PARAMETRIC STUDY OF THE AEROELASTIC STABILITY OF A BEARINGLESS ROTOR

W. EUAN HOOPER
Director, Vehicle Technology
Boeing Vertol Company
Philadelphia, Pa.

ABSTRACT

A trade study has been conducted to illustrate the sensitivity of the aeroelastic stability of a bearingless main rotor to the rotor hub coupling parameters that are available for the designer. The results are presented over the complete range of rotor speed and collective pitch available and the effects on air resonance of the 6 beam installation angles are compared together with the results of offsetting the cuff snubber attachment. The major part of the study was conducted using the FLAIR analysis which incorporates a uniform representation of the flexbeam. Results are also shown for a modified version of FLAIR in which the uniform beam is replaced by a member having the geometric tailoring resulting from structural optimization.

1. INTRODUCTION

The control of the stability of bearingless rotors by introducing coupling between blade flap, lag, and pitch freedoms has been frequently addressed in the literature in recent years. One of the most powerful stabilizing parameters has been identified as negative pitch-lag coupling, a powerful version of which was successfully demonstrated in full scale ground and flight experience on the YUH-61A.

In support of the Boeing Vertol/Army/NASA ITR Preliminary Design Program, a study was initiated to quantify in a consistent manner the sensitivity of the beam installation angles. This then served as a base to evaluate an alternate concept of adding stability by introducing a vertical offset to the cuff snubber. This offset causes favorable mechanical lag-pitch coupling while avoiding inducing unfavorable bending moments in the flexbeam. Further, since the coupling between blade freedoms is all important in determining stability, a comparison of the effect of rigorously representing the beam nonuniformity, versus the assumption of a uniform beam, was also undertaken.

The FLAIR program (written by Dewey Hodges of the U.S. Army Aeromechanics Lab) was chosen for the study because of the simplicity of representation of the major elements while employing an accurately modelled, but uniform, flexbeam. The program was well documented (Ref. 4) and thus amenable to the modifications considered necessary for the study.

Presented at the 2nd Decennial Specialists Meeting on Rotorcraft Dynamics.
Ames Research Center, Moffett Field, CA
Nov 7-9, 1984.

2. THE FLAIR ANALYTICAL MODEL

The FLAIR program models the fuselage and blades as rigid bodies separated by the flexbeam elements. The fuselage has 4 degrees of freedom (longitudinal, lateral, roll and pitch). Each blade is rigid and is attached to a uniform flexbeam extending from the hub offset to the blade attachment point. The 6 freedoms at the end of each flexbeam are:

u	axial
v	chordwise
w	flapwise
ζ	lag angle
β	flap angle
θ	pitch angle

expressed relative to the axis system at the root of the beam. In an air resonance case the beams are the only springs in the system as the fuselage freedoms are unrestrained to ground. In a ground resonance case, additional springs are inserted between fuselage and ground to represent the landing gear. The flex beams are axially loaded by the centrifugal forces and thus an iterative solution technique is required for the resulting nonlinear equations.

The beam and control system equations are rigorously modelled making no small angle assumptions and so the program was considered well suited to the intended trade study. The major modifications made to the program to facilitate the study included:

1. The input and output were made dimensional since the study was conducted in dimensional terms.

2. An additional control configuration (config. 5) was added to the 4 described in Ref. 4, Figs. 4-6, to allow the cuff snubber to be moved to points other than centered on the flex beam.

3. Additional outputs were added to illustrate the steady and vibratory deflected shapes of all freedoms.

4. A nonuniform beam was modelled to assess the validity of the uniform beam assumption.

The physical model used for the study was the wind tunnel model fabricated for the ITR program. In general arrangement the model was similar to the model described in Ref. 5 in that it is a 6 ft. dia. 4 bladed bearingless rotor driven by 2 electric motors on a fuselage which is gimballed in pitch and roll about the fuselage CG. The model is Froude scaled (1/8) from the Hughes AH-64 helicopter for which the Boeing Vertol ITR is designed. Unlike the Ref. 5 model the blades are attached by 6 inch long structurally tailored flexbeams rather than localized flexures. In all stability respects except the flexbeam design the fuselage and blades are conventional and the trade study concentrates on the design parameters for the flexbeam and cuff. Throughout the study blade structural damping is assumed to be 0.5% critical and fuselage damping for ground resonance is assumed to be zero.

3. THE MODES OF AIR AND GROUND RESONANCE

To illustrate the modes which affect the stability of a bearingless rotor the natural frequencies versus RPM are shown in Fig. 1 for 3 configurations.

a. Fixed Hub - no coupling into the fuselage and each blade is uncoupled from all other blades. Since each beam has 6 degrees of freedom the generalized coordinate transformation from rotating to fixed system axes, (Ref.2) omitting the collective and differential modes, results in 12 degrees of freedom for FLAIR. The eigenvalue analysis then gives 24 roots which occur in 12 complex pairs and the 4 most significant roots are labelled in Fig. 1 a.

b. Air Resonance - to simulate air resonance with a model, without being completely free flying, the fuselage is gimballed in pitch and roll about the fuselage CG. This adds 2 more degrees of freedom to the equations (now 14 total) and is a justifiable approximation for modelling of both air and ground resonance. Even in the latter case, when pitch and roll springs to ground are introduced, the nodes of the roll and pitch modes have to lie between the fuselage CG and a point k^2/h above the CG, where k is the radius of gyration and h is the height of the CG above the ground, Ref. (1).

   With 14 degrees of freedom the eigenvalue analysis now gives 28 roots of which:

   - 24 occur in 12 complex pairs and are directly related to the 12 pairs of the fixed hub case.
   - 2 have zero frequencies, in the nominal RPM range, resulting from the roll and pitch freedoms having no springs to ground
   - and 2 more occur in an additional complex pair having a very low frequency. This root results from

NATURAL FREQUENCIES WITH BEAM ANGLES & CUFF OFFSETS = 0.0 COLL = 10.0°

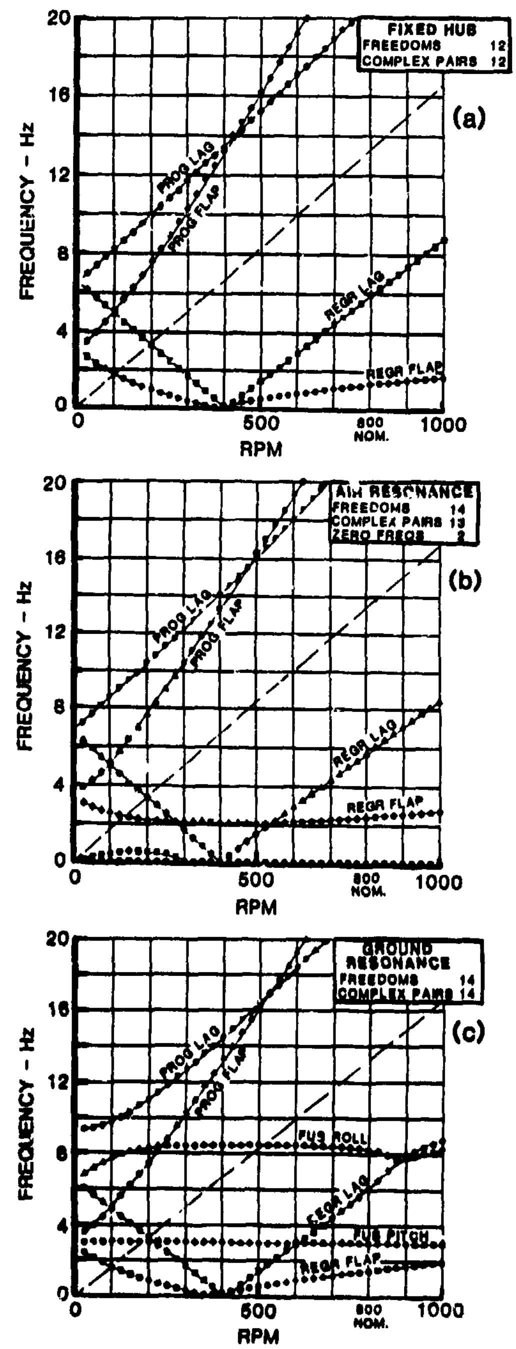


Fig. 1 Natural frequencies for fixed hub, air and ground resonance

having 2 freedoms with dampers (aero) but no springs to ground. Since the rotor strongly couples the 2 freedoms, the two 1st order lag equations then result in one 2nd order root with a very low frequency. (For a further discussion of these roots see the Appendix).

References have been made in earlier papers to 'the roll mode' and 'the pitch mode' of the fuselage in air resonance analyses as modes additional to the regressing flap mode (which couples with fuselage pitch and roll) identified in Fig. 1 b. But this paper takes issue with that characterization and invites further discussion.

c. Ground Resonance. By adding pitch and roll springs to ground, the 2 zero frequencies are removed and the 14 degrees of freedom now result in 14 complex pairs of roots all of which can be characterized as shown in Fig. 1 c.

The values of the springs added to the hover stability model approximated a heavyweight operating condition of the AH-64 and ensure that the pitch and roll mode crossings with the lag regressing mode were within the RPM range of study for the purposes of test/theory correlation.

Quantifying the stability of these equations presents a communication problem because while many engineers can readily identify with '% critical' as a measure of damping, this concept falls down when the associated frequency goes to zero. The lag regressing frequency of a bearingless rotor blade is necessarily equal to 1/rev in the rotating system (zero in the fixed system) at an RPM typically below operating RPM. Thus '% critical' goes to infinity at this RPM. This not only makes it difficult to plot out also gives a false sense of security.

An alternative measure of damping is the dimensional (1/sec) 'decrement' given by the real part of the complex root. This allows a smooth continuum of data to be plotted throughout the RPM range. To give a number which is independent of scale the real part can be normalized by the nominal rotor angular velocity. This approach was selected for this paper and the ratio of (- real part)/(nominal rotor rad/sec) is called DECREMENT RATIO.

In Fig. 2 both measures of damping are portrayed for the 3 cases of Fig. 1. The mode of most interest, regressing lag, is seen to go to infinite '% critical' at 400 RPM in each case, and this is avoided when plotting decrement ratio. Note that the decrement ratio of both regressing and progressing lag are equivalent for the fixed hub case. As will be seen later the regressing flap mode is heavily damped and off scale.

The air resonance case (Fig. 2b) shows the typical trend of a bearingless rotor, with no provers[illegible] couplings, to go unstable with increasing RPM at high collective pitch.

The ground resonance case (Fig. 2c) shows the regressing lag mode briefly coupling with fuselage pitch to give an instability at 600 RPM and giving a major instability at 900 RPM when coupling with the roll mode.

To understand the factors that affect the stability of the equations the eigenvectors from the FLAIR analysis were transformed back into the rotating system to illustrate the actual motion of the blade, relative to the hub plane, at every eigenvalue. Using the relationships defined in Ref. (2), the motion of the No. 1 blade tip is calculated from the 8 fixed system eigenvector cosine and sine components.

beam chordwise defl	v_c, v_s
beam chordwise slope	$\zeta_c\ \zeta_s$
beam flapwise defl	w_c, w_s
beam flapwise slope	β_c, β_s

The motion of No. 1 tip can then be portrayed as a Lissajous pattern as viewed along the blade looking inboard towards the hub. Movement of the blade is to the right as shown by the horizontal arrows and the arrowhead on the ellipse shows the direction of rotation of the locus. Also shown is the location on the locus and the magnitude of the maximum nose up pitch angle (θ) occurring. In Fig. 3 these blade tip loci are shown for the reference case of beam angles and cuff offsets = 0 and for collective = -2.5 deg. The data are normalized for 10° of the tip motion (flap or lag) expressed as an angle subtended about the hub center. In the lower LH corner of each tip locus box is shown the rotating system frequencies.

Below each blade tip locus is shown a superposition of:

a. The inplane CG locus. This is the fixed system locus of the rotor blade CG resulting from inplane depatterning of the blades caused by the regressing and progressing lag motions. (To simplify the plotting scales, which are all ± 10°, these loci are normalized to the magnitude of the blade tip lag motion above).

b. The hub locus. This expresses the motion of the fuselage which in the lag modes results largely from the inplane CG coupling.

The fixed system '% critical' damping is given in the CG and hub boxes together with the fixed system frequencies.

FIXED SYSTEM DAMPING WITH BEAM ANGLES & CUFF OFFSETS = 0.0 COLL = 10.0°

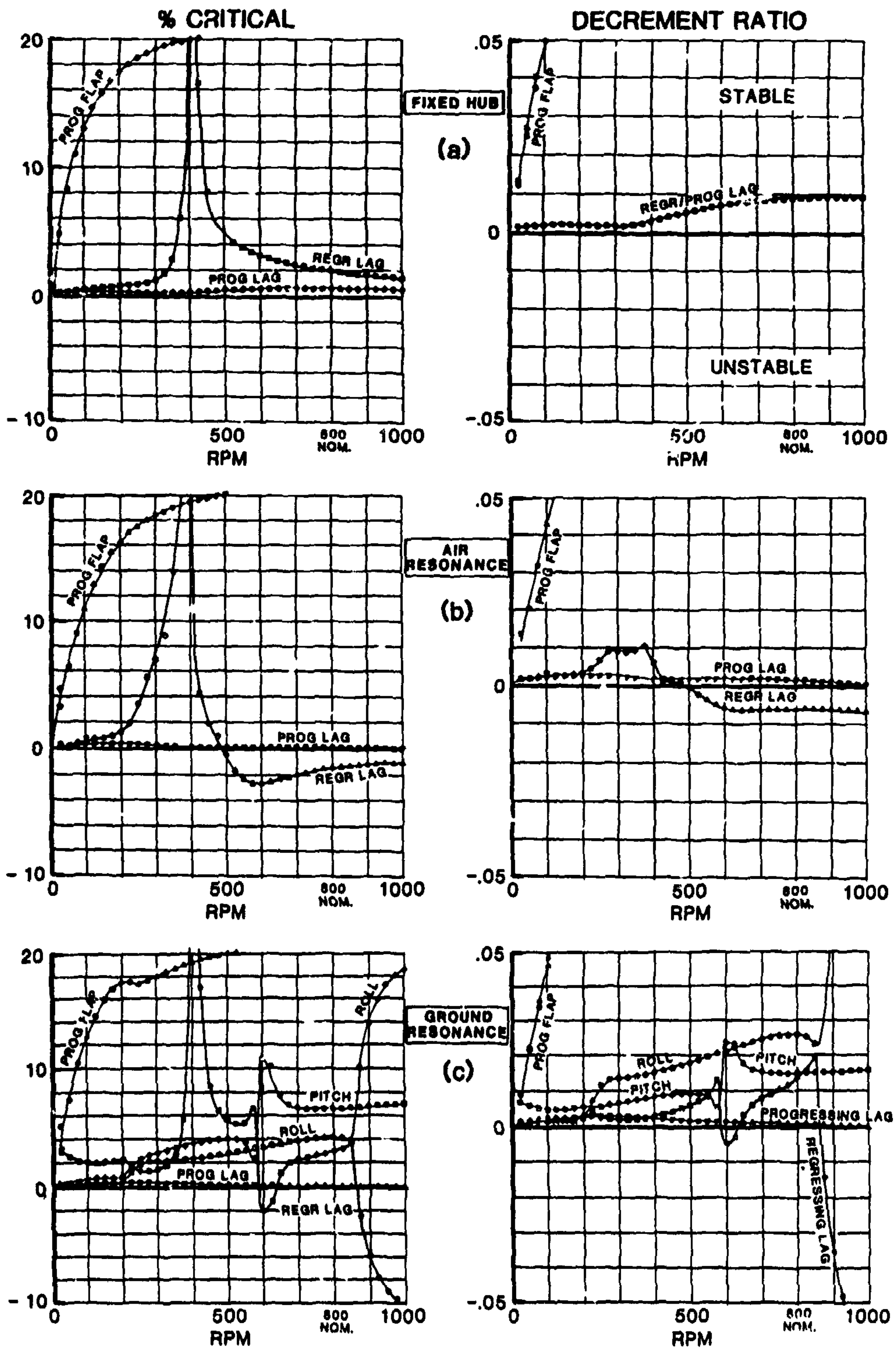


Fig. 2 Damping for fixed hub, air and ground resonance

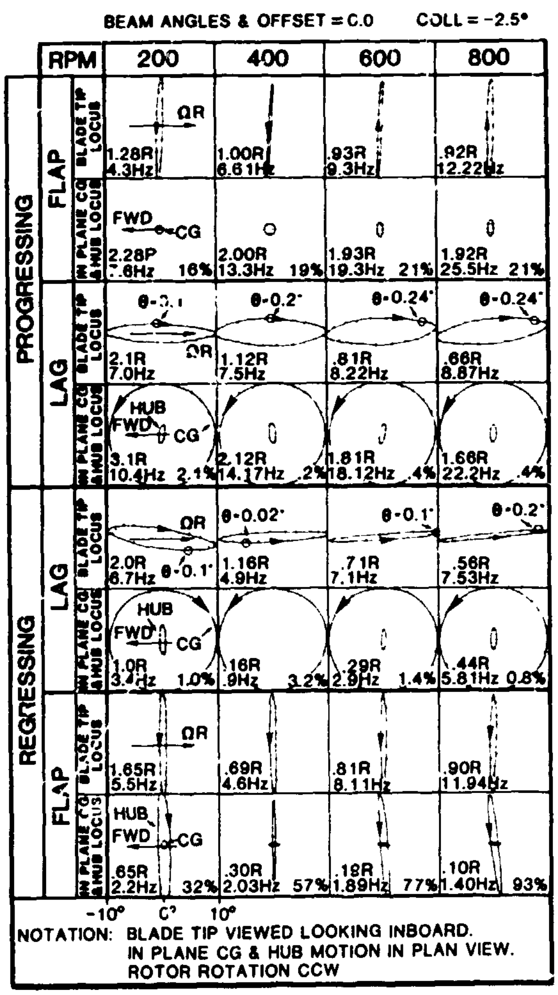


Fig. 3 Effect of RPM sweep on blade modes, collective = -2.5 deg.

Generally the blade motions do not undergo major changes of mode shape and points to note are -

- the largest hub motions are associated with the regressing flap mode.
- blade pitch motions are small (<1° for 10° of tip motions) and inconsistently phased to flap and lag.
- the largest inplane CG excitations result from the 2 lag modes.
- the predominant fuselage response is in roll for all modes.
- the loci of the flap modes are tilted forwards as might be expected from -2.5° collective.

Fig. 4 shows the same format for 10° collective, in which the lag regressing mode now goes unstable above 600 RPM but no significant change occurs in the mode shapes. Note -

- the general tilt aft of all the blade tip loci due to the high collective pitch.
- still low (<1°) pitch motion inconsistently phased to lag and flap.

Later this same format will be shown for a case that has been stabilized.

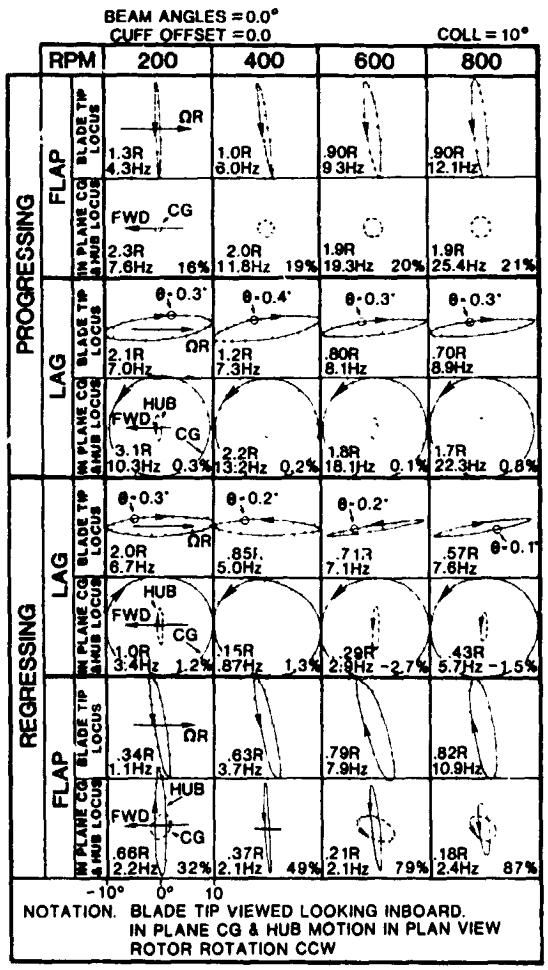


Fig. 4 Effect of RPM sweep on blade modes, collective = +10 deg.

4. THE EFFECT OF BEAM ANGLES ON STABILITY

Much previous literature and testing has established that the coupling introduced by the hub-to-beam and beam-to-blade mounting angles can strongly influence the coupling between blade lag, flap, and pitch freedoms and affect stability. In order to have a consistent display of the effects of all 6 angles to use as a base for selecting the

ITR design a systematic study was made and the results are presented below.

Since a knowledge of the stability was desired over the complete available RPM range (0 to 1000) and collective pitch range (-2.5° to 10°) a surface plot was established portraying RPM and collective on the x-y axes and the damping 'decrement ratio' on the Z axis. Fig. 5 shows the baseline case in which all 6 beam angles are zero and the cuff offset is zero (i.e. on the center line of the beam). At -2.5° collective the mode is stable (pos.) throughout but with increasing collective the decrement ratio is seen to go unstable (neg.) above 450 RPM in typical fashion is as previously seen in the literature (Ref. (3). Below the damping plot in Fig. 5 are shown the beam deflections and the blade tip loci at the nominal 800 RPM for the extreme values of collective pitch. Note that because of the uniform beam modelled by the FLAIR analysis the pitch deflection of the beam is almost a straight line with unrealistically high slopes at either end, while the flapping deflection shows more realistic curvatures.

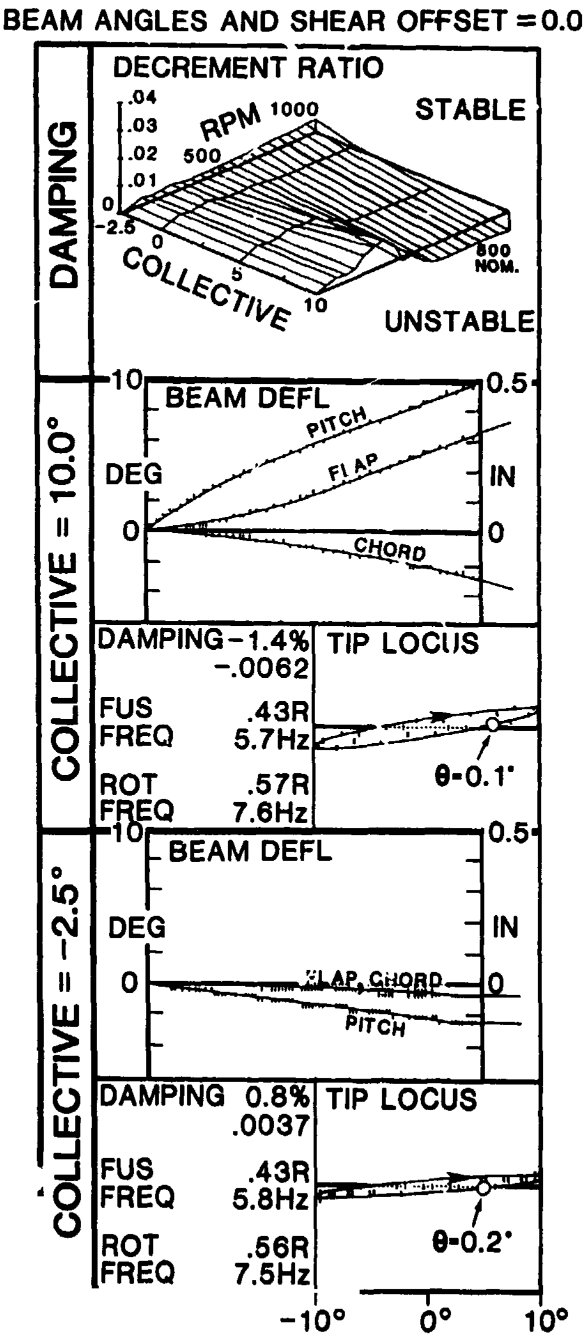


Fig. 5 Damping and modes for baseline air resonance case

Fig. 6 shows the effect of individually introducing 5 degree clevises into the hub/beam attachment. Examination of the beam deflection plots shows major changes in the resultant coupling between blade freedoms and yet none of the cases show any significant change in stability, in the problem region of high collective pitch.

Fig. 7 shows results of similar 5 degree clevises introduced at the beam/blade attachments and now it is seen that outboard coning (OUTCON) has a powerful stabilizing effect. Note that the blade pitch motion now exceeds 4° and that maximum nose up pitch occurs at maximum lag.

Considering the nonlinear nature of the stability equations the beam angles were next changed in conjugate pairs to see if other effects were introduced. In Fig. 8 it is seen that both beam deflections and blade tip loci are essentially superpositions of the previous 2 figures, taking signs into account.

5. THE EFFECT OF OTHER PARAMETERS ON STABILITY

In contemporary designs the inboard shear restraint of the cuff has been typically located on the flexure axis (UH-60 tail rotor, Model 680 main rotor). But offsetting this point vertically provides a means of introducing the desirable lag pitch coupling observed from the use of outboard coning in Fig. 7. Fig. 9 shows the result of moving the cuff below and above the flexure by 0.5 inch or 8.3% of the beam length. It is seen to have a powerful effect on the stability at high collective pitch. Again note that with positive offset the maximum blade pitch angle occurs at maximum lag as with outboard coning.

Knowing the importance of the crossover of the lag and flap regressing frequencies on stability, the effect of varying the lag frequency around the nominal value was assessed. By arbitrarily varying the chordwise stiffness (EICHD) up and down the coupled lag frequencies were changed from 0.57 down to 0.51/rev and up to 0.66/rev

ORIGINAL PAGE IS
OF POOR QUALITY

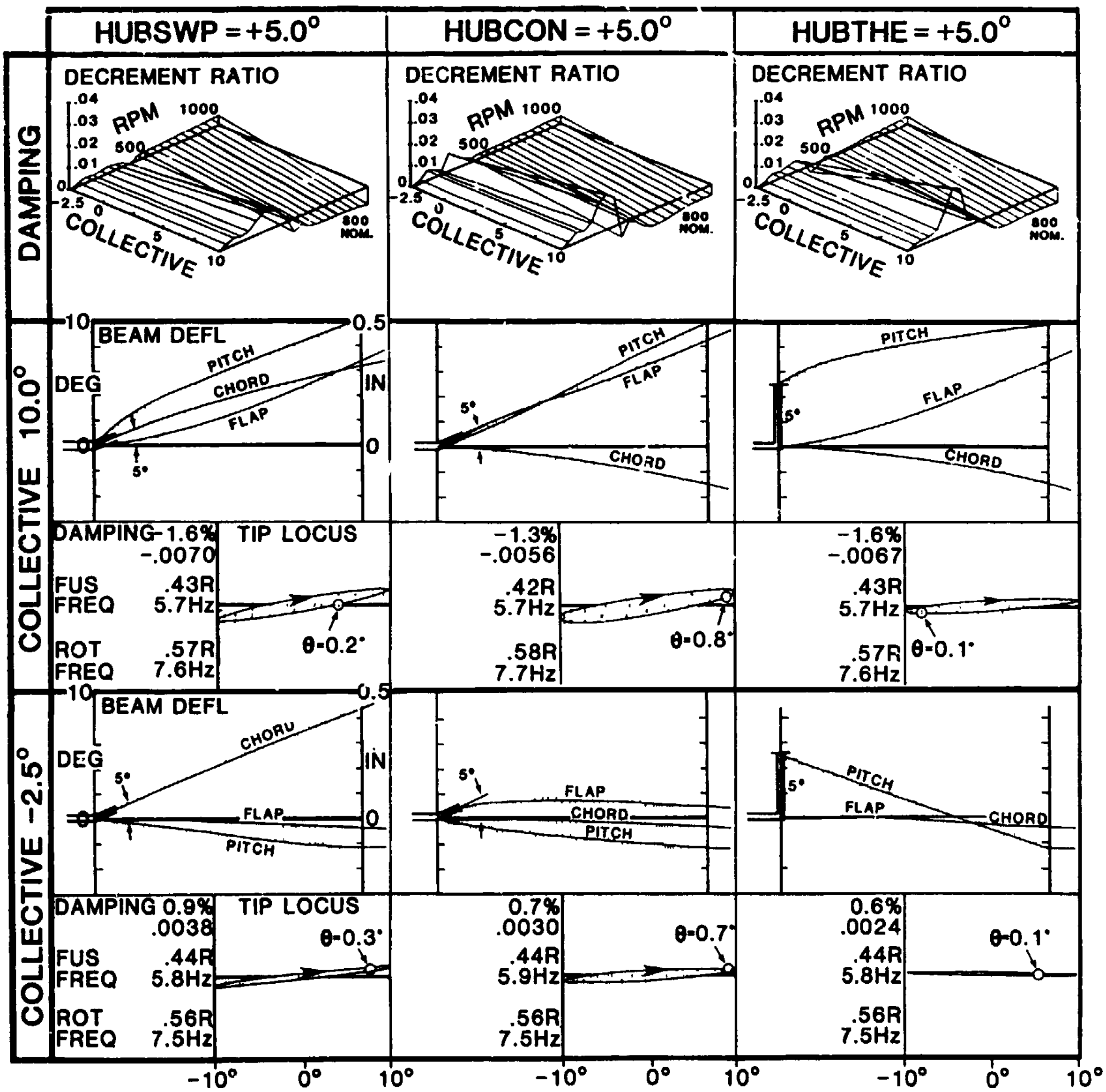


Fig. 6 Effect of hub-beam angles on damping and modes

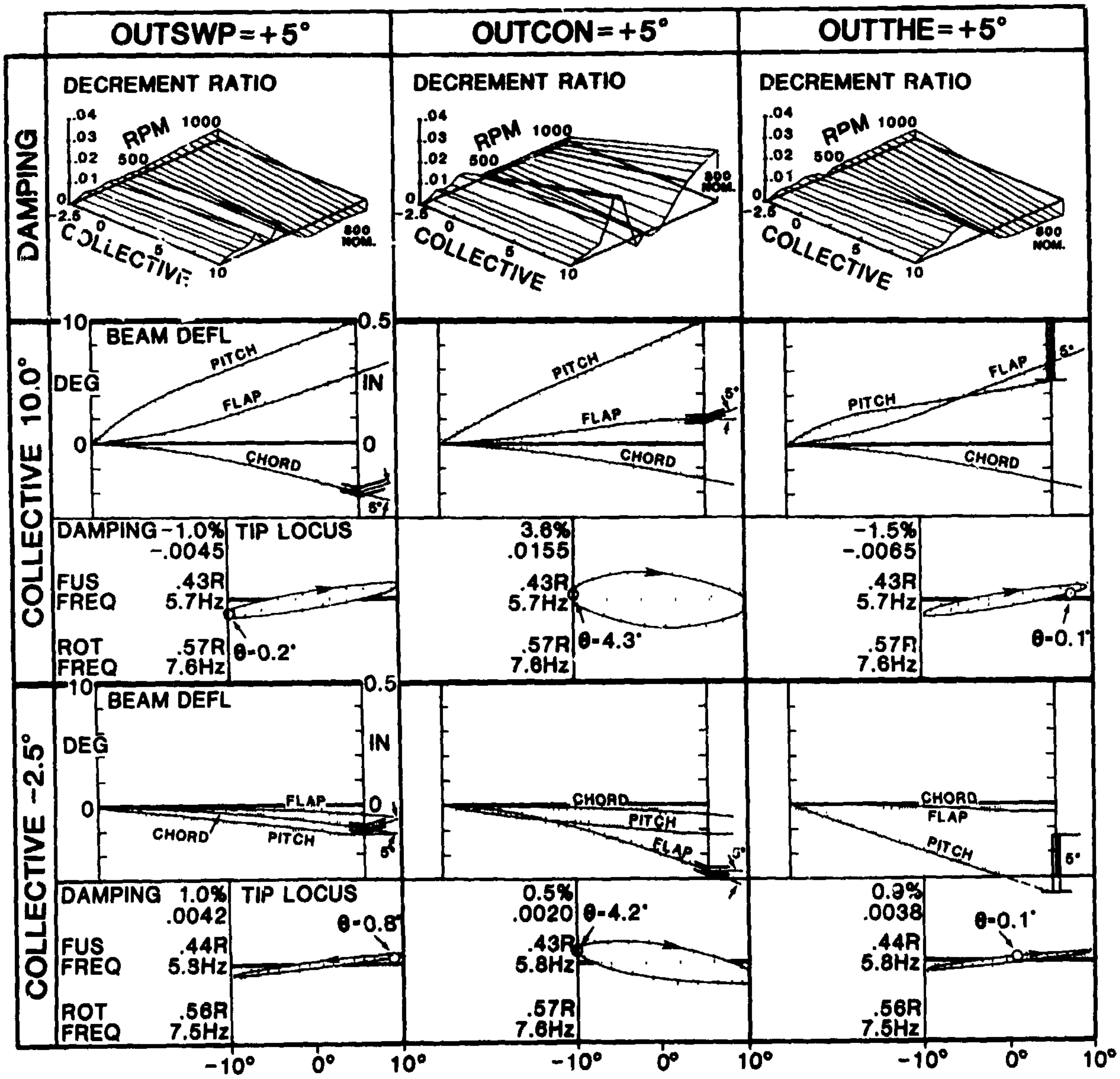


Fig. 7 Effect of beam-blade angles on damping and modes

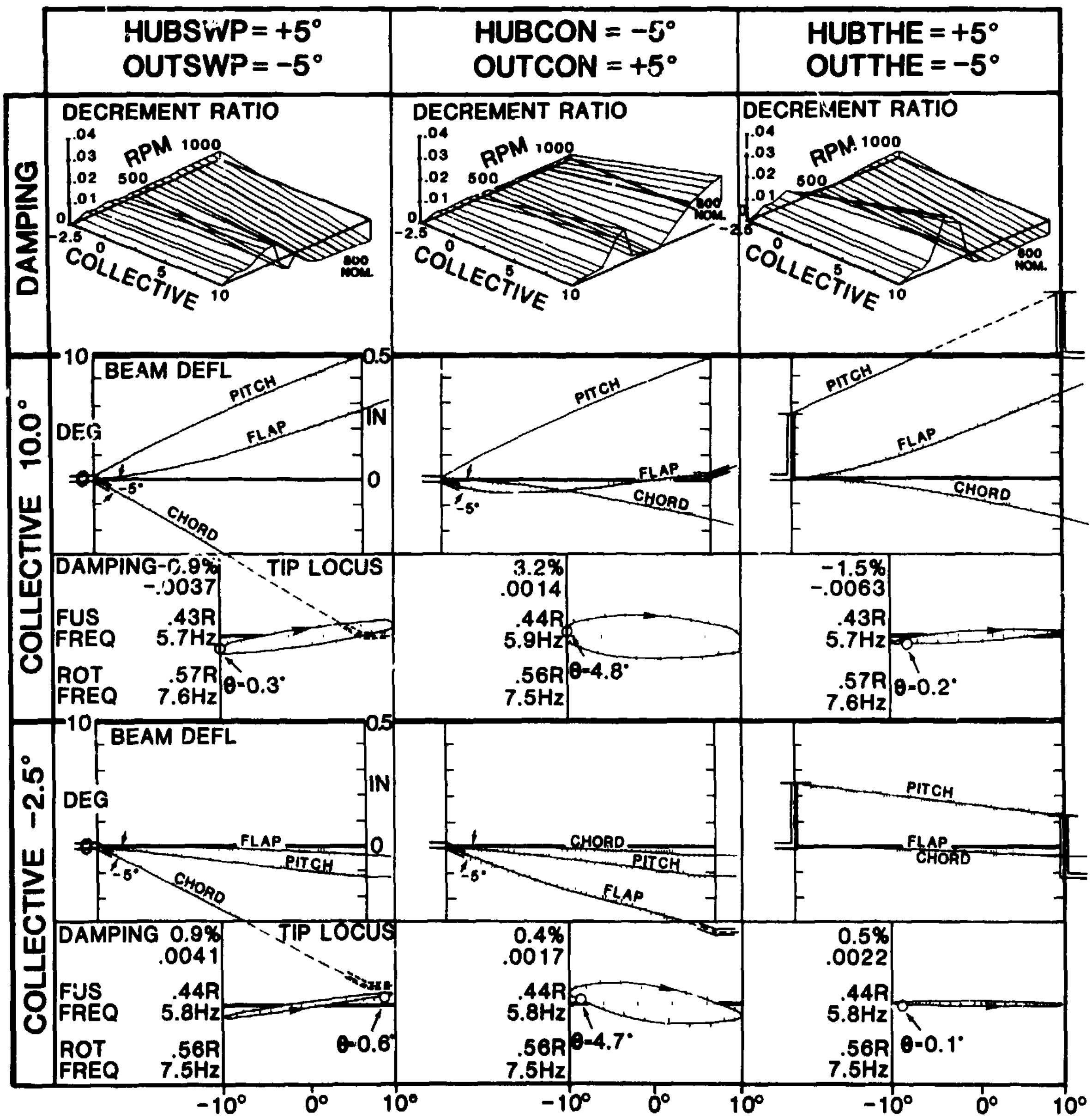


Fig. 8 Effect of changing beam angles in pairs on damping and modes

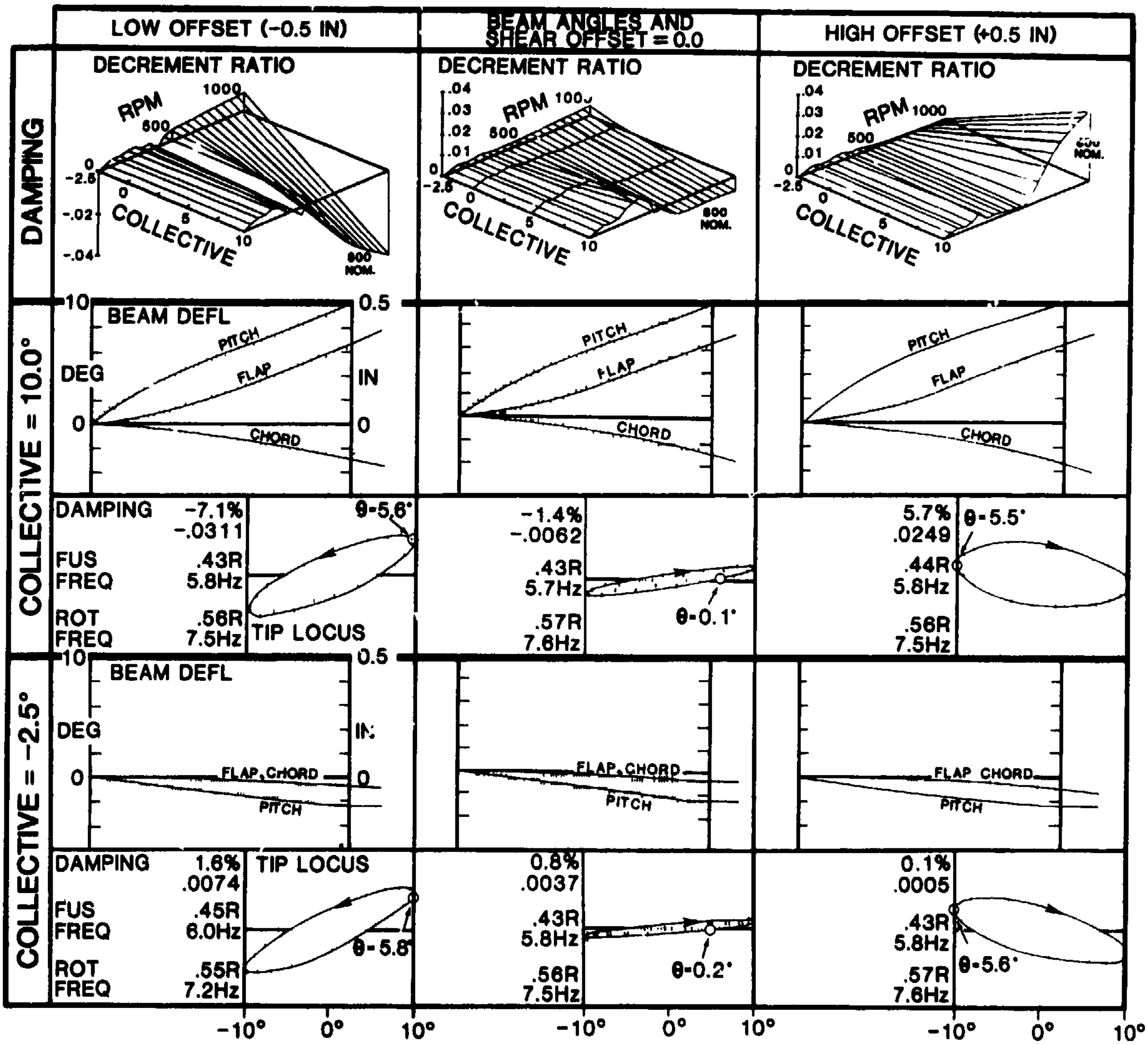


Fig. 9 Effect of cuff shear vertical offset on damping and modes

and as shown in Fig. 10 the effect on the damping decrement ratio was negligible although it does have the effect of moving the rotor speeds for instability up and down.

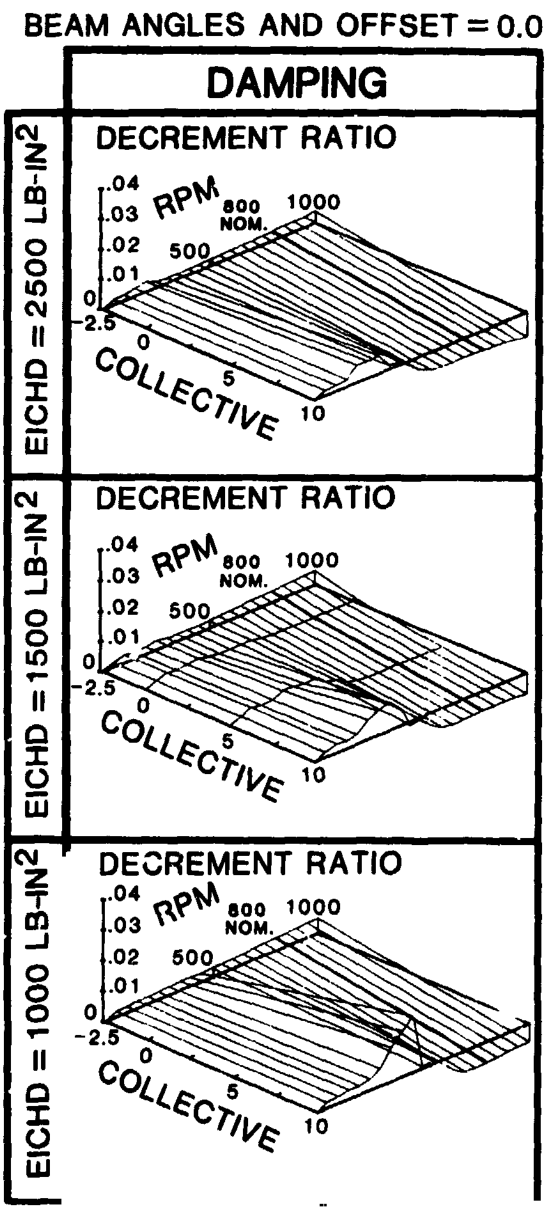


Fig. 10 Effect of chordwise EI rigidity on air resonance damping

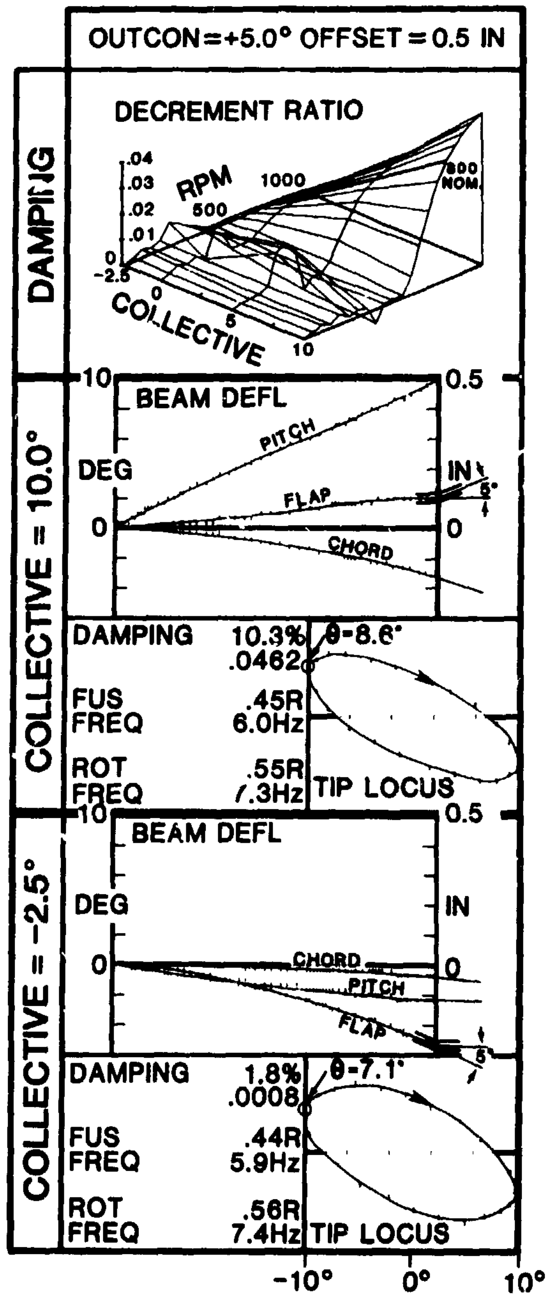


Fig. 11 Damping and modes for combined stabilizing couplings

Concern for the nonlinear nature of the equations prompted evaluating the simultaneous application of the 2 most powerful stabilizing parameters, outboard coning and positive beam offset. Fig. 11 shows the combined results and the resultant damping is 10.3% at high collective compared to the individual contribution of 3.2% from OUTCON and 5.7% from OFFSET from a base of -1.4%. Thus the combined effect is worth more than the sum of the parts. Fig. 12 shows the mode shape behavior in detail and the powerful pitch-lag coupling (8.6° pitch for 10° of inplane tip motion) causes about 7° of flap motion and a major increase in stability.

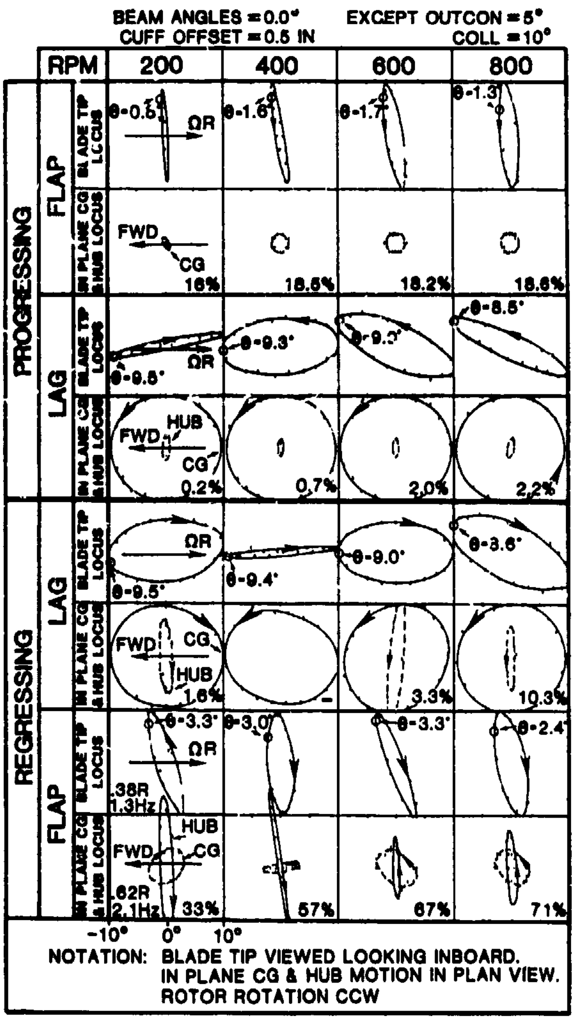


Fig. 12 Effect of RPM sweep on blade modes with combined coupling

obtained for the beam properties shown in Fig. 13 in which it is seen that the EIFLAP varies 6:1 from maximum to minimum and similar substantial changes occur in the other properties. Although there are major variations in beam rigidities, complete matching of the actual ITR beam was not possible because of convergence problems. The beam modelled in this paper represents a 1/2 way stage to the ITR properties but is still sufficiently nonlinear to be useful for assessing the effects of nonlinearity on stability.

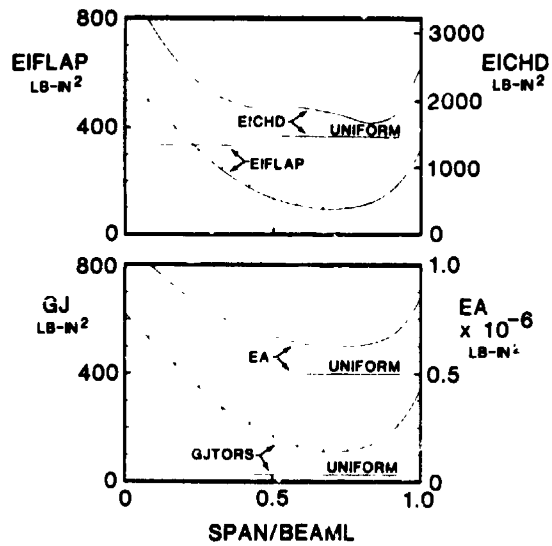


Fig. 13 Rigidities of the non-uniform beam

Finally a major objective of this study was to assess the degree that the results of the FLAIR analysis might be affected by the use of a uniform model for the flex beam. In reality the flex beam is far from uniform as its geometry results from careful optimization to achieve maximum flapping with minimum strain. Accordingly, FLAIR was modified to replace the beam by a 24 element section, defined in thickness and width, from which the correct local EI's, GJ and EA are calculated (in contrast to the original analysis which assures constant EI's, GJ and EA along the beam). The modification to FLAIR was substantial and the increased degree of nonlinearity severely taxed the convergence and integration routines used, making the analysis very sensitive to initial conditions. However, successful results were

In Fig. 14 results for the nonlinear beam of Fig. 13 are shown for the base case of zero beam angles and offset = 0, the case of OUTCON = +5°, and for the case of combining OUTCON = +5° and OFFSET = + 0.5 in. The effect of the nonlinearity is immediately apparent in the 'S' shaped distribution of pitch deflection along the beam which has hitherto been linear. Also the flap deflection of the beam is more nonlinear. But despite these substantial changes in the distribution of pitch along the beam, and the resultant accumulation into lag/flap/pitch coupling into the blade, the blade tip loci and the damping plots are relatively little affected. The most significant change occurs in the natural frequency locations and resulting rotor speeds at which the instabilities occur.

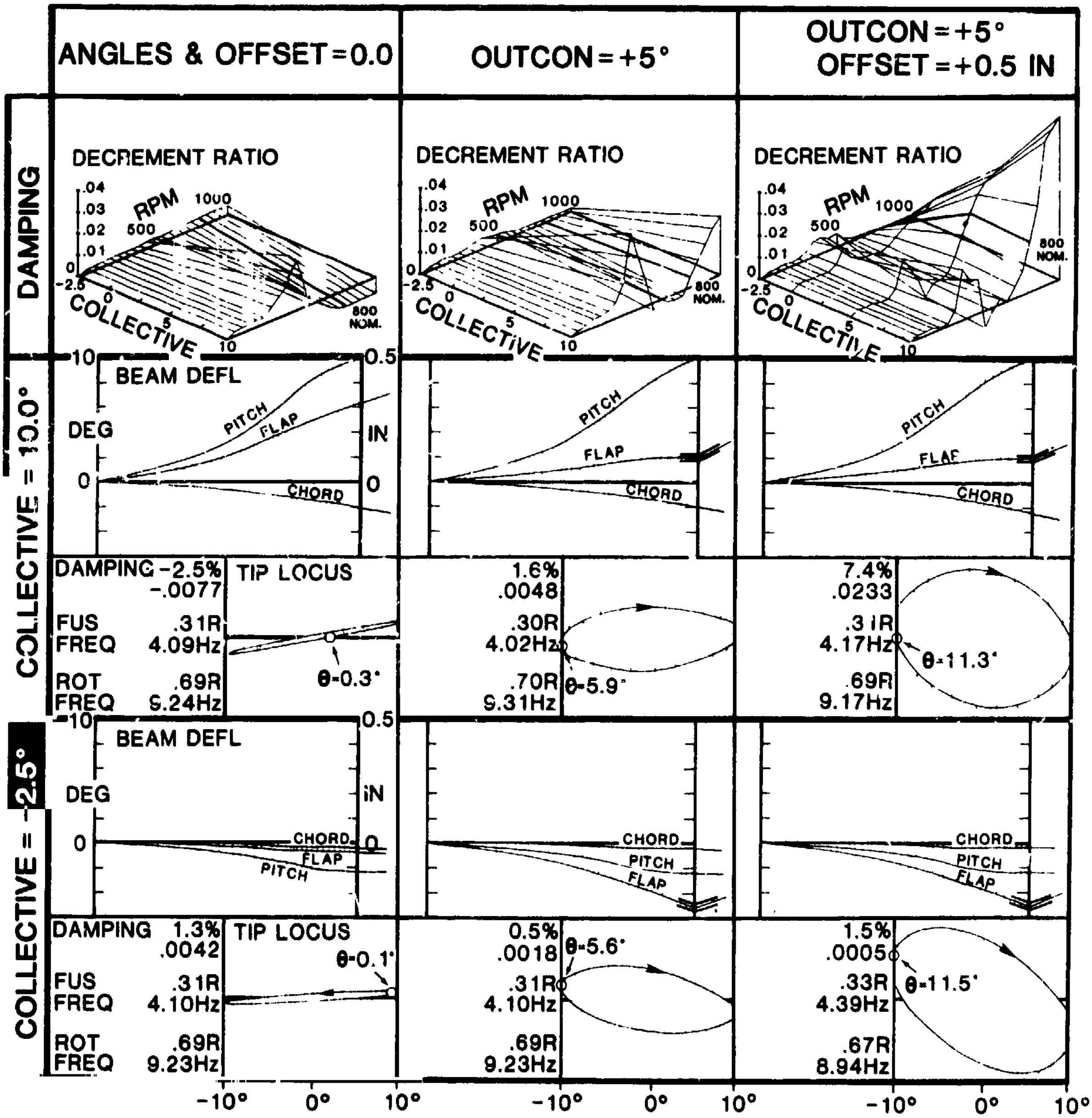


Fig. 14 Damping and modes for a non-uniform beam

6. THE EFFECT OF BLADE COUPLINGS ON GROUND RESONANCE

In Fig. 15 the effect of those couplings found to be favorable for air resonance are evaluated for ground resonance (due to the changed nature of the data the axes have been interchanged relative to the previous figures and the vertical scale changed by a factor of 3). The baseline case Fig. 15a clearly shown the small pitch instability at 600 RPM and the major roll instability at 900 RPM and a moderate stabilizing effect of collective pitch (opposite to air resonance). Adding OUTCON + +5, Fig. 15b has the effect of both increasing the stability of the stable region and increasing the instability of the unstable region. Going one stage further and adding OFFSET = +0.5 in, Fig. 15c continues the trend and now there is also a notable degradation of stability at negative collective pitch.

The pitch mode does appear to be favorably stabilized by pitch-lag coupling. But the roll mode appears to be quite immune and remains to be either avoided completely (as was the case with the YUH-61A) or suppressed by using large amounts of damping as has been the practice for articulated helicopters.

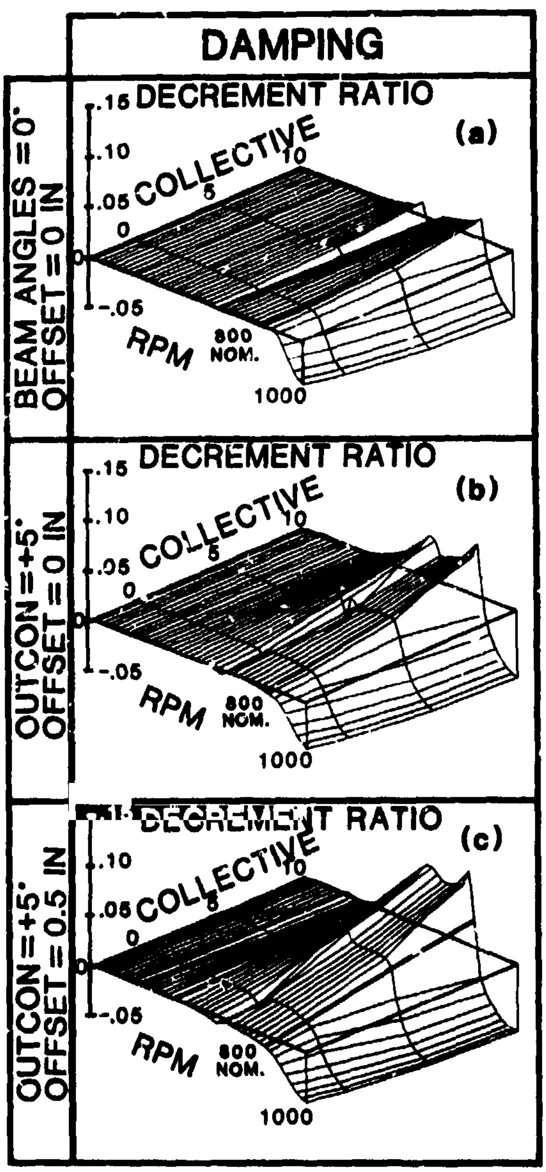


Fig. 15 Effect of pitch-lag couplings on ground resonance

7. CONCLUSION

A trade study has been completed using a modified version of the FLAIR analysis for the aeroelastic stability of bearingless rotors. The following conclusions have been drawn:

1. A baseline soft-in-plane bearingless rotor (i.e. with no flap-lag-pitch couplings introduced by beam angles or any other means) in air resonance is stable at all RPM's at low collective, but goes unstable at operating RPM at high collective. In ground resonance the typical instabilities encountered at the pitch and roll crossings with the regressing lag mode are only slightly affected by collective pitch.

2. Of the 6 available flexbeam installation angles only outboard coning (giving negative lag-pitch coupling) is powerfully effective in stabilizing air resonance at high collective pitch.

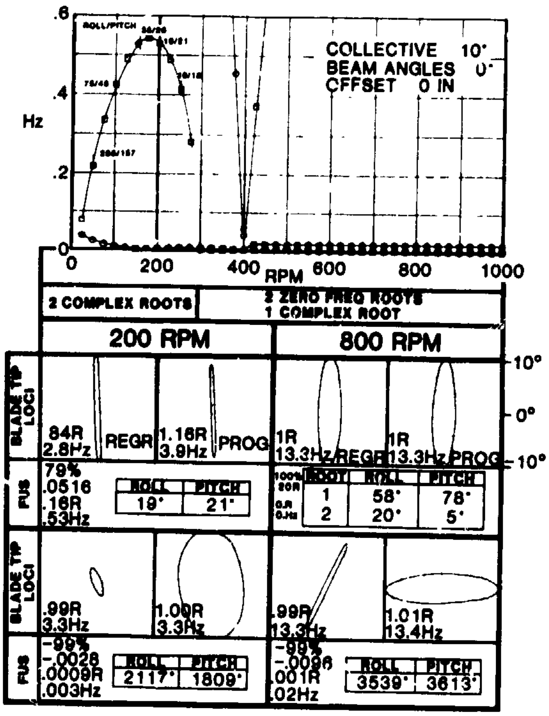
3. Vertical offset of the cuff shear pivot is shown to be equally effective in stabilizing air resonance, and the benefit is cumulative with outboard coning.

4. The effect of lag-pitch coupling on ground resonance is small at low collective, but at high collective the effect is both to increase the stability in the stable regions and to further increase the instability in the unstable regions.

5. The modification to the FLAIR program to replace the uniform flexbeam by a geometrically correct tailored flexbeam, with improved representation of coupling terms, did not affect the conclusions arrived at above for the uniform beam.

APPENDiX

BEHAVIOR OF LOW FREQUENCY ROOTS



In the 300 to 1000 RPM region, there are typically two zero roots and one very low frequency complex root. The eigenvec· rs are dominated by fuselage pitch and roll. Below 300 RPM the two zero roots combined to give another complex root still having a low frequency compared to the regressing flap mode and, whose eigenvector varies from mainly roll to mainly pitch.

ACKNOWLEDGEMENT

My special thanks are due to Ken Bartie and Dot Kane for their patience and diligence in preparing this pc ɔer.

REFERENCES

1. Hooper, W.E., "Effect of Fuselage Dynamics on Helicopter Ground Resonance," Aircraft Engineering, August 1962.

2. Hohenemser, K. H., & Yin, S.K., "Some Application of the Method of Multiblade Coordinates," Journal of the AHS, Vol. 17, No. 3, July 1972.

3. Ormiston, R.A., "Aeromechanical Stability of Soft Inplane Hingeless Rotor Helicopters," 3rd European Rotorcraft Powered Lift Aircraft Forum, Paper No. 25, Aix-en-Provence, September 1977.

4. Hodges, D.H. "Aeromechanical Stability of Helicopters with a Bearingless Main Rotor:
Part 1: Equations of Motion
Part II: Computer Program
NASA TM 78459 & TM78460, February 1978.

5. Bousman, W. G. "An Experimental Investigation of the Effects of Aeroelastic Couplings on Aeromechanical Stability of a Hingeless Rotor Helicopter", Journal of the AHS Vol. 26 No. 1, January 1981.

DISCUSSION*
Paper No. 3

PARAMETRIC STUDY OF THE AEROELASTIC STABILITY OF A BEARINGLESS ROTOR
W. Euan Hooper

Bill Weller, United Technologies Research Center: Historically, I guess I've seen this before to the degree that flap-lag stability and pitch stability by virtue of blade coning or flexure inclination angle or whatever. I've seen it in some analyses and some test programs. But the [Bell] Model 680 or [Boeing Vertol] BMR [didn't show that benefit] as far as the final stability. I think this has to do somewhat with the physical characteristics of the model being used to do these types of things as opposed to the full-scale article. Would you care to comment on the applicability of this type of phenomenon to the BMR-type rotor systems?

Hooper: Well, I wouldn't agree with you that they did not show up on the BMR. The BMR had 2 1/2 degrees of outboard coning and I think that was the main feature that stabilized it. The BMR was a good stable rotor in every flight regime except one and that was [partial power descents at low forward speed. In hover and at high forward speeds] it was very stable, just a replica of the BO 105.

Weller: The point more is the degree of the effect not that the outboard blade coning is detrimental. It's generally agreed that it is beneficial to some degree, but your effect there is proving somewhat significant. The model test that I have been associated with, the 680 system, doesn't show anywhere near the benefit as far as the degree that your analytical studies would imply.

Hooper: Well that's interesting and we have yet to complete the correlation of our [own data] with our test program. So far we have not been disappointed in the tests; we'll find out in full scale.

Bill Warmbrodt, NASA Ames Research Center: [Was there a reason for choosing the 5 degree angles] used in your ITR study?

Hooper: Just arbitrary, to give the sensitivity.

Jerry Miao, Sikorsky Aircraft: Euan, I believe all the data you show [from using] FLAIR. I believe when Fort Eustis sponsored the BMR program [there was a] lot of BMR test [data obtained]. There was [shown in that test a] favorable, stabilizing parameter [and that was prepitch or an orienting of the] flexbeam in the pitch sense. I believe there is test data from the BMR model test that [shows that effect clearly.] I believe that if you look at modal damping vs rpm with this inboard flexbeam pitch angle the stability of the air resonance [mode] improved more than twice. Have you ever tried to use FLAIR to [compare with these data?]

Hooper: No, I haven't and you raise a very interesting point. I mentioned that [we] did not get the degree of stability from the hub pitch setting that we expected. However, there is a very significant difference with this rotor in that it is much more flexible in [flap] than the BMR or our previous YUH-61A. That may be the key to it. But it certainly surprised us [and so we] also tried it with the nonuniform beam analysis [and also found no effect of hub/beam pitch. We're going to have to go] back through those cases with the FLAIR analysis [and evaluate hub/beam pitch in combination with other parameters.] Even with the nonuniform beam that [accurately represents] the distribution of [flap and chord bending and] pitch quite differently [there was] no sensitivity [to hub/beam] pitch angle. So [the different sensitivity to hub/beam pitch angle] may be due to the lack of flap stiffness.

Jing Yen, Bell Helicopter: I'd like to [back] up what Bill [Weller] said. The aeroelastic coupling will be very powerful for a hingeless type of rotor. [The hingeless rotor clearly defines the location of the pitch axis. When we go to a bearingless rotor, especially with a soft hub, the location of the pitch axis and the coupling around the pitch axis is strongly affected by flexbeam bending.] The floating of the pitch axis will in general reduce the influence of aeroelastic coupling.

Hooper: Well, the location of the pitch axis is obviously the key and we have the experience on the YUH-61A which had zero precone, zero HUBCON in this context. That aircraft was extremely stable. In that case the pitch axis was forced physically to be [in the disk plane.] The coning [occurred] outboard of the pitch axis [and resulted in strong beneficial pitch-lag coupling.]

*The transcript of this discussion is incomplete because of recording problems. Areas of ambiguous or missing text have been discussed with the person asking or answering the question and the text is indicated with brackets.

Inderjit Chopra, University of Maryland: [Inaudible]

Hooper: The basic FLAIR is a uniform beam.

Chopra: [Inaudible]

Hooper: A single load path beam, that's right. It's been subjected to a lot of scrutiny from our point of view. Evhen Mychalowycz and Pete Dixon have been very suspicious that it's not an adequate representation of a beam. I have to say it has stood up to every examination. That is why we were looking at the very detailed distribution of the flexibility along the beam to see that it behaves as it should. I've been satisfied that [FLAIR uses] a rigorous representation of the beam. There are no small angle assumptions of the beam. That's one of the attractive [points]. The beam representation and the control system all use large angles.

Harry Runyan, College of William and Mary: I think your pitch deflection is correct. I don't see why you are worried about it. It's a second derivative in θ. You only have two conditions you can put on it. One would be a zero deflection at the root, [and the other zero torque at the tip]. You have no more conditions you can put in. That's it. That's what you get. Whereas in bending you have a fourth order equation. So I think it looks correct within the limits of linear theory.

Chopra: [Inaudible]

Hooper: We'll be in a better position when we [do that] test.