AIAA-92-2258-CP

ANALYTICAL AEROELASTIC STABILITY CONSIDERATIONS AND CONVERSION LOADS FOR AN XV-15 TILT-ROTOR IN A WIND TUNNEL SIMULATION

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Abstract

Tilt-rotor stability and conversion loads results obtained from a comprehensive rotorcraft analysis are presented in this paper. These analytical results show that the XV-15 rotor with metal blades (XV-15/Metal-Blades) mounted on a propeller test rig in the NASA Ames 40- by 80-Foot Wind Tunnel is stable within its specified test envelope. Also included in this paper is a reporting of research over and above the goal of determining XV-15/Metal-Blades stability. This preliminary research shows a few interesting aspects of tilt-rotor dynamic stability: namely, the mechanisms underlying XV-15/Metal-Blades stability in contrast to those of the XV-15 with Advanced Technology Blades (XV-15/ATB); the sensitivity of tilt-rotor stability in the cruise mode to the coupling effects in the control system stiffness; and finally, the XV-15/ATB blade stability problem (this subject is discussed briefly). Limited results on the XV-15/Metal-Blades loads during conversion are also presented. These analytical loads may not be reliable in general due to a lack of adequate correlation between analytical and test loads. A comprehensive experimental data base for the conversion loads of the XV-15 rotor installed in a wind tunnel in the presence of a wing is perhaps not publicly available, but it is believed that the analysis usually underpredicts the conversion loads. A comprehensive wind tunnel test program is recommended in order to obtain test data that will help provide insight into the conversion loads problem.

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PART I - STABILITY

Analysis Objective

This part of the paper presents the aeroelastic stability of the XV-15 rotor with metal blades (XV-15/Metal-Blades) mounted on the propeller test rig (PTR) in the NASA Ames 40- by 80-Foot Wind Tunnel. Also included is a reporting of a limited amount of research, over and above the goal of determining XV-15/Metal-Blades stability. This preliminary research shows a few interesting aspects of tilt-rotor dynamic stability: namely, the mechanisms underlying XV-15/Metal-Blades stability in contrast to those of the XV-15 with Advanced Technology Blades (XV-15/ATB); the sensitivity of tilt-rotor stability in the cruise mode to the coupling effects in the control system stiffness; and finally, the XV-15/ATB blade stability problem.

Analytical Stability (Flutter) Model

The flutter analysis involved 38 degrees of freedom. These included blade bending, blade rigid body pitch and torsion, gimbal modes, rotor speed, inflow, and fixed system modes due to the PTR. The current simulation is that of a wind tunnel test in which the rotor torque is maintained at a specified level. The analysis used was the comprehensive rotorcraft analysis code, CAMRAD/JA, by Johnson (Ref. 1).

Results and Discussion

Figure 1 shows the XV-15/Metal-Blades stability without any PTR modes at a very high torque condition.

As expected, a high (120% of baseline) control system stiffness case is more stable than a low (80% of baseline) control system stiffness case. All the plots shown in this figure are for cases that include the blade torsion mode. In the figure and elsewhere in this paper, CSS refers to the control system stiffness.

Figure 2 shows the results of a parametric study in which the PTR modes and blade torsion are the variables. Clearly, the XV-15/Metal-Blades stability analysis must include both the PTR fixed system modes and the blade torsion mode.

Comparisons Involving the XV-15/Metal-Blades, XV-15/ATB, and the V-22

Figure 2 also brings out an important aspect of the XV-15/Metal-Blades stability as compared to the XV-15/ATB (Refs. 2 and 3) stability. From Fig. 2 it can be stated that even though the XV-15/Metal-Blades configuration is stable, the XV-15/Metal-Blades stability involves characteristics of both whirl flutter and classical blade pitch-flap flutter.

The XV-15/ATB results showed evidence of only blade pitch-flap flutter at high airspeeds (310 to 350 knots , CAMRAD/JA boundaries, depending on the CSS value) without any significant involvement of the fixed system (Ref. 3).

In order to put the XV-15/Metal-Blades, XV-15/ATB, and the V-22 stability analyses in perspective, note that the V-22 rotor mounted on the PTR (Ref. 4) was analytically shown to be stable "for the entire flight envelope." Also, Ref. 5, which considers a 1/5 scale wind tunnel model of the V-22, presents data which show the presence of the whirl flutter mechanism involving the fixed system modes (in this case, the wing modes). Thus, it may be reasonable to rule out blade pitch-flap flutter in the case of the V-22 blades as the primary mechanism determining V-22 stability within the same airspeed range.

Continuation of XV-15/PTR Results

The next four figures (3 to 6) show that at the operating RPM of 421 the XV-15/Metal-Blades is stable within the test speed range (maximum 280 knots).

Figures 7 to 9 present results for the high RPM (589) case. These show that the XV-15/Metal-Blades stability is reduced compared to the 421 RPM condition; in any case, the XV-15/Metal-Blades is stable within the test envelope. Similar trends—namely, reduced stability with increasing RPM—were also found in the V-22/PTR study (Ref. 4).

Coupling Effects of the Control System Stiffness

The parametric study of Fig. 2 showed the importance of the various modes, both fixed system and blade (torsion), on XV-15/Metal-Blades stability (whirl flutter and blade pitch-flap flutter). The blade torsional behavior is important in determining pitch-flap flutter. This brings up the design factors that determine blade torsional behavior—namely, control system stiffness, c.g. offset, etc. Attention was given to the control system stiffness and the c.g. offset, and some of the important results are presented next.

Considering the complexity of the PTR CSS formulation, simplifications to the CSS matrix are attractive. At the outset it is not clear why the off-diagonal terms in the control system stiffness matrix would be important for stability in the cruise mode of a tilt-rotor (even in the presence of a small inclination of the thrust vector). This condition is not unlike that of a helicopter in vertical (axial) flight. For such a tilt-rotor/helicopter, there should not exist any significant asymmetries, i.e., cross-couplings.

In an attempt to simplify and better understand the complex CSS problem, the XV-15/Metal-Blades configuration was simulated with the CSS off-diagonal terms zeroed out (in the present cruise mode). Figure 10 confirms what has been hypothesized in the preceding paragraph: in the cruise mode, CSS cross-couplings are not important for the XV-15/Metal-Blades stability.

A second case was considered, that of the XV-15/ATB, which also showed in a general sense that the off-diagonal terms do not affect the system stability boundary; i.e., for the XV-15/ATB, an unstable condition remained unstable. At the same time, the present short work on the XV-15/ATB brought out a disturbing aspect of the ATB design—namely, its disregard of basic principles in designing a flutter free blade within the operating envelope. Figures 11 to 13, which illustrate this point, are discussed below.

Figures 11 and 12 show that for the XV-15/ATB, off-diagonal terms in the CSS seem to make a difference in the detailed behavior of the blade. Actually, this is not really so, since the blade pitch-flap flutter mechanism involves both pitch and flap degrees of freedom and either one of these may become unstable under flutter conditions. In the case of the ATB, because of poor design, the blade is exhibiting a high degree of sensitivity to these detailed manifestations, unlike the metal blade which is stable to begin with.

In another important vein, if it is believed that the CSS should not have any significant cross-couplings, then the stability boundary is really determined by the lower stability boundary in Fig. 11, with this CAMRAD/JA boundary being at approximately 250 knots and pitch-flap flutter manifested through the torsion degree of freedom. It is fortunate that for the XV-15/ATB the control system sensitivity is in the direction of increasing flutter speed, with the flutter speed being determined by the boundary in Fig. 12 (with flutter manifested through the bending degree of freedom). Thus the XV-15/ATB may have significant beneficial sensitivity associated with the control system.

Limited Discussion on the Effect of Blade C.G. Offset on Blade Torsional Behavior

The other topic of interest, the effect of the c.g. offset (x_I) on torsional behavior, was briefly investigated. The standard parameters, though not all, that determine blade pitch-flap flutter boundaries are

$$I_x = \int_0^1 x_I rm \, dr \, , \quad I_f = \int_0^1 I_\theta \, dr$$

$$\frac{I_x}{I_f} < \text{function} \, (\omega_{torsion}, \text{CSS}, \ldots)$$

Figure 13 shows a comparison of the spanwise distribution of the c.g. offset for the XV-15 metal blade, the XV-15 ATB, and the V-22 blade. The XV-15 ATB blade c.g. offset is not well placed compared to the XV-15 metal blade and the V-22 blade, with the ATB having a particularly adverse placement near the tip. This poor c.g. placement is most likely responsible for the ATB exhibiting pitch-flap flutter at high airspeeds (over 310 knots, CAMRAD/JA boundary). A starting point to alleviate this flutter problem (if not already done) would be to examine the integrals , I_x, I_f, etc.

PART II – CONVERSION LOADS

Analytical Model for Loads Prediction

The XV-15/Metal-Blades analytical loads that are presented in this paper include oscillatory pitch link loads, hub loads (3P shears and moments) and blade loads (oscillatory flatwise and lagwise bending moments). These conversion loads were obtained from an analytical model (Ref. 1) that included nonuniform inflow (prescribed wake) through the proprotor in the presence of a wing. Note that Ref. 6 presents conversion loads for a single XV-15 rotor installed in the 40- by 80-Foot Wind Tunnel; these results from Ref. 6 include both analytical and wind tunnel loads (Ref. 7). The present configuration differs from that considered in Ref. 6 due to the inclusion of the wing and because the analytical model in Ref. 6 had a inflow variation that is linear. A preliminary and very limited comparison of the pitch link load and flatwise blade bending moment from the present analysis with that of the test data of Ref. 7 has shown that the results from the present application of CAMRAD/JA can be considered reasonable.

Results

A rotor torque of 21,000 ft-lb corresponding to a high power wind tunnel condition was specified. For the range of rotor torques under consideration, this level is associated with the highest conversion loads.

The present analytical results show that generally the conversion loads reach a maximum at a nacelle tilt angle of 50 to 75 deg.

Figure 14 shows that at high conversion speeds the endurance limit for the pitch link load is exceeded at nacelle angles greater than 40 deg. Note that the endurance limit shown is applicable to the cruise mode, with the endurance limit for the conversion mode being slightly smaller.

Figures 15 to 20 show 3P fixed system hub loads trends with nacelle angle and airspeed. Generally, the trends are as could be expected from basic physics, with the flow being generally symmetric at the cruise and hover conditions, thus leading to small vibratory loads. Conversion angles between 0 and 90 deg. entail non-symmetric flow conditions and cause an increase in the hub loads.

Figures 21 to 26 show detailed blade bending moment variations with spanwise stations for the higher airspeeds. These trends appear to be consistent with the pitch link and hub loads trends.

Note that, to our knowledge, comprehensive experimental data on conversion loads for the XV-15/ Metal-Blades installed in a wind tunnel in the presence of a wing do not exist and the present predictions may or may not be reliable. This is so even though these predictions appear reasonable. A comprehensive wind tunnel test program is recommended in order to obtain test data that will help provide insight into the conversion loads problem.

Concluding Remarks

This analytical study has considered aeroelastic stability and conversion loads for a tilt-rotor that is to be tested in the NASA Ames 40- by 80-Foot Wind Tunnel. In addition to verifying the stability of the tilt-rotor within the specified test envelope, the stability study shows a few interesting aspects of tilt-rotor dynamics. The results from the conversion loads study appear reasonable; however, due to the limited or non-existent experimental data base (for the XV-15 rotor installed in a wind tunnel in the presence of a wing) that can verify these predictions, a wind tunnel test program is recommended in order to establish a correlation data base and to obtain insight into the conversion loads problem.

Acknowledgments

We gratefully acknowledge the help given to us by Ruth Heffernan, Jan van Aken, Alexandra (Frerking) Swanson, and Mike Derby. Their many useful suggestions during the course of the study are very much appreciated.

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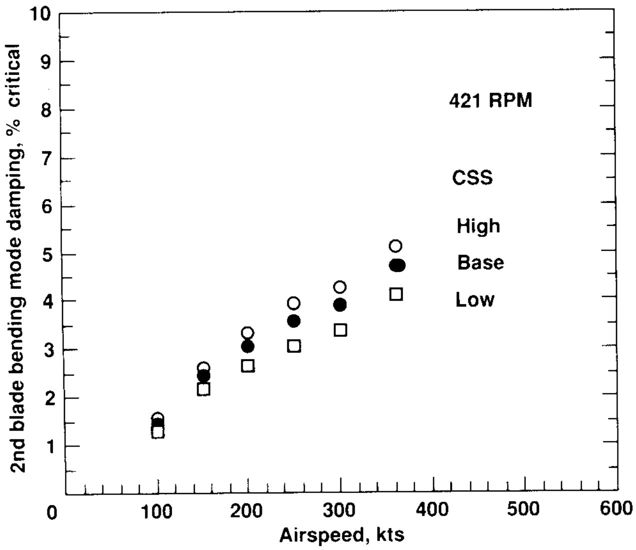

Fig. 1 Variation of XV-15/metal-blades stability with airspeed, torque = 21,000 ft-lb, no PTR modes.

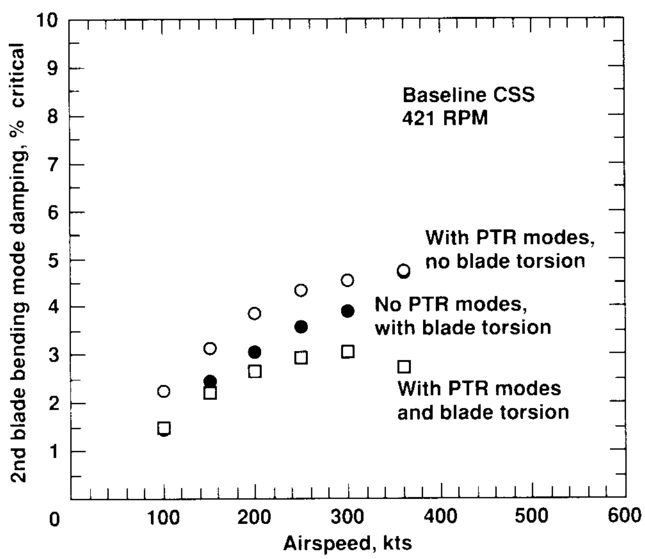

Fig. 2 XV-15/metal-blades stability with varying assumptions, torque = 21,000 ft-lb.

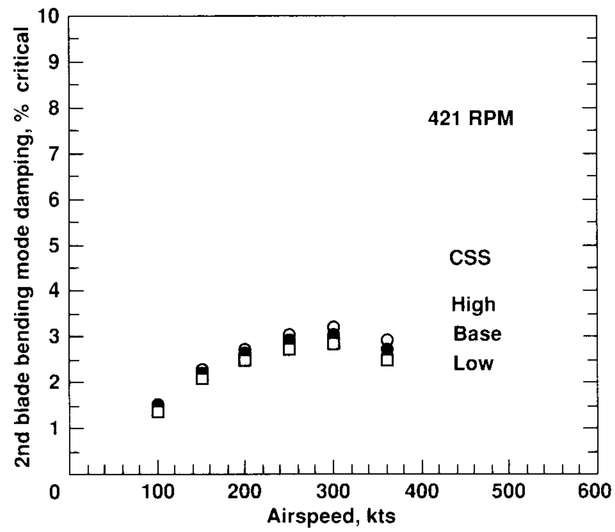

Fig. 3 XV-15 metal-blades stability variation with airspeed and control system stiffness, torque = 21,000 ft-lb.

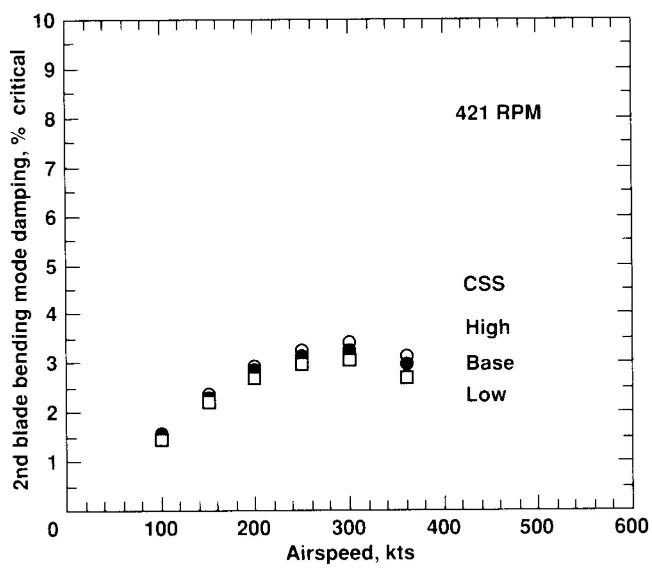

Fig. 4 XV-15/metal-blades stability variation with airspeed and control system stiffness, torque = 12,000 ft-lb.

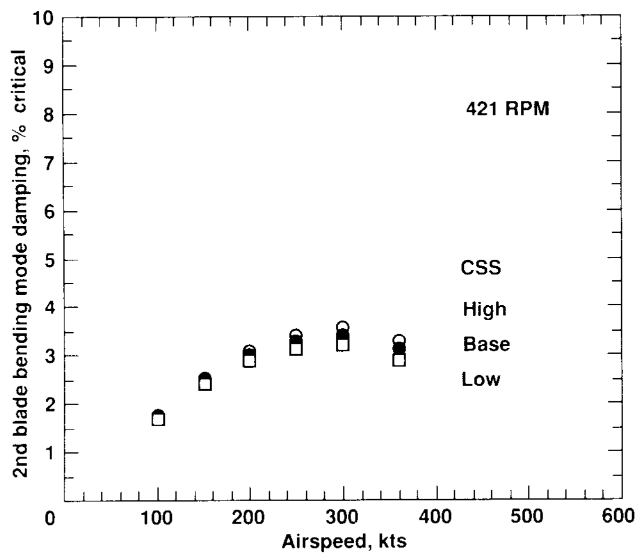

Fig. 5 XV-15/metal-blades stability variation with airspeed and control system stiffness, torque = 6,000 ft-lb.

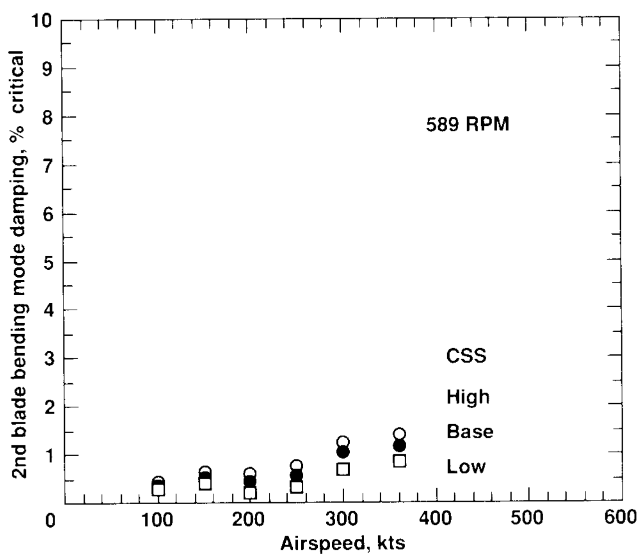

Fig. 7 XV-15/metal-blades stability variation with airspeed and control system stiffness, torque = 12,000 ft-lb.

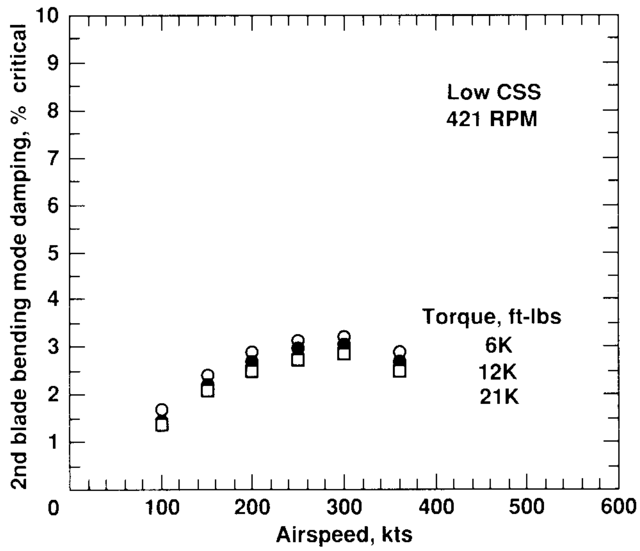

Fig. 6 XV-15/metal-blades stability variation with airspeed and torque.

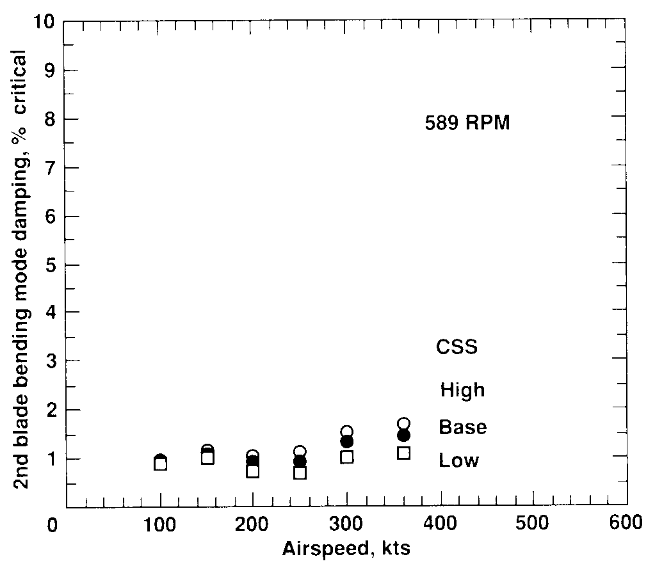

Fig. 8 XV-15/metal-blades stability variation with airspeed and control system stiffness, torque = 6,000 ft-lb.

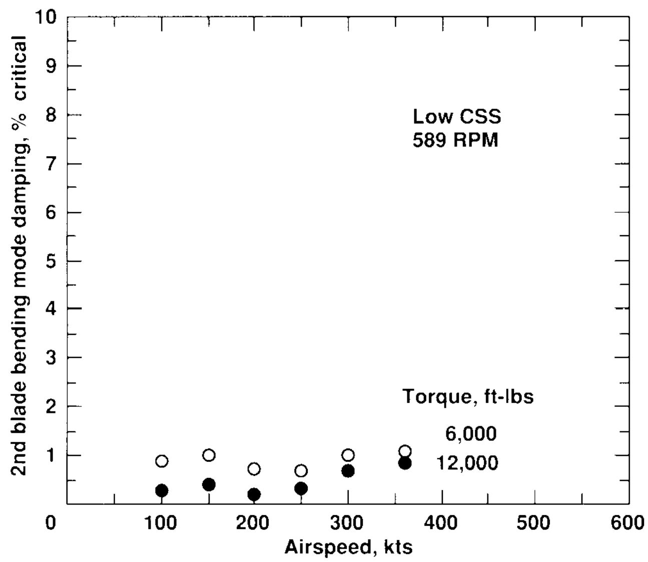

Fig. 9 XV-15/metal-blades stability variation with airspeed and torque.

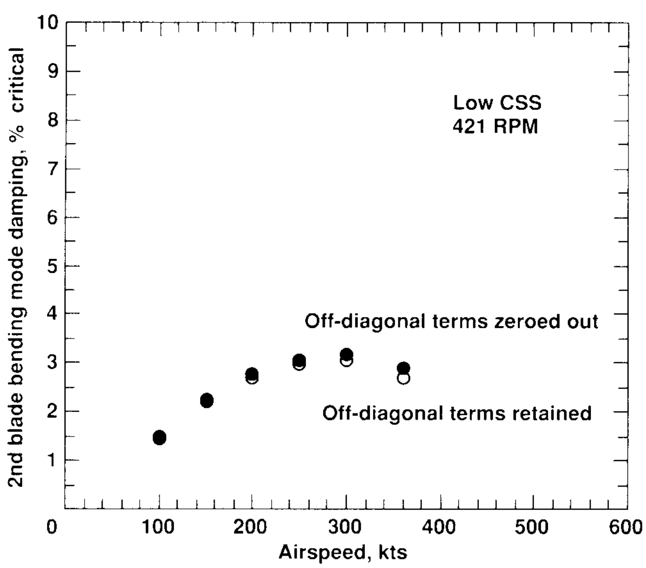

Fig. 10 Effect of off-diagonal terms on XV-15/metal-blades stability, torque = 12,000 ft-lb.

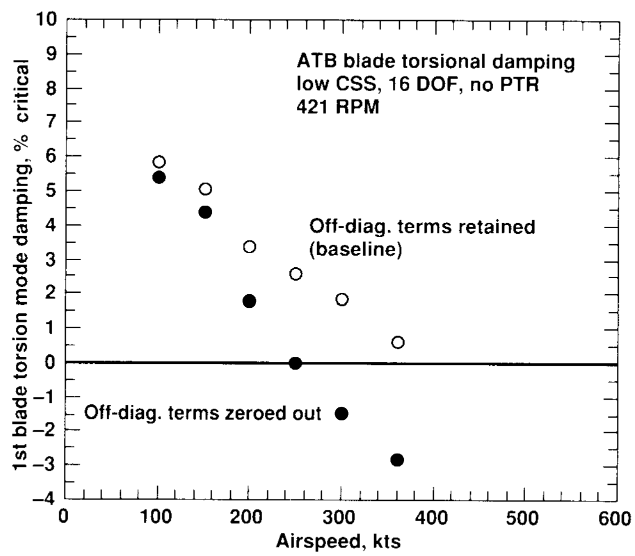

Fig. 11 Effect of off-diagonal terms on XV-15/ATB stability – blade torsional mode, torque = 12,000 ft-lb.

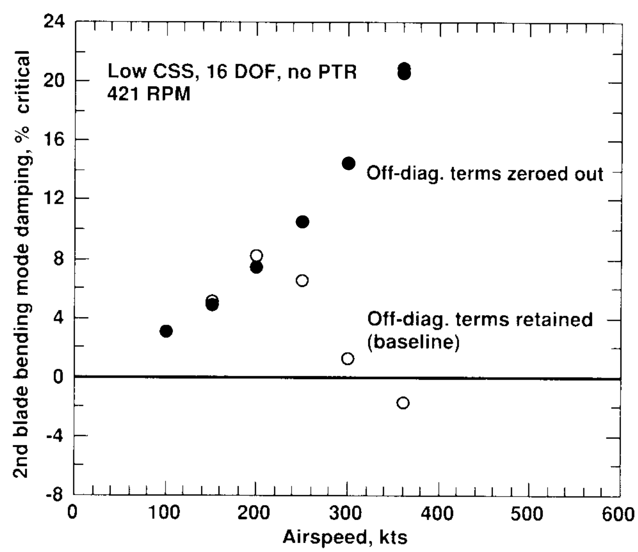

Fig. 12 Effect of off-diagonal terms on XV-15/ATB stability – blade bending mode, torque = 12,000 ft/lb.

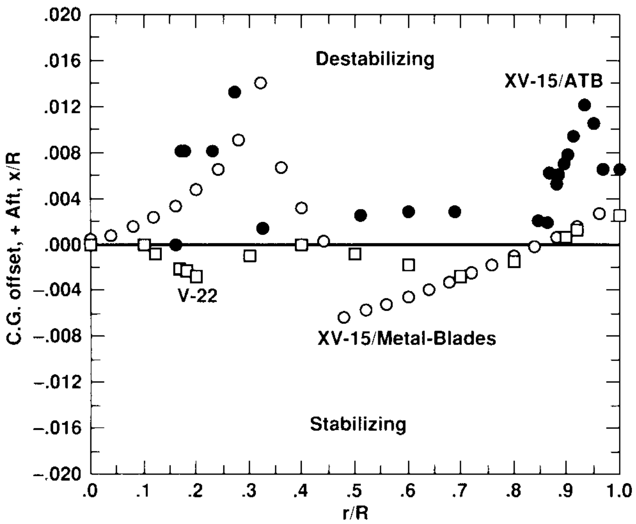

Fig. 13 Blade c.g. offset comparison for the XV-15/ metal-blades, XV-15/ATB, and V-22.

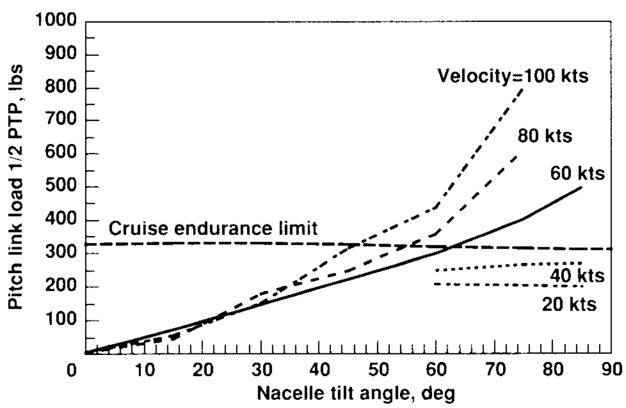

Fig. 14 Pitch link load variation with nacelle angle and airspeed for the XV-15/metal-blades with wing, torque = 21,000 ft-lb.

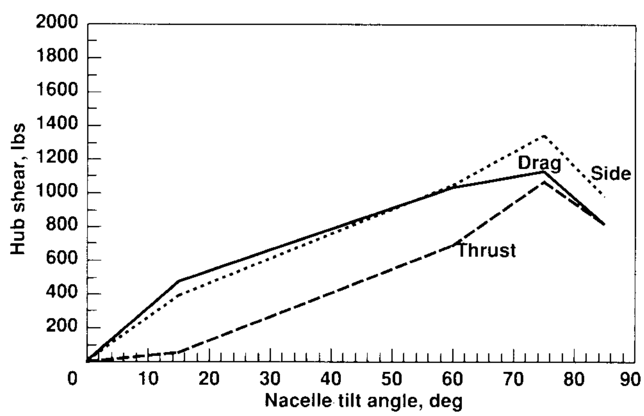

Fig. 15 3P fixed system hub shears for the XV-15/metal-blades with wing, velocity = 60 knots, torque = 21,000 ft-lb.

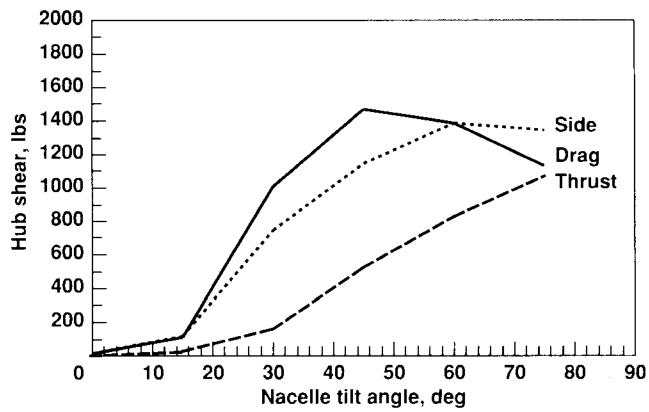

Fig. 16 3P fixed system hub shears for the XV-15/metal-blades with wing, velocity = 80 knots, torque = 21,000 ft-lb.

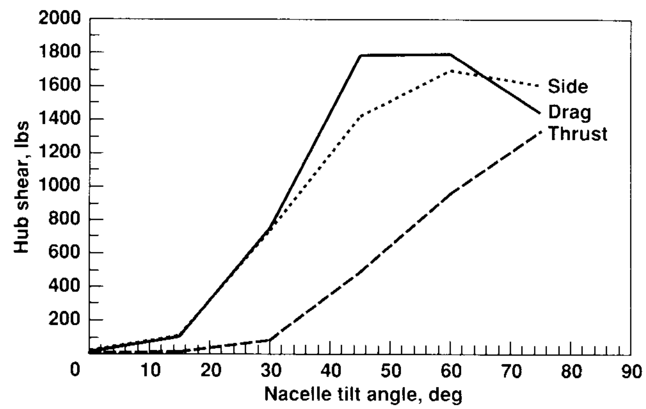

Fig. 17 3P fixed system hub shears for the XV-15/metal-blades with wing, velocity = 100 knots, torque = 21,000 ft-lb.

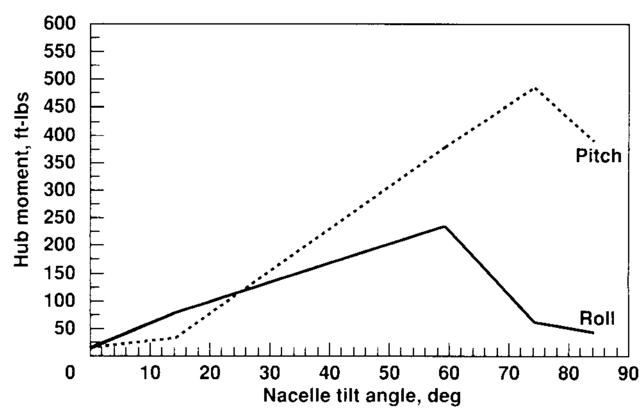

Fig. 18 3P fixed system hub moments for the XV-15/ metal-blades with wing, velocity = 60 knots, torque = 21,000 ft-lb.

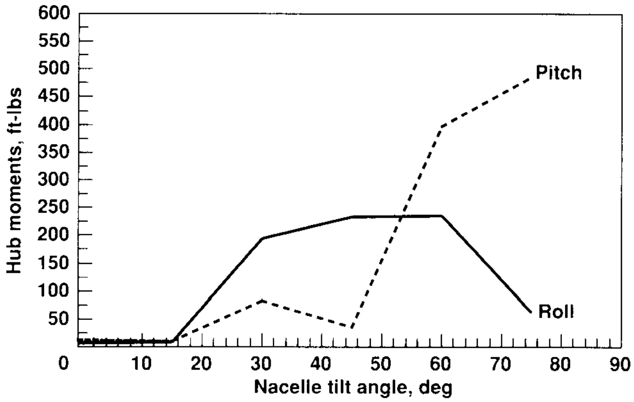

Fig. 19 3P fixed system hub moments for the XV-15/metal-blades with wing, velocity = 80 knots, torque = 21,000 ft-lb.

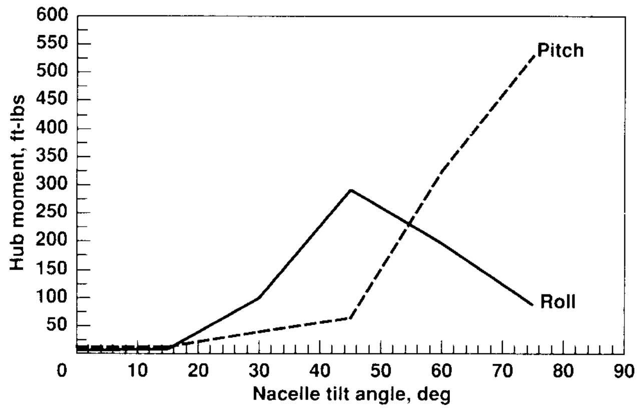

Fig. 20 3P fixed system hub moments for the XV-15/metal-blades with wing, velocity = 100 knots, torque = 21,000 ft-lb.

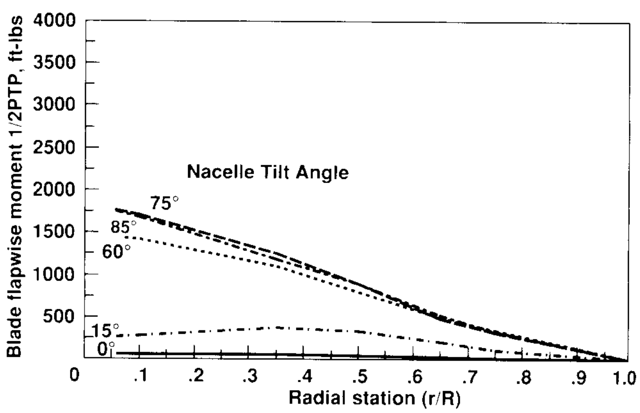

Fig. 21 Blade flapwise moment for the XV-15/metal-blades with wing, velocity = 60 knots, torque = 21,000 ft-lb.

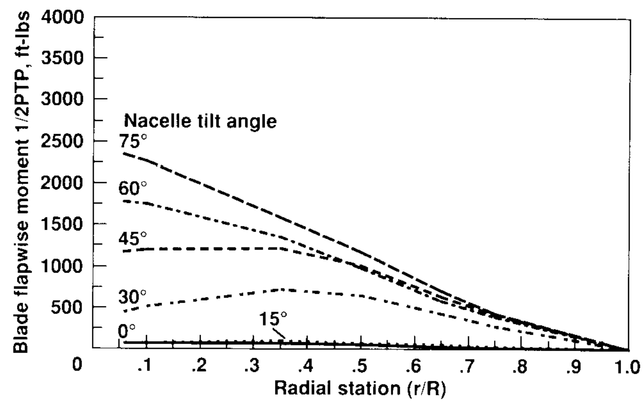

Fig. 22 Blade flapwise moment for the XV-15/metal-blades with wing, velocity = 80 knots, torque = 21,000 ft-lb.

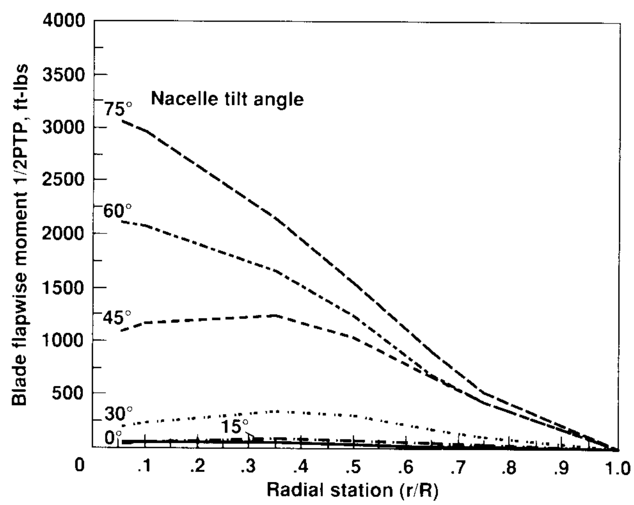

Fig. 23 Blade flapwise moment for the XV-15/metal-blades with wing, velocity = 100 knots, torque = 21,000 ft-lb.

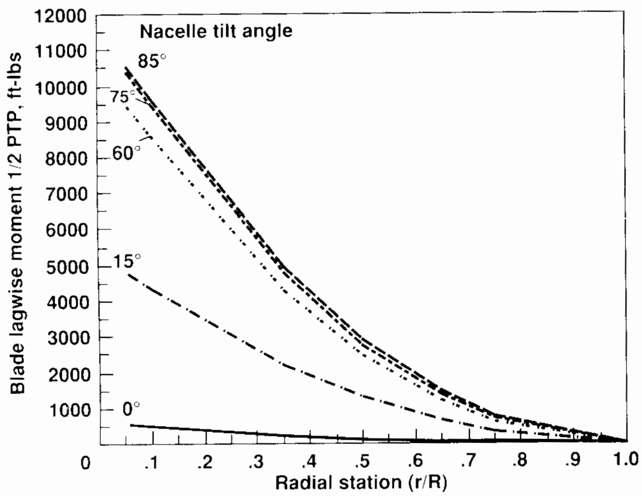

Fig. 24 Blade lagwise moment for the XV-15/metal-blades with wing, velocity = 60 knots, torque = 21,000 ft-lb.

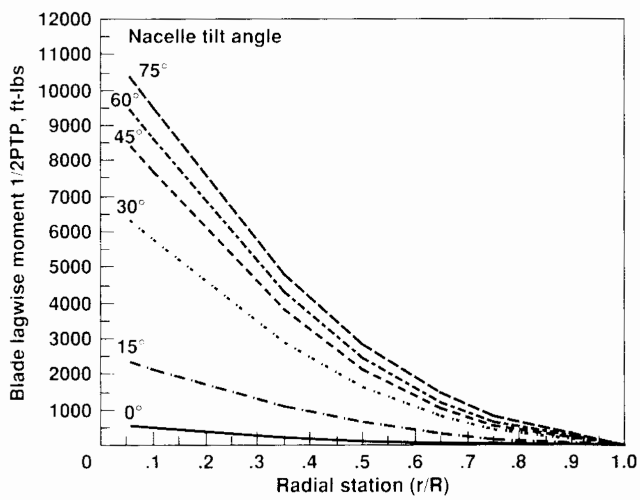

Fig. 25 Blade lagwise moment for the XV-15/metal-blades with wing, velocity = 80 knots, torque = 21,000 ft-lb.

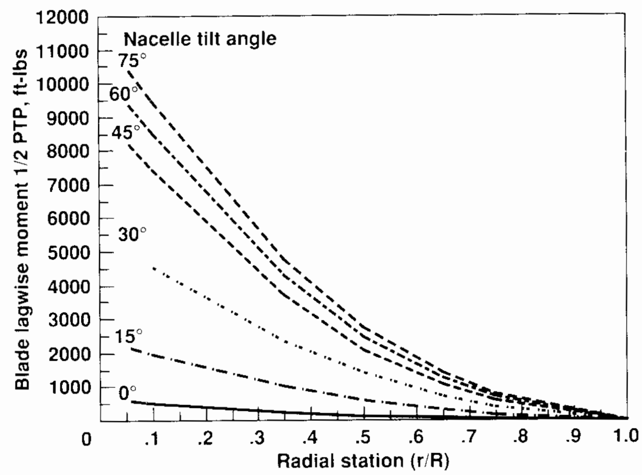

Fig. 26 Blade lagwise moment for the XV-15/metal-blades with wing, velocity = 100 knots, torque = 21,000 ft-lb.