending stress is a routine consideration. Figure 18 shows the stability boundary for the reference case and the effect of deviating from the nominally ideal case of built-in pre-coning matching the coning that would result from a 1-g load of a centrally hinged, articulated rotor. It is seen immediately that "over-coning" destabilizes and "under-coning" stabilizes for the entire range of lead-lag frequency ratios. This suggests that a direct, profitable trade-off between steady bending stress and air resonance stability exists. That is reduce coning by structural action and enhance stability. Figure 19 continues this theme by showing the influence of a concentrated tip weight on the air resonance instability. In this case it is seen that tip weight is beneficial and stabilizing, providing the lead-lag frequency ratio is of the order of three-fourths or greater ($\omega_{\ell\ell} \geq .75$). Figure 20 shows the design effect of an RPM reduction at fixed gross weight. This would increase coning and the data shows a consistent loss of stability for the various lead-lag frequency ratios.

Aerodynamic scaling for very large helicopters appears to be barred by the adverse trend of coning at constant mean rotor lift coefficient and tip speed, unless blade number is increased beyond four blades. For example increasing gross weight from 48,000 pounds to 72,000 pounds was considered by increasing disk loading and solidity by fifty percent - that is adding two blades to the original four-blade design. This yields the beneficial effect of no increase in coning angle and only a minor modification of the stability boundary. This is illustrated in Figure 21. The dash or ghost line on this figure represents a second mode of marginal stability at a high frequency. This is discussed at length in reference 15. The implication is that a high frequency air resonance instability might become a factor in very large hingeless rotor helicopters. However, the effect of including the additional rotor degrees of freedom suppressed by the "quasi-normal" or "multi-blade" coordinate transformations requires additional, careful study since the current analysis limits rotor flapping type motions to those which result in either collective or cyclic flapping of the individual blades.

Air Resonance with Feedback

Proportional feedback and control action proves to be a very effective means of stabilizing air resonance. Figure 22 shows the influence of proportional roll control action for the reference helicopter; roll corrections alone are found to be highly effective over the entire range of lead-lag frequency ratios, whereas aircraft pitching motion is found to be a relatively small component of the air resonance instability mode and not a productive avenue for closed loop stabilization.[15] Figure 23 examines the efficacy of proportional roll control for a case of maximum air resonance instability when $\omega_{\ell\ell}$=.60. It is seen to be very effective and virtually a linear influence on stability over the range of practical interest.

Sensing aircraft roll rate is also found to be highly effective in closed loop control, but less so for pitch rate because of the relatively small participation of pitch in the air resonance instability. However the complex phase relationships which exist in the mode of air resonance instability[15] make it very desirable that aircraft roll and pitch control actions be mixed (i.e. the interacting control actions referred to above[5]).

This is illustrated in Figure 24 which shows the influence of pitch control action for several levels of roll control action (where both are based on roll rate feedback information). The linearity of this stabilization method is made evident by cross-plotting the influence of pitch control action for a magnitude of roll control action which results in (almost) neutral stability.

Closed Loop Stabilization

The foregoing data illustrates that an appropriate mix of aircraft roll and roll rate information, in conjunction with aircraft roll and pitch control action, permits straightforward artificial stabilization of both the air and ground resonance instabilities of hingeless rotor helicopters under very adverse design conditions. More importantly, perhaps, the data indicates that the marginally stable configurations resulting from the lead-lag frequency ratio being tuned to .70-.80 and/or internal damping levels for this oscillation being of the order of ½% of critical or less can be easily stabilized by utilizing existing, conventional control systems.

A significant difference between the ground resonance and air resonance modes of instability is the phase relationship between rotor cone tilting and fuselage rolling motion. Also the fact that a slight positive or regenerative roll feedback and control action can be beneficial in stabilizing ground resonance. The reverse is true for air resonance. The common, beneficial element for both instabilities is in sensing aircraft roll rate and utilizing this information for negative feedback to implement roll control action. This in effect is stability augmentation of the aircraft roll damping both on the ground and in the air. The additional control action for aircraft pitch has been found to be beneficial for stabilizing air resonance[15] and not detrimental for stabilizing ground resonance.[6] Thus the interacting, closed loop control system driven by roll rate information emerges as a simple, evolutionary approach to complete artificial stabilization, or stability augmentation of the hingeless rotor helicopter air and ground resonance instabilities.

Conclusions

1. The ground and air resonance instabilities of hingeless rotor helicopters are marginal ones, but they will persist as design considerations because of the natural tendency of the lead-lag frequency ratios to be less than unity (and conceivably as small as .60), while internal damp-

ing levels will be slight, unless special materials and design measures which increase internal damping can be found and which are acceptable with respect to other design and operating constraints.

2. The air resonance instability is very sensitive to blade coning, while ground resonance is not. Reductions in coning by a variety of means are beneficial, but the possibility of accepting a modest level of steady bending stress in lieu of other approaches (such as tip weights) is worthy of more consideration (since this would also reduce Coriolis-type fatigue loads in steady forward flight).

3. Completely artificial stabilization of both the air and ground resonance instabilities is possible, by utilizing the concept of interacting controls. This is not suggested as a serious approach to design, but as an indication that a modest stability augmentation approach, in conjunction with adherence to simple design criteria and objectives, can eliminate both the air and ground resonance instabilities.

4. The ground resonance instability which was studied exhaustively in Reference 6 is seen to be inherently the same, whether conventional oleo shock strut or skid type landing gear are used, providing the effective stiffness and damping are properly represented in the overall system design. On the other hand, failure or malfunction of a single element of the system which destroys the assumed symmetries (e.g. a single blade damper on an articulated rotor system) must be evaluated on an *ad hoc* basis since the system might then become unstable despite the stability of the normal system.

References

1. Donham, R. E., Cardinale, S. V., and Sachs, I. B., "Ground and Air Resonance Characteristics of a Soft In-Plane Rigid-Rotor System," AIAA/AHS VTOL Research, Design and Operations Meeting, Georgia Institute of Technology, Atlanta, Georgia, February 1969.

2. Woitsch, W. and Weiss, H., "Dynamic Behavior of a Fiberglass Rotor," AIAA/AHS VTOL Research, Design and Operations Meeting, Georgia Institute of Technology, Atlanta, Georgia, February 1969.

3. Lytwyn, R. T., Miao, W., and Woitsch, W., "Airborne and Ground Resonance of Hingeless Rotors," 26th Annual Forum of The American Helicopter Society, Washington, D.C., June 1970, Preprint No. 414.

4. Young, M. I., "The Dynamics of Blade Pitch Control," Journal of Aircraft, Vol. 10, No. 7, July 1973.

5. Ogata, K., Modern Control Engineering Prentice-Hall, Englewood Cliffs, N.J., 1970, pp. 377-396.

6. Bailey, D. J., "Automatic Stabilization of Helicopter Ground Instabilities," University of Delaware, Master of Mechanical and Aerospace Engineering Thesis, May 1973.

7. Young, M. I., "A Simplified Theory of Hingeless Rotor Helicopters," Proceedings of the Eighteenth Annual National Forum of The American Helicopter Society, Washington, D.C., May 1962, pp. 38-45.

8. Ward, J. F., "A Summary of Hingeless Rotor Structural Loads and Dynamics Research," Journal of Sound and Vibrations, 1966, Vol. 4, No. 3, pp.358-377.

9. Young, M. I., Hirschbein, M. S., and Bailey, D. J., "Servo-Aeroelastic Problems of Hingeless Rotor Helicopters," University of Delaware, Department of Mechanical and Aerospace Engineering, Technical Report No. 155, August 1972, (Revised October 1973).

10. Kelley, B., "Rigid Rotors vs. Hinged Rotors for Helicopters," Annals of The New York Academy of Sciences, Vol. 107, Article 1, 1964, pp. 40-48.

11. Marda, R. S., "Bending Vibrations of Hingeless Rotor Blades," University of Delaware, Master of Mechanical and Aerospace Engineering Thesis, April 1972.

12. Young, M. I. and Lytwyn, R. T., "The Influence of Blade Flapping Restraint on the Dynamic Stability of Low Disk Loading Propeller-Rotors," Journal of The American Helicopter Society, Vol. 12, No. 4, October 1967, pp. 38-54.

13. Hohenemser, K. H. and Sheng-Kuang, Y., "Some Applications of Multiblade Coordinates," Journal of The American Helicopter Society, Vol. 17, No. 3, July 1972, pp. 3-12.

14. Seckel, E., Stability and Control of Airplanes and Helicopters, Academic Press, 1964, pp. 456-457.

15. Hirschbein, M. S., "Flight Dynamic Stability and Control of Hovering Helicopters," University of Delaware, Master of Mechanical and Aerospace Engineering Thesis, October 1973.

16. Huber, H. B., "Effect of Torsion-Flap-Lag Coupling on Hingeless Rotor Stability," Preprint No. 731, 29th Annual National Forum of the American Helicopter Society, Washington, D. C., May 1973.

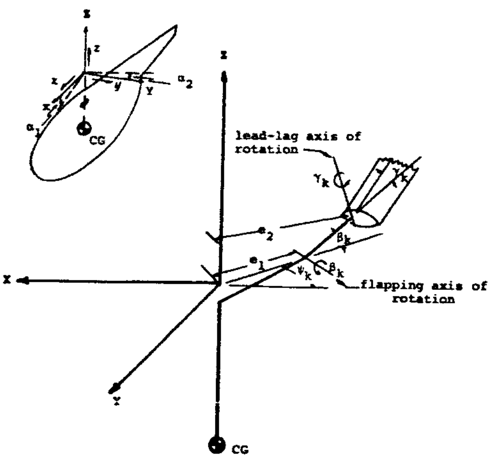

Fig. 1 XYZ - coordinate system, x, y, z, α_1, α_2 - displacements.

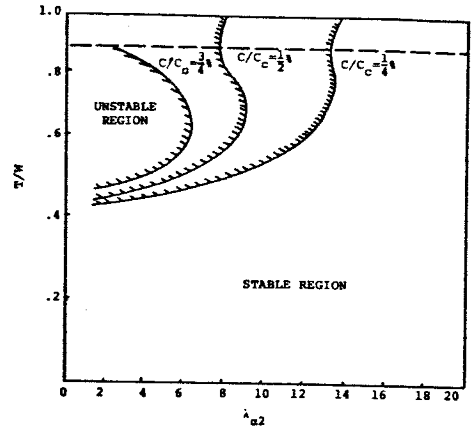

Fig. 3 Stability boundary as a function of roll damping.

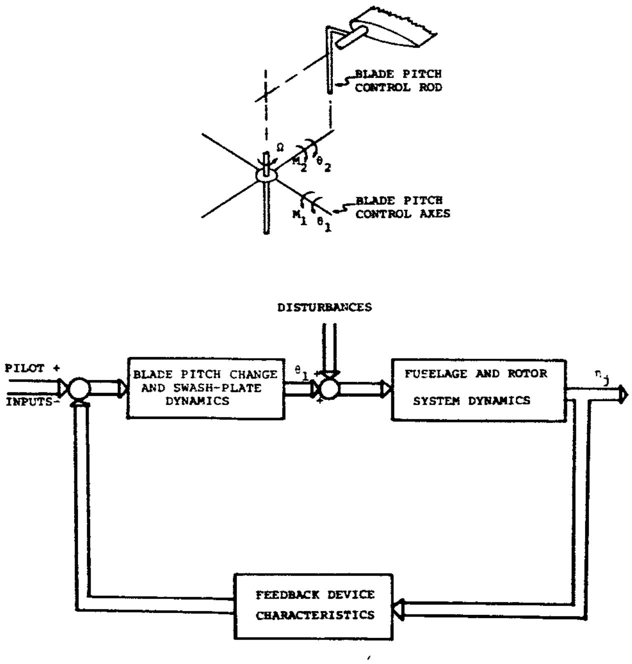

Fig. 2

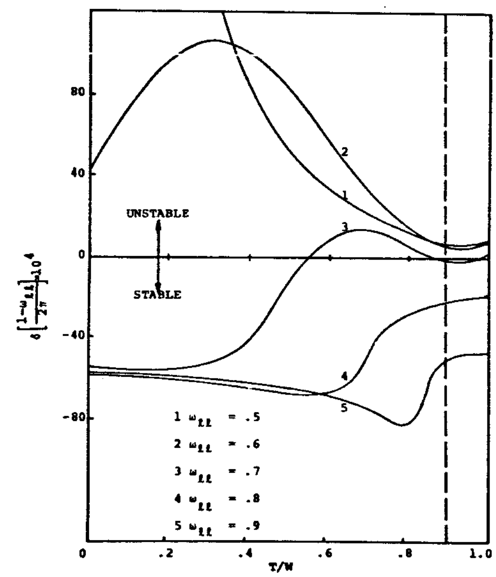

Fig. 4 The effect of lead-lag natural frequency ratio.

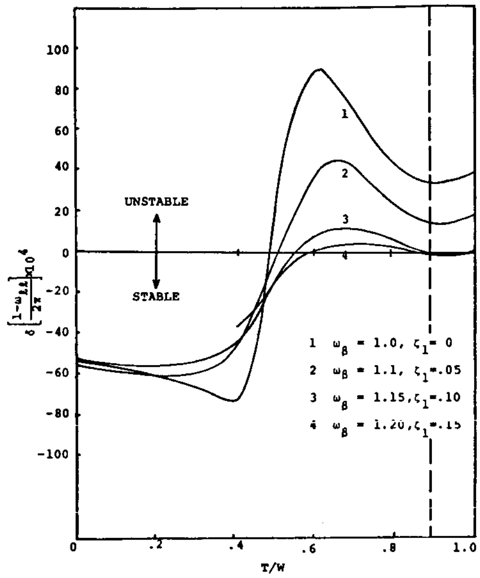

Fig. 5 The effect of flapping natural frequency ratio and virtual flapping hinge offset.

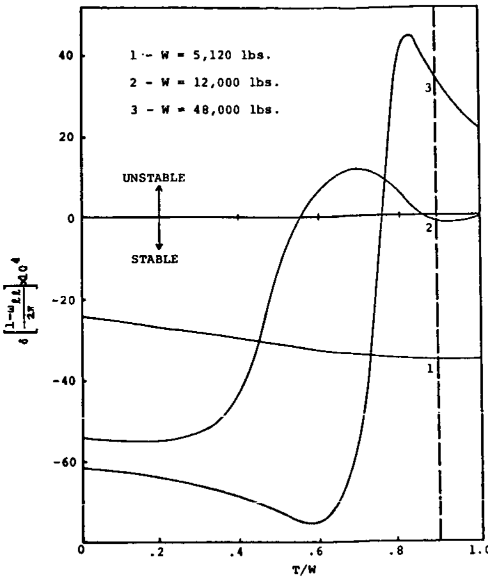

Fig. 7 Size effects.

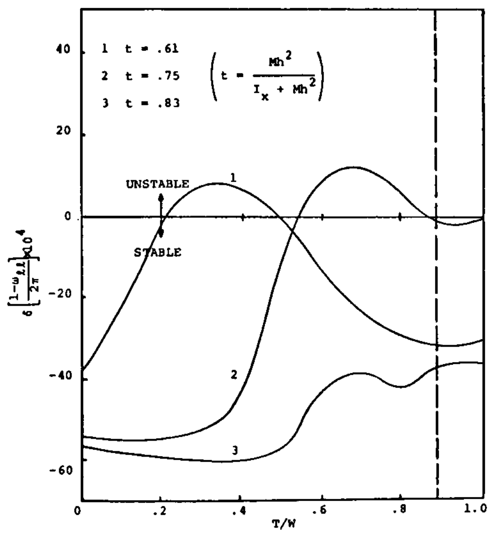

Fig. 6 The effect of coupling between lateral and rolling motion.

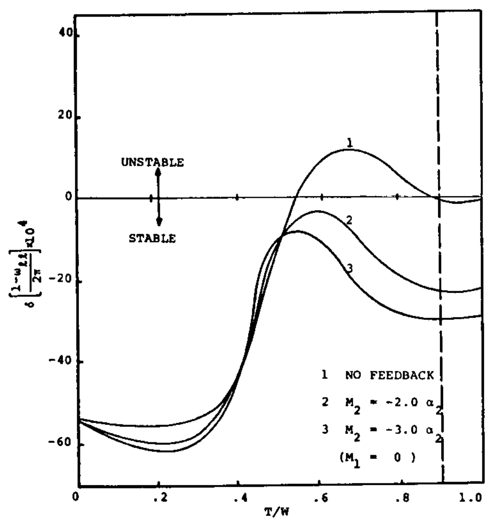

Fig. 8 The effect of roll position feedback control.

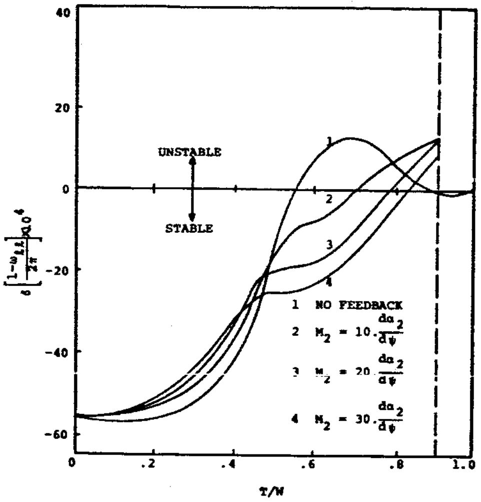

Fig. 9 The effect of roll rate feedback control.

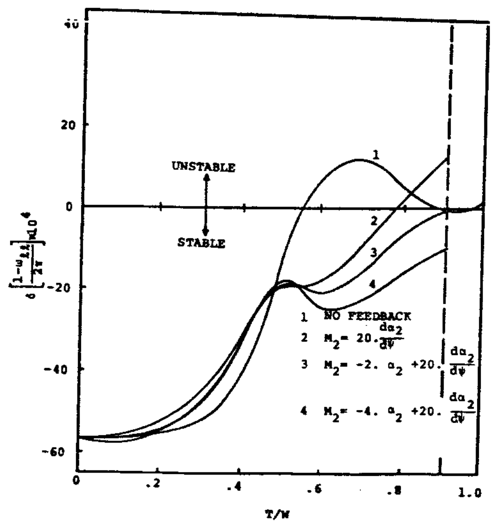

Fig. 10 The effect of roll position and roll rate feedback control.

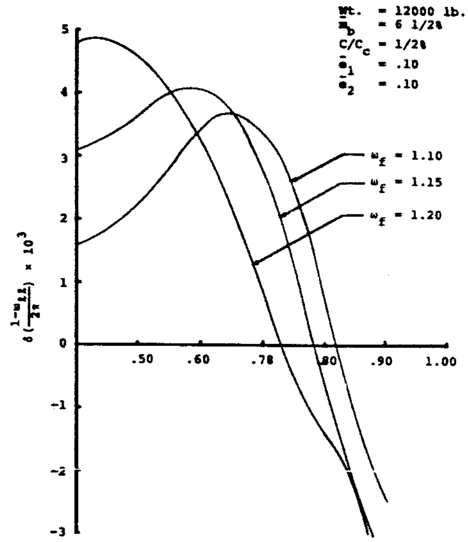

Fig. 11 The effects of lead-lag natural frequency ratio.

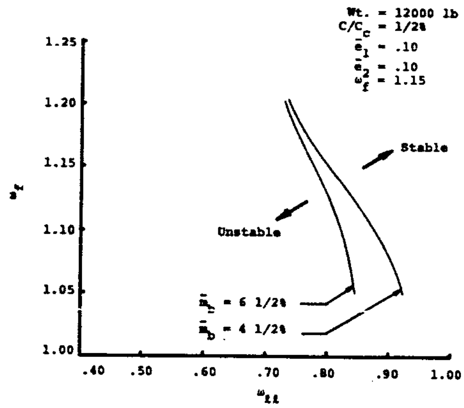

Fig. 12 Flapping-in-plane natural frequency ratio stability boundary.

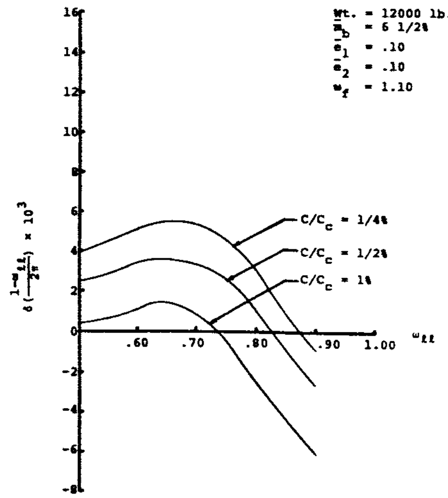

Fig. 13 The effect of in-plane blade structural damping.

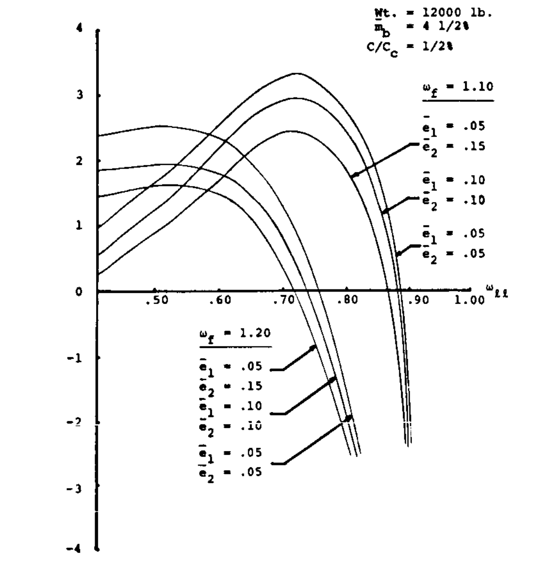

Fig. 14 The effect of virtual hinge offset.

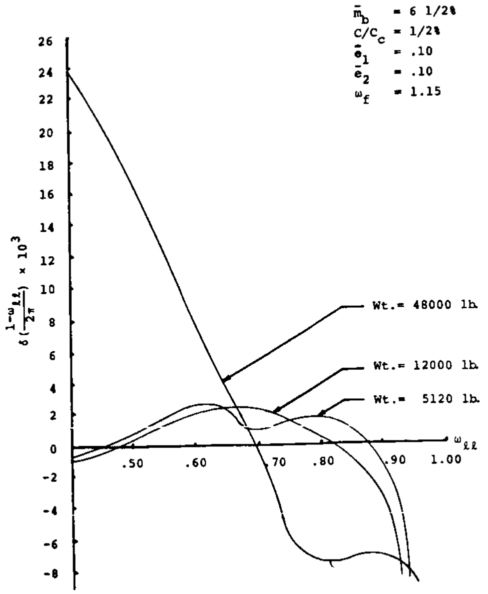

Fig. 16 The effect of scaling.

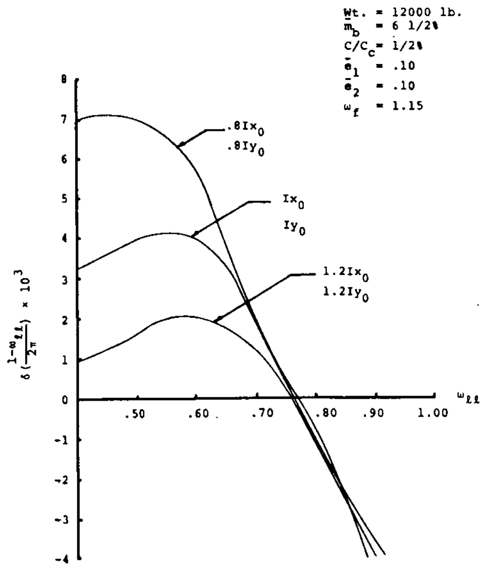

Fig. 15 The effect of changes in the body moments of inertia.

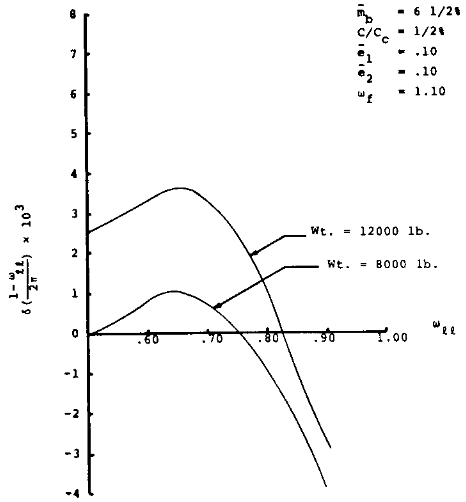

Fig. 17 The effect of off loading without changing Ix_0 and Iy_0.

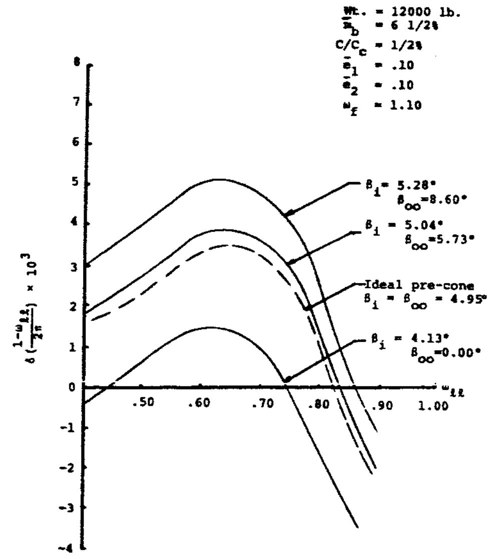

Fig. 18 The effects of pre-cone angle.

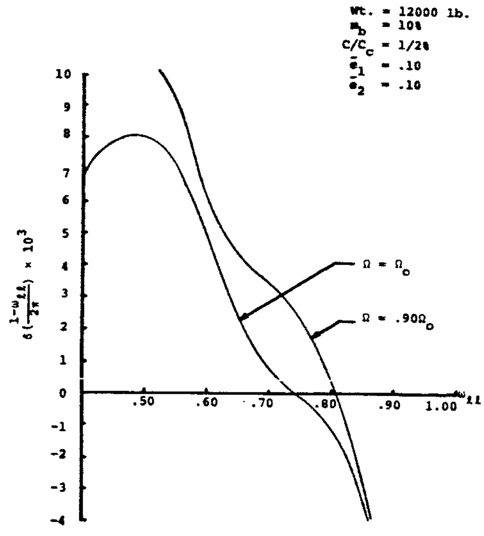

Fig. 20 The effects of a 10% RPM reduction.

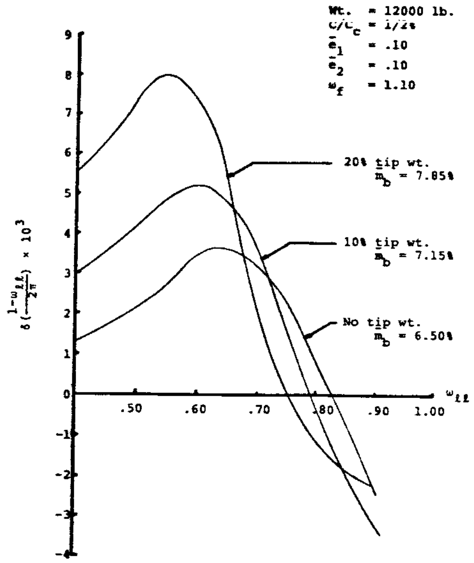

Fig. 19 The effect of tip weights.

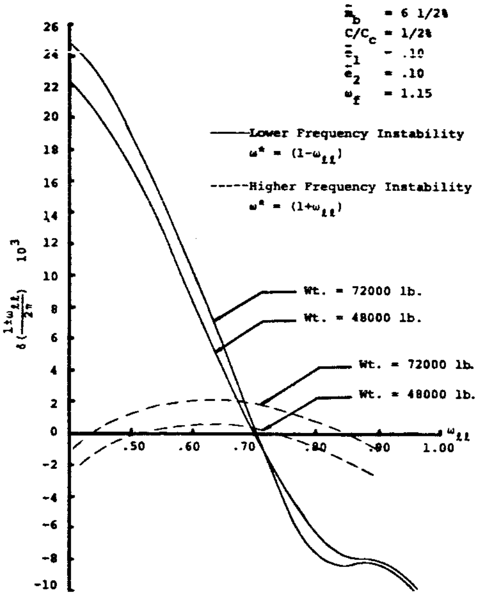

Fig. 21 Stability of heavy helicopters.

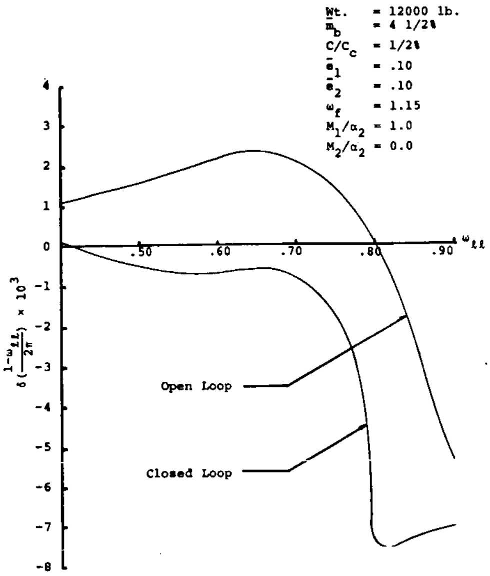

Fig. 22 Comparison of open loop stability to closed loop stability with roll position feedback.

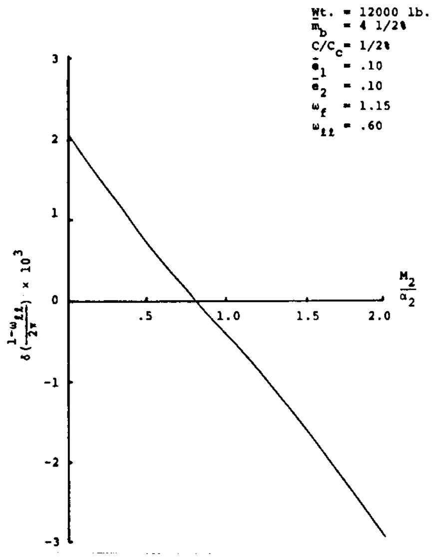

Fig. 23 The effect of roll position feedback control at maximum instability.

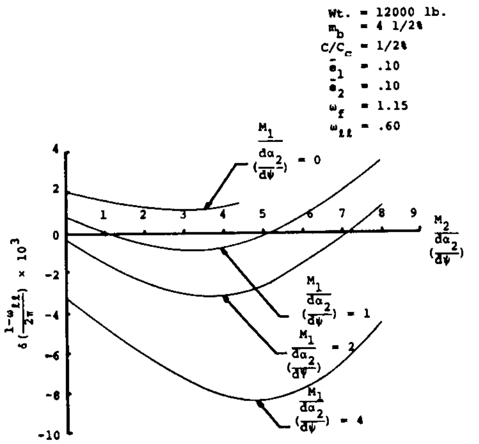

Fig. 24 The effect of roll rate feedback with pitch and roll interacting control actions.