COMPARISON OF FLIGHT DATA AND ANALYSIS FOR HINGELESS ROTOR REGRESSIVE INPLANE MODE STABILITY

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Abstract

During the development of the AH-56A, a considerable amount of analytical and experimental data was obtained on the stability of the regressive inplane mode, including coupling with other modes such as body roll and rotor plunge. The data were obtained on two distinctly different control systems; both gyro controlled, but one with feathering moment feedback and the other with direct flapping feedback. The paper presents a review of the analytical procedures employed in investigating the stability of this mode, a comparison of analytical and experimental data, a review of the effect of certain parameters, including blade droop, sweep, δ_3, α_1, vehicle roll inertia, inplane frequency, rpm and forward speed. It is shown that the stability of this mode is treatable by analysis and that adequate stability is achievable without recourse to auxiliary inplane damping devices.

Notation

B	subscript referring to blade feathering
$C_{1/2}$	measure of damping, cycles to half amplitude
F	subscript referring to fuselage
g	structural damping ratio
I	imaginary part of root, rad/sec
K_{θ_o}	collective feathering stiffness, ft-lb/rad/blade
K_β	root flapping moment per unit of blade flapping, ft-lb/rad
L	rotor lift, pounds
M	moment, ft-lb
M_{xy}	blade product of inertia about feathering axis, slug-ft^2
N_R	normal rotor speed
R	real part of root, per second, subscript referring to rotor, or rotor radius, ft
V	airspeed, knots
X_F	airframe longitudinal motion, ft
Y_F	airframe lateral motion, ft
Z_F	airframe vertical motion, ft
α_1	pitch lag coupling - positive nose up feather due to lag aft of blade
β_o	rotor blade collective flapping or coning, radians
δ_3	pitch flap coupling angle - $\tan^{-1}(-\theta/\beta)$
∂	to indicate partial differentiation
ϵ_x	rotor blade cyclic inplane motion sine component, positive forward, radians
ϵ_y	rotor blade cyclic inplane motion cosine component, positive to the right, radians
ζ	fraction of critical damping
θ	pitch motion, radians
θ_o	blade collective feathering, radians
$\bar{\lambda}$	blade effective sweep angle, radians
τ_s	servo time constant, sec
ϕ	roll motion, radians
ω	frequency, rad/sec
ω_{nip}	inplane natural frequency, rad/sec
Ω	rotor rotational speed, rad/sec

Presented at the AHS/NASA-Ames Specialists' Meeting on Rotorcraft Dynamics, February 13-15, 1974.

In hingeless rotors two fundamental types of coupled rotor body inplane mode stability problems exist. One is associated with a soft inplane system having the inplane frequency less than rotational speed, and the other with a stiff inplane system where the inplane frequency is above rotational speed. The soft inplane system when coupled with a basic body mode is unstable in the absence of aerodynamics, and therefore its stability must be provided by aerodynamic or auxiliary damping. This type of system is discussed in References 1, 2, and 3. In contrast, the stiff inplane system does not exhibit this inherent mechanical instability, and so its stability is less dependent upon aerodynamic or auxiliary damping.

Both types of modes, however, are subject to aeroelastic phenomena which can be stabilizing or destabilizing. Also, both types can exhibit response characteristics caused by pilot and/or gust inputs which are undesirable. The critical inplane mode in the soft inplane system is advancing in the stationary system, whereas for the stiff inplane system, the mode is regressive. The frequency of the mode in each case is the magnitude of (ω_{nip} - Ω) or (Ω - ω_{nip}).

This paper deals specifically with the stiff inplane system. The various types of coupled rotor body regressive inplane stability/response problems associated with this type of system are discussed. The paper deals with both a feathering moment feedback gyro-controlled system and a direct flapping moment feedback gyro-controlled system.

These two types are described in more detail in Reference 4. The inplane mode characteristics of the direct flapping moment feedback type system would be more characteristic of any direct control hingeless rotor system employing a stiff inplane rotor.

The stiff inplane hingeless rotor system is worthy of serious consideration because of its inherent characteristics of being free from ground/air resonance mechanical instability type phenomena and its ability to provide a stable, highly maneuverable, rotary wing vehicle.

The absolute level of the stability of the inplane mode is not the only consideration in establishing design criteria. An equal or even more important criterion is that of response of the mode as a result of pilot or gust disturbances. The stability of the mode can appear adequate, but if it is easily excited by either pilot or gust inputs, the mode can be unsatisfactory. Conversely, the mode may exhibit very low damping characteristics, but not be easily excited by either pilot and or gust excitations, and be quite satisfactory because no high loads or undesirable body motions occur.

Besides the basic stability considerations of the regressive inplane mode, certain other basic types of coupled rotor body regressive inplane mode stability/response problems may be encountered. Some of these may be either low or high airspeed phenomena or virtually independent of airspeed.

It is not intended here to go into a complete theoretical treatise describing each of these types of phenomena, but the effects of some parameters and flight conditions on stability/response characteristics for particular rotor vehicle configurations are presented. Because stability and response characteristics depend on considerations of the detail design, generalized conclusions cannot always be drawn as to the effect of each parameter discussed.

The fundamental types of regressive inplane mode stability/response problems discussed include those associated with:

- The basic regressive inplane mode.
- The coupled regressive inplane body roll mode.
- A coupled regressive inplane-roll-rotor plunge mode.

The first type can exhibit itself to the pilot as an apparent rotor weaving or rotor disc fuzziness with very little body response. The second type appears to the pilot as rotor tip path plane response and body roll or just body roll oscillation. Depending on the frequency of this mode, and the gain of the feed forward loop of the control system, this mode may be subject to pilot-induced or pilot-coupled oscillations. The last type basically exhibits itself to the pilot as a rotor umbrella mode and a vertical plunge of the vehicle. This mode can exist in the absence of the inplane mode but can be seriously affected by its presence. The mode has been characterized as a "Hop" mode because of the plunge response of the airframe.

Analytical Method

The analytical method employed in the study consists of a fundamental 13-degree-of-freedom representation of the coupled rotor body control system. The body is characterized by 5 degrees of freedom – yaw being ignored. Likewise, the rotor is represented by eight multiblade coordinates including rotor disc plunge, pitch and roll; lateral and longitudinal inplane; and pitch, roll, and collective elastic feathering/torsion. The model is shown schematically in Figure 1. The equations are solved as linear constant coefficient equations, modified as required to represent the control system being considered.

For the solutions shown, certain simplifying assumptions were made. These include neglecting the effects of retreating blade stall, reverse flow, and advancing tip Mach number.

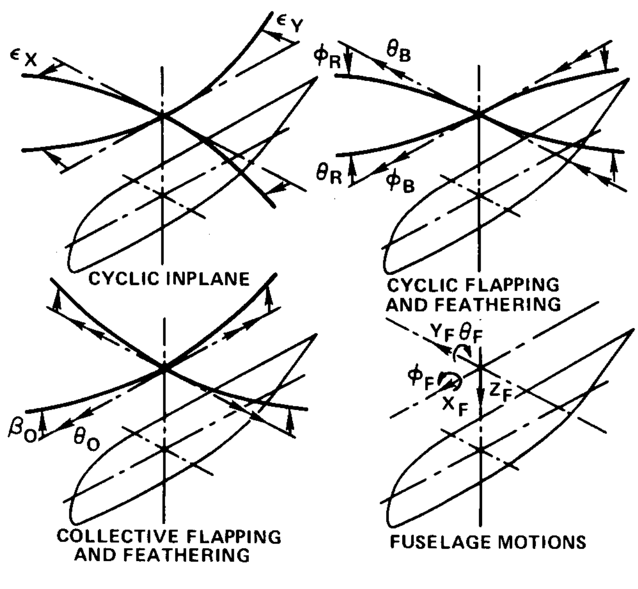

Figure 1. Description of Analytical Model.

The model includes the effects of elastic coupling phenomena of inplane moments times flapping deflections causing feathering moments. A simplified inflow model is used which characterizes the induced velocity from low transition speed to high speed as a trapezoidal distribution with upwash at the front of the rotor and downwash at the back of the rotor, for positive rotor lift.

To gain a fairly comprehensive understanding of such modes as the regressive inplane mode as well as the other coupled rotor body fundamental aeroelastic modes, it is felt this type of model is a necessity.

Effect of Parameters

Following is a discussion of each type of mode and the relevant parameters which affect the stability/response of the mode together with some parametric effects.

Basic Regressive Inplane Mode

The basic regressive inplane bending mode can be lightly damped without any problem, provided it is not easily excited by the pilot or by gusts. The mode if its frequency is well separated from any other rotor body control mode frequencies, behaves very much as a single blade would behave.

Figure 2 shows a complex plane plot of a typical mode of response of the regressive inplane mode. It is noted that motions of all other degrees of freedom are small compared with the response of the blade inplane ϵ_x and ϵ_y. This would be for a case where the inplane mode frequency is well separated from other rotor-body control mode frequencies, and the inter-coupling with these modes is not large. In this case the inplane mode is reasonably above the body roll mode, with a frequency ratio of 1.32 in nonrotating coordinates.

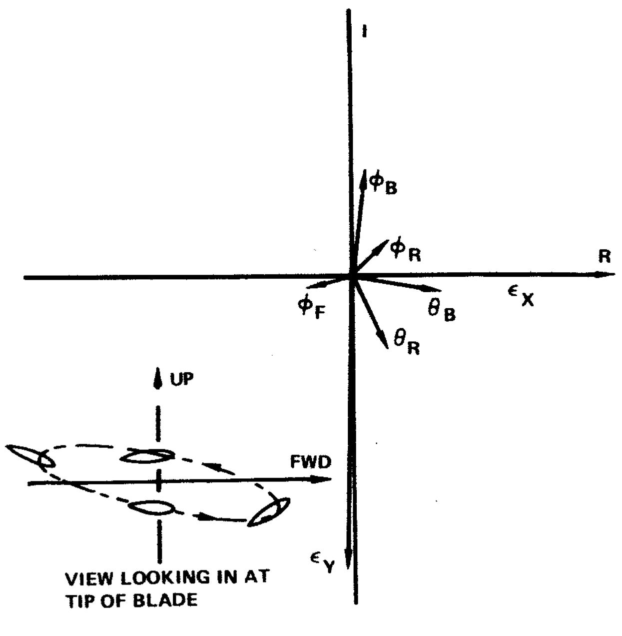

Figure 2. Complex Plane Plot of Typical Regressive Inplane Mode, V = 20 KN, $\omega_\epsilon/\omega_{Roll} = 1.32$.

For this case, the effect of several parameters is examined. The stability/response of the mode is largely controlled by such parameters as discussed in Reference 4 and 5. That is, parameters such as blade kinematic and elastic pitch-flap-lag couplings are extremely important. Also, such items as precone, feather bearing location, hub/blade stiffness distributions and control system flexibility play important roles in the stability of the mode. A discussion of each of several parameters affecting the stability of the mode follows.

Inplane Damping. Figure 3 shows a locus of roots as a function of equivalent structural damping in the inplane mode. Identified on this figure are lines of constant damping in terms of one over cycles to half amplitude, $1/C_{1/2}$. This figure shows the expected results. That is, computing the approximate change in fraction of critical damping from the root locus plot by taking an increment of change in the real part of the root due to the change in modal structural damping, g_{ST}, and dividing it by the sum of the imaginary part of the root and rotational speed results in a value of damping roughly half the change in equivalent structural damping. This is consistent with the well known relationship of $g \simeq 2\zeta$ where $g << 1$.

Since some centrifugal stiffening effect is existant in the inplane mode, the actual change in damping, 2ζ, is less than the change in equivalent structural damping in the mode.

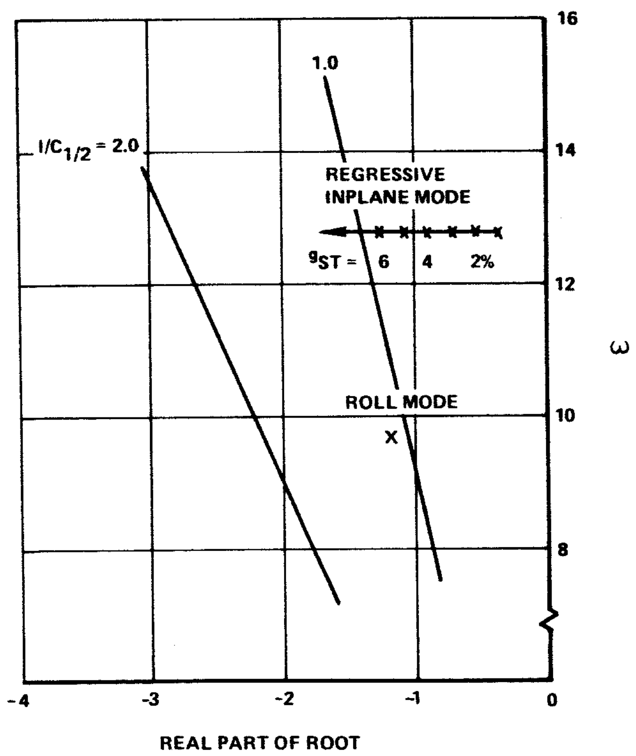

Figure 3. Locus of Roots – Effect of Structural Damping, V = 20 KN.

Kinematic Pitch Lag Coupling. Figure 4 shows the change in damping due to a variation in pitch lag coupling. The indicated sense of this coupling for improved stability is nose down feathering due to lag aft of the blade for the stiff inplane system whereas Reference 6 showed that the opposite coupling is stabilizing for articulated or soft inplane system. The effect of this parameter on the stability of the regressive cyclic inplane mode is similar to the effect on the stability of the reactionless inplane mode as indicated in Reference 5. The fundamental mechanism of the α_1 coupling is to cause blade flapping to couple through coriolis forces to damp the inplane mode. This can be deduced by examining Figure 2.

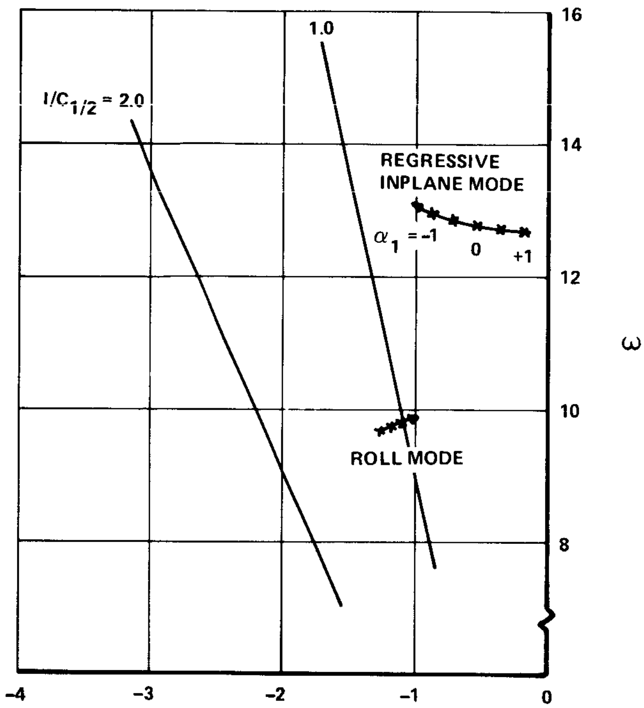

Figure 4. Locus of Roots – Effect of Pitch Lag (α_1) coupling, V = 20 KN.

A schematic of the response of a single blade for this mode looking in at the blade tip is shown in the lower left corner of Figure 2. The response shown is a stable response. With the inplane frequency above the basic flapping frequency, nose up blade feathering when the blade is forward, positive α_1, will cause the blade to flap up as the blade is going aft. The up flapping velocity of the blade generates a Coriolis force which reduces the inplane motion.

Blade Droop. Blade droop is the built in vertical angular offset of the blade below the feathering axis (see Reference 5) and causes an elastic pitch lag coupling which is similar in effect to stabilizing α_1 coupling. The droop effect though is somewhat more effective in stabilizing this particular mode since some additional phase lag results in the response of the elastic blade feathering which improves the amount of flap induced Coriolis damping in the mode. This is accomplished through an increment of up flapping velocity at the time the blade is moving aft, causing a Coriolis force forward to reduce the inplane motion. The effect of blade droop on the regressive inplane mode is shown in Figure 5.

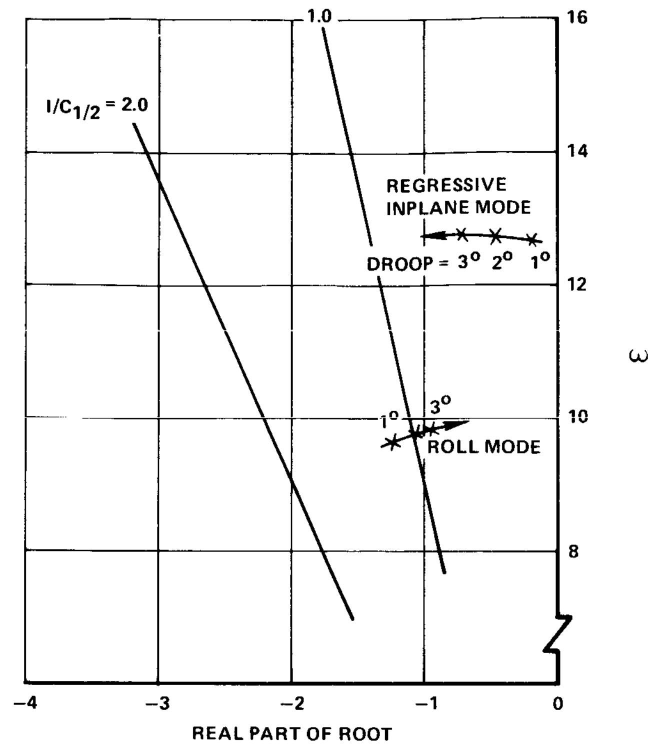

Figure 5. Locus of Roots – Effect of Blade Droop Angle, V = 20 KN.

An additional insight into the effect of droop on the characteristics of the system is shown in Figure 6. Shown is a predicted frequency response of inplane response and of vehicle roll rate response due to lateral stick excitation as a function of excitation frequency. It is noted that the inplane becomes quite responsive at low values of blade droop. It is also noted that even with the fairly large separation of the roll mode and inplane mode frequency, an influence of blade droop is seen on the roll mode. This influence is seen to make an increase in the peak response of roll rate at its peak response frequency with increasing blade droop.

Other Parameters. Other parameters such as built in blade sweep forward or aft of the feathering axis, δ_3 coupling, control system flexibility, stiffness distribution of the blade and hub and location of the feather bearings influence the stability of this mode. Again, it is pointed out that the influence of each parameter depends to a large part on the detail design. However, in general, for a stiff inplane hingeless rotor, couplings which result in nose down feathering due to lag aft of the blade add damping to the regressive inplane mode. Also, with the inplane mode frequency above the flapping mode frequency, couplings which act as a negative spring increment to the flapping mode or a positive spring increment to the inplane mode are stabilizing to the inplane mode. These couplings may, however, influence the stability/response characteristics of other modes, in particular the roll mode.

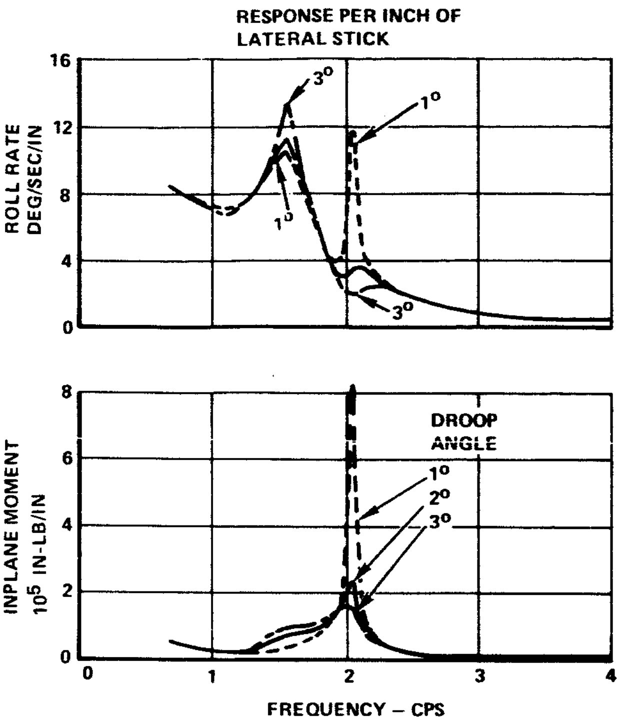

Figure 6. Effect of Blade Droop on Inplane and Vehicle Roll Frequency Response Characteristics, V = 20 KN.

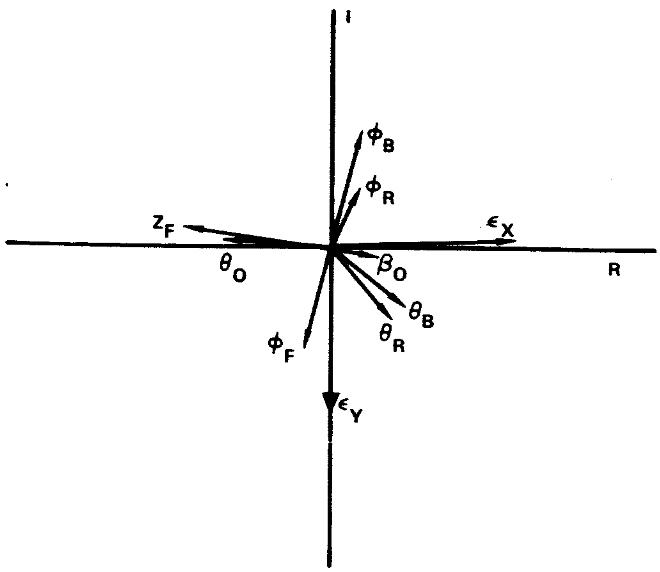

Figure 7. Complex Plane Plot of Typical Coupled Regressive Inplane Roll Mode, V = 160 KEAS, $\omega_\epsilon / \omega_{Roll} = 1.1$.

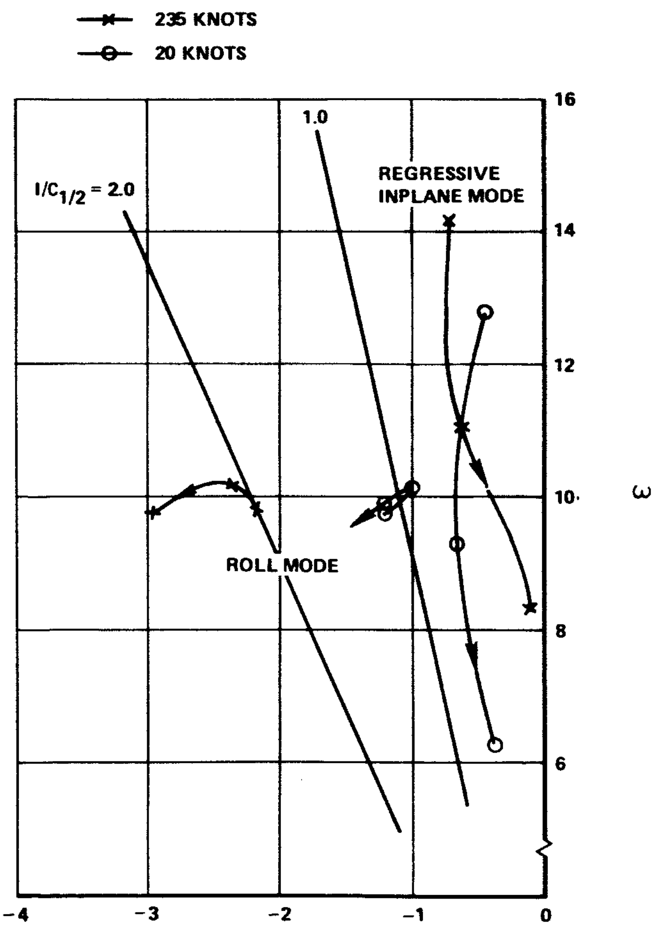

Figure 8. Locus of Roots – Effect of Inplane Frequency.

Coupled Regressive Inplane Body Roll Mode

Next is considered the coupled regressive inplane bending-body roll mode where the frequency of the inplane mode and of the roll mode are nearly coalescent. Figure 7 is a complex plane plot of a typical coupled regressive inplane-roll mode for a direct flapping moment gyro control type system where the inplane to roll mode frequency ratio is 1.1. Comparing this figure with Figure 2, it is noted that the roll response of the airframe relative to the inplane is significantly larger in this mode. In this case, the phase relationships between inplane, the rotor pitch and roll, and the cyclic blade angle are still in a damping phase for the inplane but the rotor roll-airframe roll phasing is such as to provide a slight driving to the airframe roll motion. For this particular case, the net damping of the regressive inplane mode would be somewhat reduced. Again, a discussion on the effect of significant parameters which influence the characteristics of this mode follows.

Inplane Frequency. Figure 8 shows the influence of inplane frequency on coupled regressive inplane bending-roll mode damping. Data are shown for a low-speed, 20-knot case and a high-speed, 235-knot condition (compound helicopter flight mode). It is interesting to note that at low speed, the roll mode loses damping due to frequency coalescence whereas at the high-speed condition, it is the inplane mode that tends to lose stability.

Blade Droop. The influence of blade droop, where the inplane mode and roll mode frequencies are close, is shown in Figure 9. These data show a significant effect of droop on the tradeoff of damping between the two modes. It is noted that increasing droop has a significant effect in increasing the damping of the inplane mode, but an equally significant effect in reducing the damping of the roll mode.

Vehicle Roll Inertia. Figure 10 shows the influence of vehicle roll inertia. In the case shown, a small reduction in damping of the regressive inplane mode and a significant improvement in damping of the roll mode result from increasing the roll inertia. A reduction in roll frequency is also seen. Ordinarily, a roll mode in the 0.6 to 1.3 Hz frequency region, with the damping sufficiently low, can be subject to pilot-coupled oscillations. As can be seen from Figure 10, this problem is avoided by the corresponding large increase in damping of the roll mode as the frequency decreases into this range with the increasing roll inertia.

Pitch Flap (δ_3) Coupling. The influence of pitch-flap coupling on coupled regressive inplane-roll mode stability is shown in Figure 11. This figure shows the inplane mode to be little affected by $\delta_3$coupling with flap-up, pitch-down coupling being slightly stabilizing. The effect on the roll mode is to increase its frequency with positive coupling and also to improve its damping. The inplane mode frequency is decreased as was expected, but the damping increase was not expected. For a case (not shown) where the inplane frequency was considerably above the roll mode frequency, the influence of the more positive pitch flap coupling was to destabilize the inplane mode slightly with a more significant effect of improving the stability of the roll mode.

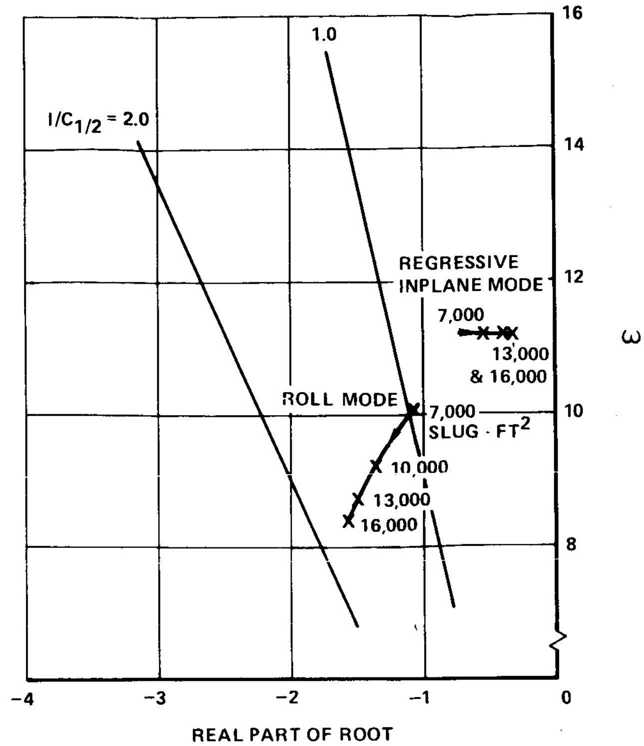

Figure 10. Locus of Roots – Effect of Airframe Roll Inertia, V = 20 KN.

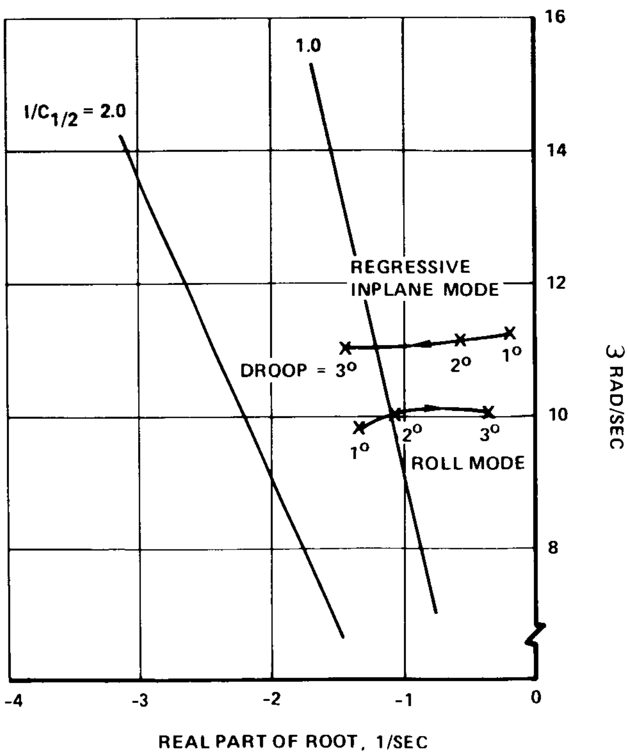

Figure 9. Locus of Roots – Effect of Blade Droop Angle, V = 20 KN.

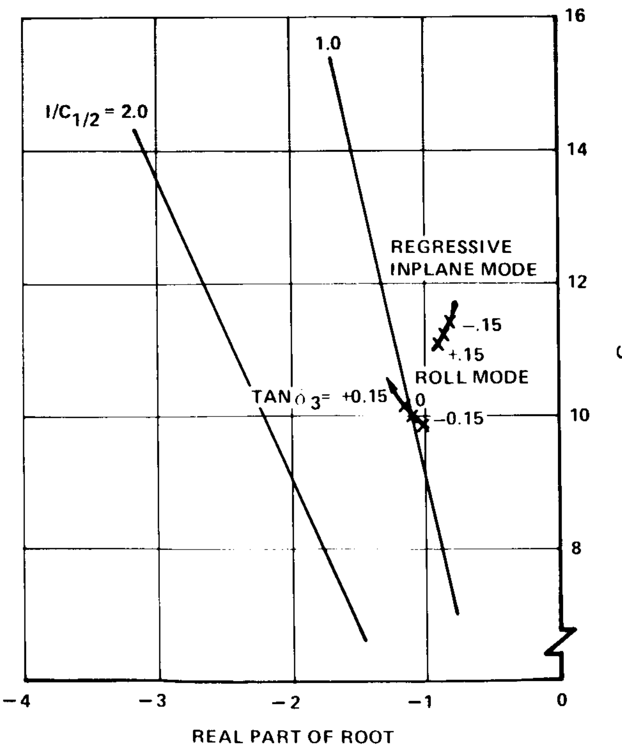

Figure 11. Locus of Roots – Effect of Pitch Flap (δ_3) Coupling, V = 20 KN.

Feedback Ratio. Feedback ratio, λ, is the ratio of the moment applied to the control gyro by rotor cyclic flapping moment or shaft moment to the corresponding rotor shaft moment. This parameter is described in detail in Reference 4. It is used both to prevent excessive rotor shaft moments while the vehicle is in contact with the ground, and to aid in tailoring the vehicle handling qualities. This ratio is defined by the following equation:

$$\lambda = \frac{M_{gyro}}{M_{shaft}}$$

The influence of this parameter on coupled roll regressive inplane mode stability is fundamentally on the roll mode. As shown in Figure 12, increasing the magnitude of this parameter increases the frequency of the roll mode and reduces its damping while increasing the damping of the inplane mode.

Servo Time Constant. For the configuration being discussed, the blade cyclic feathering is obtained through irreversible servo actuators which are slaved to the control gyro. The lag in the servos then causes a lag in the response of the cyclic blade feathering as commanded by the control gyro. The influence of the cyclic servo time constant is shown in Figure 13. It is noted that the effect of increasing servo time constant is to reduce the frequency and damping of the roll mode and the damping of the inplane mode. The effect of the cyclic servo time constant becomes increasingly important with increasing speed in determining the damping of the third type of mode, discussed below.

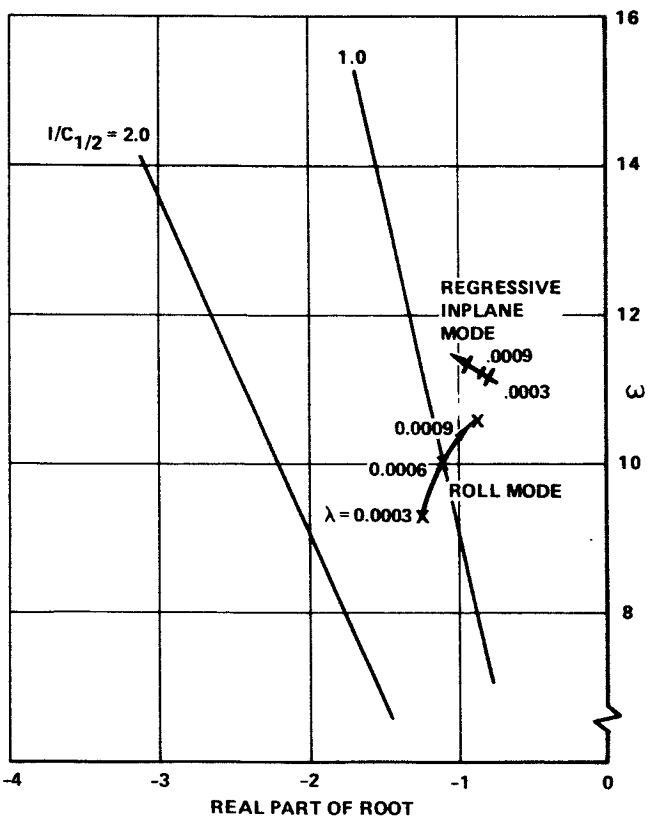

Figure 12. Locus of Roots – Effect of Feedback Ratio, V = 20 KN.

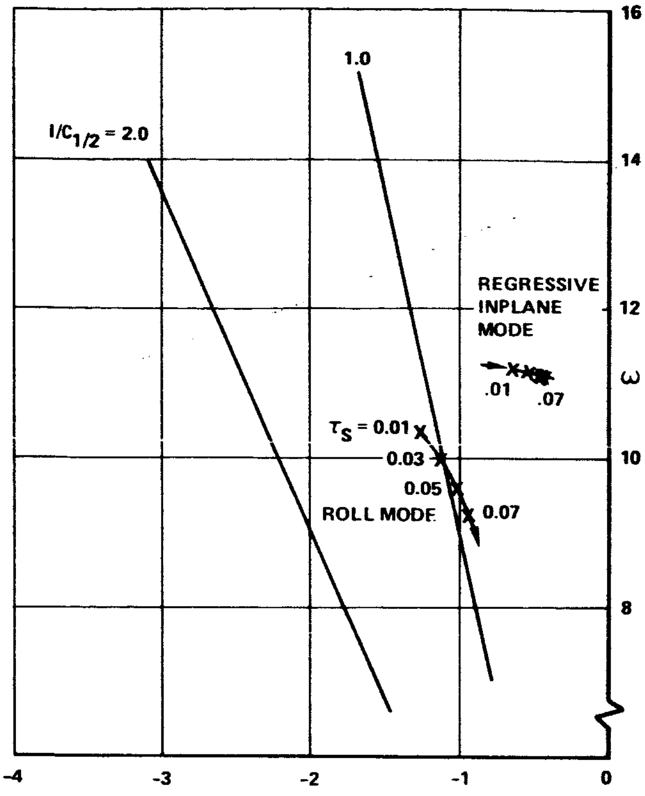

Figure 13. Locus of Roots – Effect of Cyclic Servo Time Constant, V = 20 KN.

Coupled Regressive Inplane-Roll-Rotor Plunge Mode

This mode is most critical in high-speed flight. It has been characterized as a Hop mode because plunging of the rotor disc results in a vertical bounce of the airframe. The parameters strongly influencing the stability of this mode in a feathering moment feedback system are inplane frequency, collective control stiffness, pitch-flap coupling, blade product of inertia relative to the feathering axis and blade sweep. A typical mode shape for this type of mode is shown in Figure 14. It is noted that a considerable amount of rotor inplane pitching, rolling and plunging, and airframe vertical and rolling motion occurs. The mode may become critical with increasing speed if the rotor plunge mode and coupled roll inplane mode are allowed to approach coalescence.

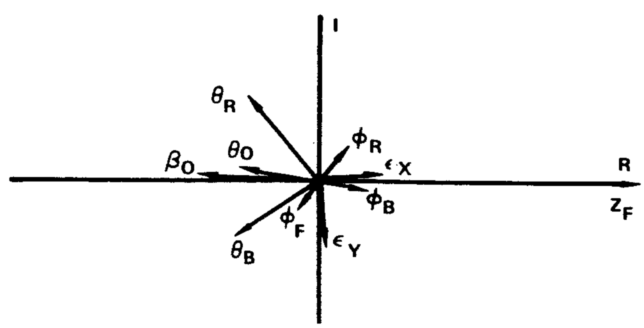

Figure 14. Typical Mode Shape of Coupled Regressive Inplane Bending – Roll – Rotor Plunge Mode, V = 180 KEAS.

This coalescence can be caused by the influence of several factors. First, any couplings that cause the rotor plunged mode to decrease in frequency with increasing forward speed may cause coalescence. This can be due principally to collective control system flexibility, blade sweep, adverse pitch-flap coupling and blade product of inertia effects; all affecting the collective pitch response to vehicle normal acceleration or rotor coning. On a first-order basis, a negative or positive aerodynamic spring on the collective plunge or coning mode of the rotor can be expressed by the following equation:

$$\frac{\partial L}{\partial \theta_o} = \frac{1}{K_{\theta_o}}\left(K_{\theta_o}\,\delta_3 - \Omega^2 \Sigma\, Mxy - \lambda K_\beta\right)\frac{\partial L}{\partial \Theta_o}$$

where $\frac{\partial L}{\partial \Theta_o}$ approximately doubles between hover and 120 knots.

Another source of coalescence or near coalescence can be due to the coupled roll-inplane mode increasing in frequency with increasing speed. As the lift due to collective blade angle increases with speed, so do the aerodynamic derivatives associated with the cyclic motions of the rotor disc, and the aerodynamic coupling terms between cyclic and collective rotor disc motions. Any kinematic or aeroelastic couplings that phase these aerodynamics to act to stiffen the coupled roll inplane mode with increasing speed will cause an increase in the frequency of this mode with speed.

Absolute coalescence of these two modes is not necessary for instability to occur. Both coupling between the modes and frequency proximity are key to stability. Couplings which cause cyclic aerodynamic forces or moments due to lift or plunge response of the rotor, which in turn result in cyclic response of the rotor disc which cause rotor disc lift or plunge driving forces, can be destabilizing. When these couplings are sufficiently strong and properly phased, the system will be unstable.

The significant aerodynamic coupling terms between these two modes, which are strongly affected by forward speed, are a rolling moment on the rotor due to change in collective blade angle, a pitching moment on the rotor due to change in coning of the rotor, and lift or plunge aerodynamic loadings due to roll velocity of the rotor or to change in longitudinal cyclic blade angle. These are direct aerodynamic couplings between these two modes.

Indirect aerodynamic couplings exist through the inplane response of the rotor system. This is particularly true in a feathering moment feedback system, because relatively high inplane exciting forces are generated as a result of changes in rotor lift. The resulting inplane responses can couple through blade static and elastic coning relative to the feather axis and cause perturbational cyclic feathering responses. These cyclic featherings result in aerodynamic forces which can be either stabilizing or destabilizing.

Again Figure 14 shows a typical mode shape or eigenvector for this type of coupled roll-regressive inplane bending rotor plunge mode. In this case, which happens to be stable but lightly damped, the collective feathering is at an amplitude and phase with respect to β_0, collective coning of the rotor, to act as a negative aerodynamic spring on the coning mode. Likewise, θ_0, collective blade angle, acts in conjunction with longitudinal cyclic blade angle in causing the rotor to pitch up. As can be seen from this figure, the rotor pitch response is lagging the collective blade angle response by approximately 45 degrees, whereas the coning response is actually leading the collective blade feathering response by a small phase angle.

Further examination of Figure 14 shows that the coning response, in addition to the rotor pitch response, is also being driven by longitudinal cyclic blade angle. It is interesting to note that the lateral inplane response is leading the rotor coning response by approximately 90°. Positive lift on the rotor combined with lateral cyclic blade angle causes a lateral inplane excitation. Positive lift results in an increase in lateral inplane bending to the left, which is aft bending on the aft blade and forward bending on the forward blade. The fact that the lateral inplane response is lagging its excitation by approximately 90° and the response is virtually pure regressive indicates that the inplane mode is very close to being in resonance. The inplane response, in coupling through the feathering axis, is a prime source of the longitudinal cyclic blade angle.

Even though the mode shown in Figure 14 is stable, one can see the potential for the mode to lose damping, which it does for the case shown, with increasing air speed. Lift and rotor disc rolling moment due to θ_0 and longitudinal cyclic both increase with air speed, as well as rotor disc pitching moment, due to coning of the rotor. These aerodynamic terms in conjunction with the inplane aerodynamics due to rotor coning are the principal coupling terms between rotor disc plunge and coupled roll regressive inplane response. It is through these terms and the choice of rotor/control system parameters that the coupled rotor vehicle system can be made to have adequate damping at high speed.

Figure 15 shows the effect of pitch flap coupling, blade product of inertia, control system collective stiffness, and blade sweep which, as indicated earlier, are key parameters in influencing the stability of this mode.

Studies are also presented for the stability characteristics of this type mode, for the direct flapping moment feedback type control system. In this system, one other parameter was intro-

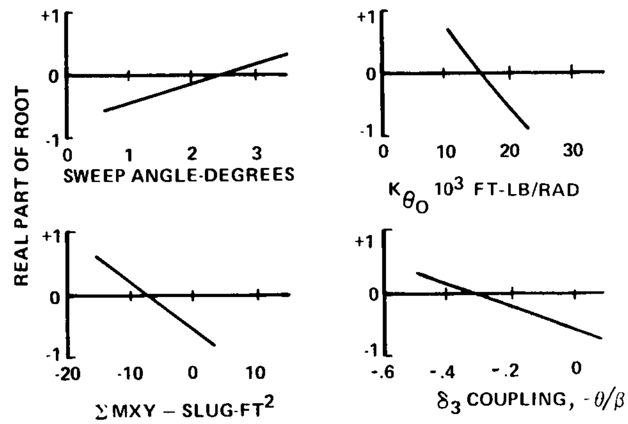

Figure 15. Effect of Parameters on Stability of Coupled Regressive Inplane Bending -- Roll -- Rotor Plunge Mode, V = 180 KEAS.

duced which has a significant effect on this mode. The parameter is the time constant or frequency response characteristic of the main power cyclic actuators. It is through these actuators that the control gyro commands cyclic blade feathering. As indicated earlier, a lag in the servo response results in a lag in the cyclic blade feathering, which can have an adverse effect on the stability of the hop mode. Inasmuch as the hingeless rotor depends on corrective control such as by stabilizing gyro to prevent pitchup at high speed, it is recognized that lag in the corrective control may lead to dynamic instability. This influence or effect is shown in Figure 16.

Figure 16 shows also the effect of δ_3 coupling as well as collective control system stiffness and inplane frequency.

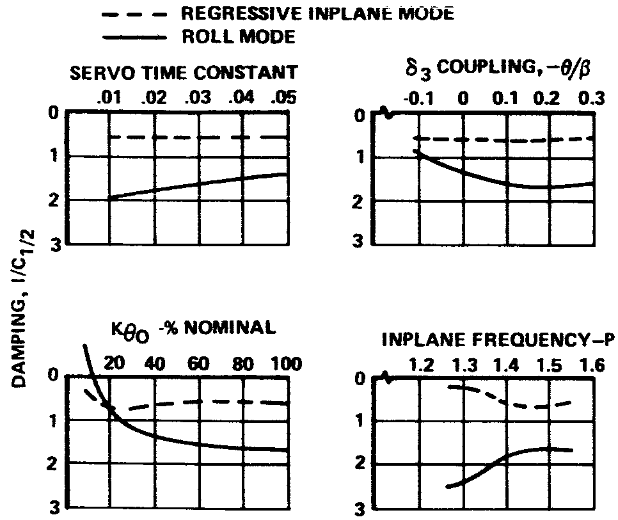

Figure 16. Effect of Parameters on Rotor Vehicle High Speed Dynamic Stability – Direct Flapping Moment Feedback Control System, V = 280 KEAS.

Experimental and Analytical Comparison

The experimental and analytical comparison is based upon data obtained during the development of the AH-56A. Early in the development of the AH-56A, a vehicle equipped with an experimental rotor system in which the blades had been modified by adding torsional doublers encountered a dynamic Hop phenomenon. The principal effect of the torsional doublers on this mode was to lower the inplane frequency and cause it to become more critically coupled with the rotor plunge/body roll mode. An analytical study was undertaken to define this phenomenon which extended the coupled rotor body linear analysis method available at that time and led to the development of the linear math model discussed earlier.

Figure 17 shows a comparison of the experimental and analytical data obtained for the vehicle configuration which initially encountered the Hop or coupled roll-regressive inplane bending-rotor plunge mode phenomenon. Additionally, the following table summarizes the normalized roll rate, chord moment and collective control load comparison obtained for this condition. In both the experimental and analytical data, the responses are due to a roll doublet excitation and are normalized on vehicle c.g. vertical acceleration.

	95% N_R		100% N_R	
	Test	Analysis	Test	Analysis
Roll Rate, deg/sec/g	20	19.1	15.5	9.2
Collective Control Load, lb/g	2700	2820	2370	2610
Inplane Moment, in. lb/g	424K	420K	770K	670K
Frequency Ratio, ω/Ω	0.52	0.51	0.54	0.54
Speed, KEAS	190	180	178	180

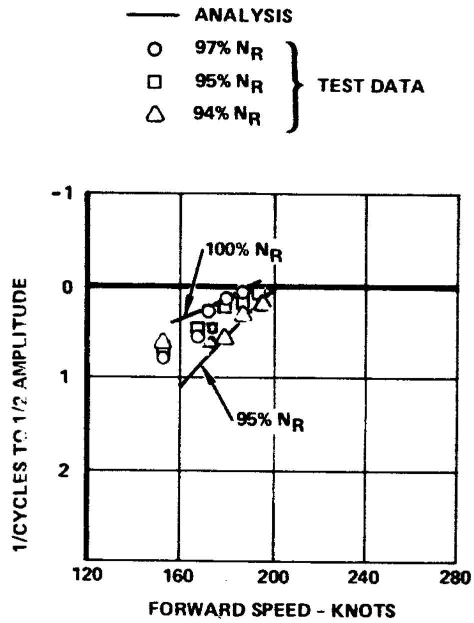

Figure 17. Comparison of Theory and Test Damping vs Speed For Initial Encounter With Hop on Early AH-56A Development Configuration.

The loss in damping was caused by a coalescing of the rotor body roll mode, the inplane mode (with both modes exciting blade cyclic feathering), and the rotor plunge mode. The terms discussed in the equation for $\partial L/\partial\theta_0$ previously given were such as to cause the rotor coning or plunge mode to decrease in frequency with increasing speed. In hover, the frequency of this mode was close to 1P. With increasing speed, the frequency dropped into the 0.5 to 0.6P frequency range in the 200-knot speed regime and coalesced with the lower-frequency body roll, regressive inplane modes. This resulted in the observed reduction in damping of the Hop mode with increasing forward speed.

A modification was made to the system which included approximately doubling the collective control system stiffness, reducing the pitch-flap coupling from a value of 0.27 to a value of 0.05 at a collective blade angle of 5 degrees, increasing the blade sweep from 2.5 to 4 degrees sweep forward, and reducing the inplane frequency from approximately 1.55P to 1.4P. The reduction in pitch-flap coupling and the increase in collective control system stiffness were done specifcally to eliminate the Hop phenomenon within the flight envelope. The increase in sweep and reduction in inplane frequency were done to improve certain handling quality characteristics. These changes resulted in the frequency of the collective coning mode remaining virtually constant with increasing forward speed. The changes also resulted in the coupled roll regressive inplane mode remaining at nearly a constant frequency with speed. The resultant effect was to increase significantly the speed at which the predicted coupling between these modes became critical.

Figure 18 shows a comparison of the predicted damping of the coupled roll-regressive inplane bending mode with test results for this modified configuration as a function of speed. This figure indicates fairly good agreement between the measured and predicted values. Figure 19 shows a comparison between the predicted and measured chord-bending response due to a lateral stick doublet at 170 knots. As can be seen, good agreement between the two responses was obtained.

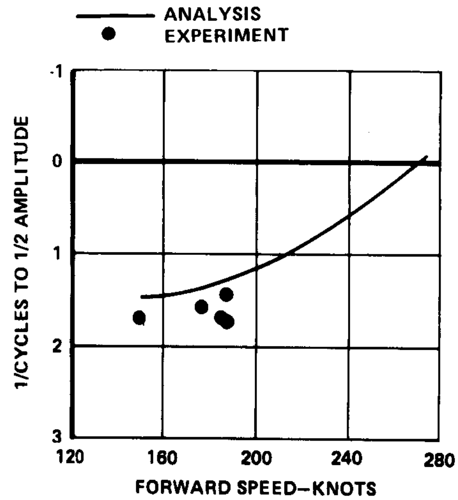

Figure 18. Comparison of Theory and Test Damping vs Speed For Modified Rotor – Control Configuration.

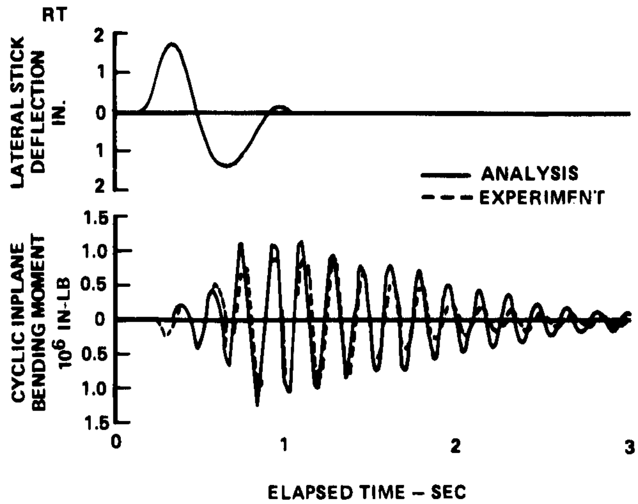

Figure 19. Comparison of Experimental and Analytical Transient Chord Bending Response Due to Lateral Stick Doublet, V = 175 KN.

The rotor system was then modified to increase the blade droop from 2°20' to 3°10' (Reference 5). This configuration change had little effect on the high-speed coupled roll-regressive inplane mode stability characteristics, and the vehicle was subsequently flown to 240 knots' true airspeed with no indication of a high-speed dynamic stability problem.

This latter configuration change however, did, lower the damping of the coupled roll regressive inplane mode in hover and low-speed flight because of the increase in blade droop. The mode was characterized by roll oscillation and inplane response due to pilot lateral stick inputs. The frequency of the mode was approximately 1 Hz. This, coupled with the roll oscillation of the airframe, made the mode susceptible to pilot coupled oscillation.

Figure 20 shows a comparison of the experimentally determined and predicted roots of the coupled roll-regressive inplane mode for the two different blade-droop configurations. Again, fairly good agreement is seen between experimental and analytical results.

A major revision was then made to the control system which replaced the feathering-moment feedback system with a direct flapping-moment feedback system. This change necessitated placing the main cyclic power actuators between the control gyro and blade feathering instead of between the pilot and the gyro.

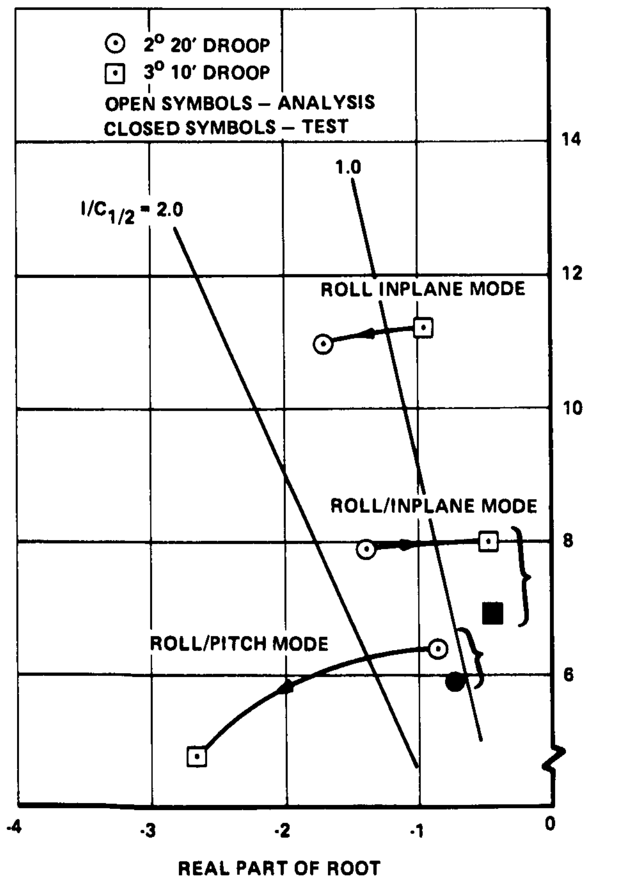

Figure 20. Effect of Droop Angle on Low Speed Roll Mode Stability – Comparison of Experiment and Analysis, V = 20 KN.

The rotor and control system parameters were selected to provide a system that was completely free of either the undesirable Hop or roll mode characteristics discussed earlier. The various parameters, which were established to be critical by extensive parametric studies, using the linear analysis method adapted to computer graphics, were established and controlled very carefully. These parameters included both cyclic and collective pitch flap coupling, inplane frequency, main cyclic power actuator time constant, gyro to blade-feathering gear ratio and phasing, blade sweep and droop, and shaft-moment to gyro-moment feedback ratio.

The initial configuration, when tested on the whirl tower, was determined to have met all criteria except that the inplane frequency was below the criteria value by about 0.05P, or 0.21 Hz. Some limited flight testing was performed with this configuration to validate the criterion, after which the final configuration, conforming to the original criteria, was reached by removing 6.8 pounds tip weight from each blade. The results with both configurations, are discussed in the following.

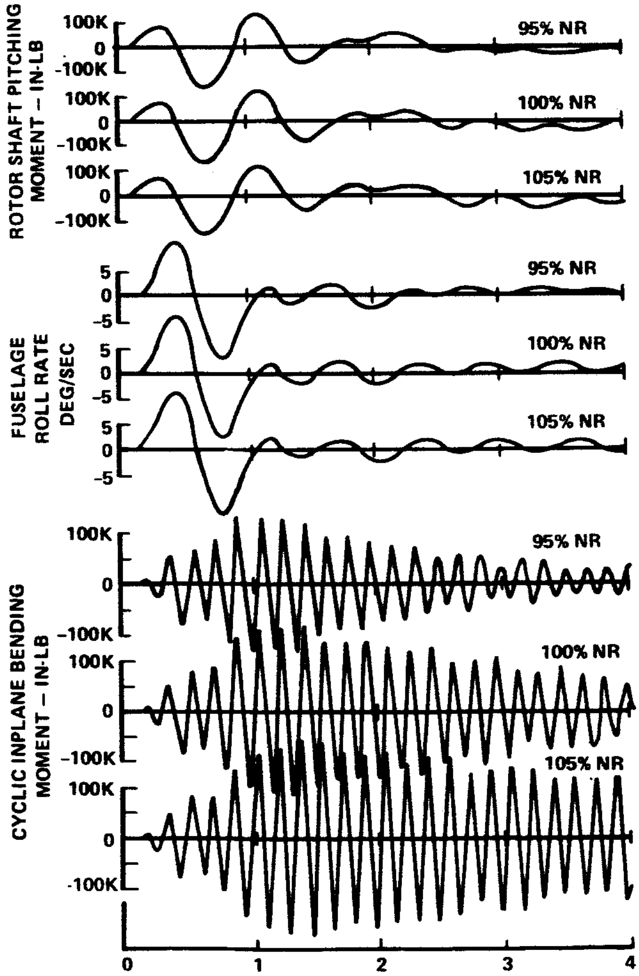

Figure 21. Rotor Speed Effect on Transient Response Due to Lateral Stick Doublet, V = 160 KEAS.

Figure 21 shows the effect of predicted rotor vehicle responses as a function of rotor speed for a lg, 160-knot flight condition with the degraded inplane frequency. The excitation in each case is a lateral stick doublet at 1.5 Hz which is the technique used in flight test for exciting coupled rotor-body dynamic modes to determine their stability characteristics.

It is noted that with increasing rotor speed, the damping of all responses decreases, and the magnitude of the pitch response of the rotor disc in the mode increases. This was noted by the pilot as a characteristic of the mode in that, with similar excitations, the rotor disc tip path oscillations would be imperceptible at lower rotor speeds but would become increasingly responsive at higher rotor speeds.

Figure 22 shows a comparison between the calculated roots and the experimentally determined damping and frequency for this configuration at 160 knot airspeed. The actual vehicle responses contain a varying mix of the two roots, increasing in inplane content with increasing rpm.

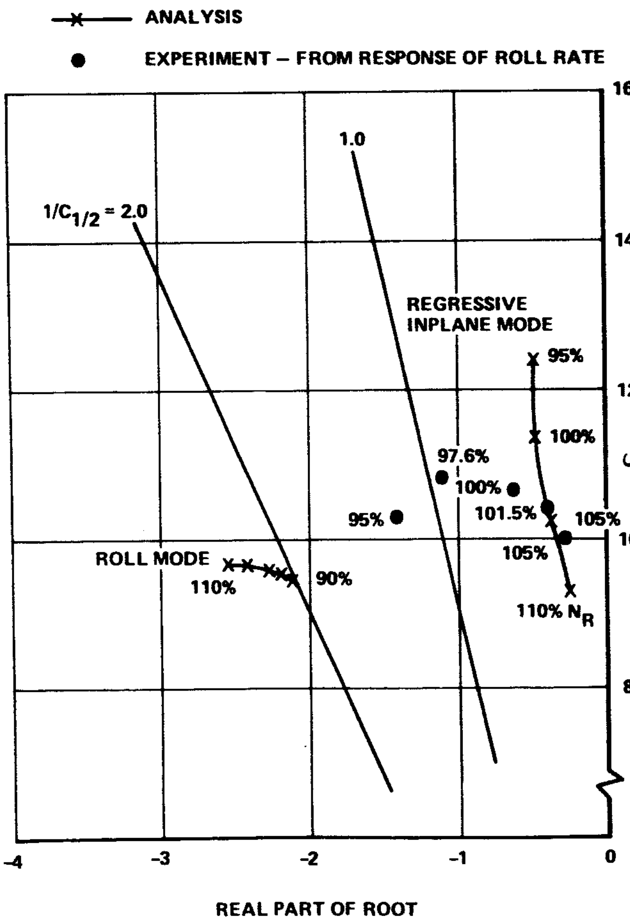

Figure 22. Locus of Roots – Comparison of Test and Analysis – Reduced Inplane Frequency, V = 160 KN.

Figure 23 shows the predicted effect of increasing the inplane frequency by removal of tip weight on the frequency and damping of the coupled roll-regressive inplane modes. Figure 24 shows the corresponding predicted transient response at 105 percent of normal rotor speed with the tip weight removed. The comparison in roots shown on Figure 23 and the comparison of the 105 percent rpm transient response in Figure 24 with the 95 and 105 percent rpm cases in Figure 22 show a significant improvement in the damping and transient response characteristics at rotor overspeed for the configuration with the tip weight removed to give the desired inplane frequency placement.

For the final configuration, Figure 25 shows a comparison of the measured and predicted damping as a function of forward speed. The data show good agreement in measured and predicted damping levels from hover through transition and in higher-speed flight. Experimental data on damping of the regressive inplane mode consist of only one point because even though the mode was not excessively damped, it was extremely difficult to excite by the pilot with lateral stick doublet type excitations to amplitudes sufficiently large to obtain a reliable determination of its stability. This final configuration was tested over a very large flight envelope covering speeds to 220 knots true airspeed and maneuvering load factors from -0.2g to 2.6g in the 180 to 200-knot true airspeed flight regime. The pilot reported "excellent" to "deadbeat" damping and minimal responses to air turbulence in high-speed flight.

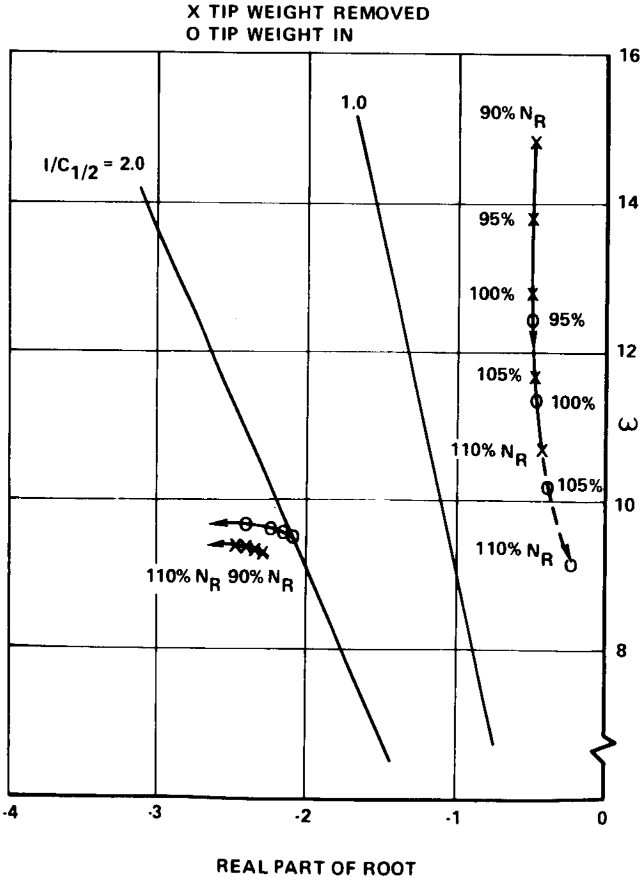

Figure 23. Locus of Roots – Effect of Tip Weight, V = 160 KEAS.

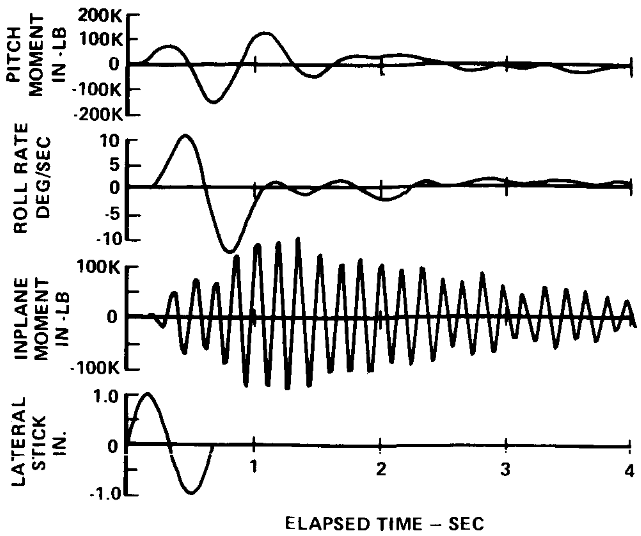

Figure 24. Transient Response Due to Lateral Stick Doublet – Tip Weight Removed, V = 160 KEAS.

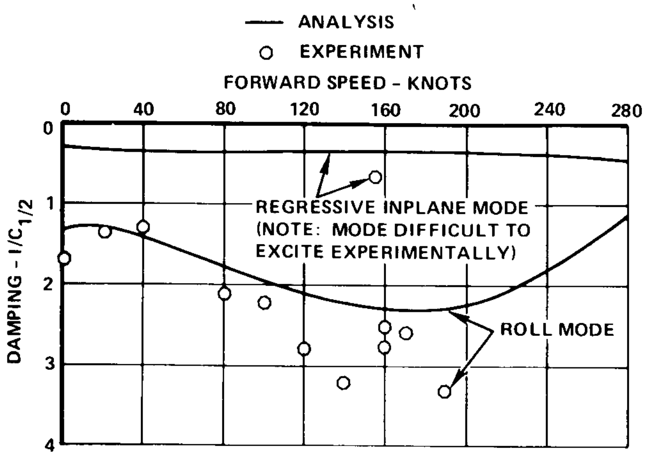

Figure 25. Damping vs Forward Speed – Comparison of Test and Analysis For Final AH-56A (AMCS) Configuration.

Conclusions

Several types of modes can exist in a stiff inplane hingeless rotor which involve coupling with the regressive inplane mode. These include phenomena where the inplane mode is not well coupled with the rest of the system, phenomena where the inplane mode and body roll mode are the primary participants, and even phenomena where the rotor plunge mode is heavily involved in the total system dynamic behavior. These phenomena, particularly the first two types, are not limited to any particular flight regime but can be critical in either stability or response in either low- or high-speed flight or can exhibit characteristics which are virtually independent of speed. Each of the modes is treatable by analysis, and certain parameters such as blade droop, control system stiffness, pitch-flap and pitch-lag couplings, blade sweep, blade product of inertia, inplane frequency and control system parameters are influential in controlling the stability and response characteristics of these modes. Additionally, a totally satisfactory system can be achieved without recourse to auxiliary damping devices.

References

1. Burkam, J.E.; Miao, Wen-Liu; EXPLORATION OF AEROELASTIC STABILITY BOUNDARIES WITH A SOFT-IN-PLANE HINGELESS-ROTOR MODEL, Journal of the American Helicopter Society, Volume 17, Number 4, October 1972

2. Huber, H.; EFFECT OF TORSION-FLAP-LAG COUPLING ON HINGELESS ROTOR STABILITY; Preprint No. 731, Presented at the 29th Annual National Forum, Washington, D.C., May 1973

3. Donham, R.E.; Cardinal, S.V.; Sachs, I.B.; GROUND AND AIR RESONANCE CHARACTERISTICS OF A SOFT IN-INPLANE RIGID-ROTOR SYSTEM, Journal of the American Helicopter Society, Volume 14, Number 4, October 1969

4. Potthast, A.J.; Blaha, J.T.; HANDLING QUALITIES COMPARISON OF TWO HINGELESS ROTOR CONTROL SYSTEM DESIGNS, Preprint No. 741, Presented at the AHS 29th Annual National Forum, Washington, D.C., May 1973

5. Anderson, W.D.; INVESTIGATION OF REACTIONLESS MODE STABILITY CHARACTERISTICS OF A STIFF INPLANE HINGELESS ROTOR SYSTEM, Preprint No. 734, Presented at the AHS 29th Annual National Forum, Washington, D.C., May 1973

6. Chou, P.C.; PITCH-LAG INSTABILITY OF HELICOPTER ROTORS, Journal of the American Helicopter Society, Volume 3, Number 1, July 1958.