EFFECTS OF ROTOR DESIGN VARIATIONS ON TILTROTOR WHIRL-MODE STABILITY

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ABSTRACT

Tiltrotor performance is constrained by coupled wing/rotor whirl-mode aeroelastic instability. Two parallel research efforts are currently underway at NASA Ames Research Center to investigate methods of expanding the whirl-mode stability boundary for proprotors. Results of the first effort, analyses of design changes to the V-22 rotor, indicate that moderate amounts of blade sweep at the tip substantially increase the stability of the symmetric wing beam bending mode. Adding either a chord-balance mass or a tip mass on a boom considerably enhances the beneficial effects of sweep. To validate the predictions at minimum cost, a second research effort is to carry out a small-scale wind-tunnel test of a modified rotor. Cost will be minimized by exploiting the technology of radio-controlled models, from which off-the-shelf components can be used in a dynamically-scaled wind-tunnel model with only minor modifications. This report summarizes the results to date for the V-22 and describes the proposed wind-tunnel proprotor model.

INTRODUCTION

Increases in tiltrotor cruise speeds beyond current levels are limited by coupled wing/rotor whirl-mode aeroelastic instability. Increased power, thrust, and aerodynamic efficiency are not enough: the whirl-mode stability boundary must also be improved. Such considerations also apply to tiltrotors with longer wings, which will be needed for more efficient long-range cruise. With current technology, very stiff, thick wings of limited aspect ratio are essential to meet the stability requirements, which severely limits cruise efficiency and maximum speed. Larger and more efficient tiltrotors will need longer and lighter wings, for which whirl-mode flutter is a serious design issue. Reference 1 gives a brief history of tiltrotor aeroelastic stability research and its application to tiltrotor design and flight test.

Numerous approaches to improving the whirl-mode airspeed boundary have been investigated, typically focusing on wing design (Ref. 2), active stability augmentation (Ref. 3), and variable geometry rotors (Ref. 4). The research reported herein applied the simpler approach of sweeping the outboard blade sections. The effects of additional anti-flutter masses were also studied. References 5 and 6 discuss the evolution of the concept and cover the first phase of the research, which was focused on the XV-15.

This paper summarizes the technical approach by presenting key results for the XV-15. Two parallel research efforts, one analytical and one experimental, are then described: analyses of V-22 modifications and a simple wind-tunnel proprotor model. Selected results of the V-22 studies are presented. Options for long-term research are briefly discussed.

XV-15 WHIRL-MODE PREDICTIONS

A CAMRAD II model of the XV-15 was used to analyze parametric variations of rotor design parameters. See Refs. 7 and 8 for correlation of CAMRAD predictions with measured stability and loads.

Figure 1 illustrates the XV-15 with pertinent dimensional data; the moderate aspect ratio of the thick wing is clearly evident. (Detailed specifications are given in Ref. 9; see also Ref. 1.) The model used here was altered in several ways from the actual XV-15, including a simplified drive train. The changes are discussed further below.

XV-15 Analytical Model

The baseline rotor used in the study was the original XV-15 steel-blade rotor, with a 2.5° precone titanium hub and –15° delta-three (nominal). The rotor is rigid (stiff-in-plane) with a gimbaled hub (Ref. 9). The inboard aerodynamic sections start with a 17-in chord at 12% radius, linearly tapering to a 14-in chord at 25% radius; the chord is constant from there to the tip (Fig. 2). Total effective blade twist is 45° over a 150-in radius. The entire blade has a 1° aft aerodynamic sweep, with the quarter-chord line intersecting the pitch axis at 75% radius.

To calculate aeroelastic stability, CAMRAD II couples externally generated wing modes to an internally generated dynamic rotor model (Ref. 10). For all cases analyzed, each rotor was modeled with a gimbal, two bending modes, one

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torsion mode, and flexible pitch links. The airframe was modeled in NASTRAN to get modal data for input into CAMRAD. The left-right symmetry of the XV-15 was exploited by calculating symmetric and antisymmetric modes separately. The CAMRAD analysis included a "rigid" drive train model that included the engine and gearbox inertias, but not drive-train flexibility or damping.

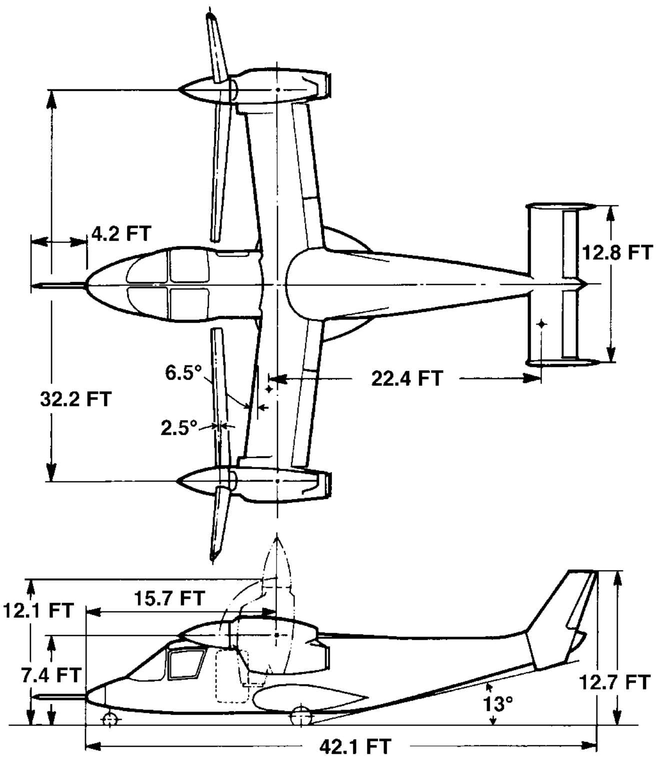

Fig. 1. XV-15 tiltrotor aircraft layout (Ref. 9).

The rotor was trimmed to 458 rpm (76% of hover design rpm), at sea-level standard conditions because it is a nominal design point and highlights the effects of the parametric variations. The aircraft was trimmed to level flight up to the torque-limited airspeed, then allowed to descend as necessary to achieve the desired airspeed at the torque limit. Here a torque limit of 130,000 in-lb was used, reached at 250 knots for the unmodified XV-15.

XV-15 Design Modifications

Initial research efforts suggested that extending masses ahead of the blade leading edge could greatly increase whirl-mode stability (Refs. 5 and 6). In classic flutter theory, the distance between the center of gravity (CG) and the aerodynamic center (AC) is a key parameter. This suggested that moving the AC aft should have effects similar to moving the CG forward. Studies with CAMRAD II showed that both types of offset were beneficial, and more so at the tip than at the root (Refs. 5 and 6). Also, AC offsets were much more effective than CG offsets. These results implied that modest amounts of outboard blade sweep would be beneficial.

Figure 2 shows an example XV-15 blade with a swept tip, having 10° of sweep over the outer 20% radius. Sweep was modeled by sweeping the elastic axis (EA) and quarter-chord (QC) lines. In CAMRAD II, structural and aerodynamic parameters are referenced to the elastic axis and quarter-chord loci, respectively, so they are automatically swept with the EA and QC (Ref. 10). The swept blade in Fig. 2 has its elastic axis and center of gravity swept one-half as much as the quarter chord. Although unconventional, such a blade would be feasible as long as the sweep did not start too far inboard. This maximizes the beneficial effects of sweep. Because the results shown below were more than adequate to illustrate the benefits of the concept, no further optimization of the blade design was undertaken.

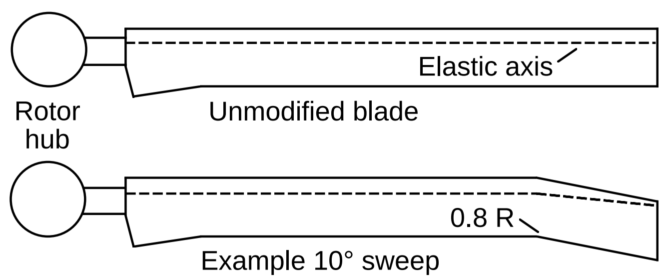

Fig. 2. XV-15 rotor blade planform (45° twist and 1° baseline sweep not shown).

The stiffness of the control system has a strong effect on aeroelastic stability. Previous research (Ref. 6) showed that a large increase in stability was obtained with double the baseline pitch stiffness, but further increases in stiffness yielded progressively diminishing increases in damping. A stiffness factor of two was used for the examples below. The V-22 has roughly three times the scaled pitch stiffness of the XV-15, so a factor of two is reasonable.

XV-15 Delta-Three Effects

To illustrate the benefits of blade sweep, the XV-15 model was destabilized by increasing the magnitude of delta-three. Delta-three (δ_3) is the kinematic coupling between blade flapping and pitch (Ref. 11). As defined herein, positive δ_3 causes nose-down pitching for upwards blade flapping (Fig. 3). This decreases stability for some blade modes, typically lag modes. The realization that negative δ_3 is stabilizing for flap-lag coupling was a major conceptual breakthrough necessary for the successful development of the XV-15 (Refs. 1 and 12).

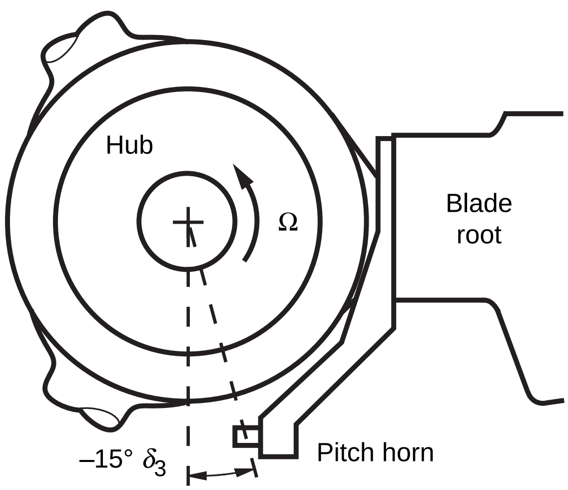

Fig. 3. XV-15 hub and trailing pitch horn.

Because the effective flapping hinge is at the center of rotation of a gimbaled rotor, a literal skewed hinge is not possible on the XV-15, and therefore offset pitch horns must be used. Furthermore, it is extremely difficult to arrange the pitch horns to achieve small values of δ_3 without mechanical interference, especially for rotors with four or more blades. As the magnitude of δ_3 increases, whirl-mode stability rapidly decreases.

These effects constrain practical design values of δ_3 to a narrow range of negative values. The XV-15 design value of δ_3 is –15° (Ref. 9), realized by a trailing, offset pitch horn. All values of δ_3 discussed herein are nominal values; the actual value varies slightly as the pitch horn moves with changing collective and cyclic control inputs.

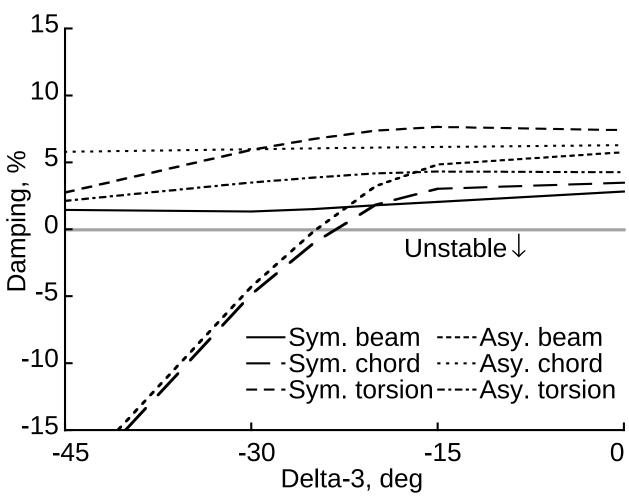

Fig. 4. Variation of damping with δ_3 for the XV-15 and unmodified rotor at 300 knots.

Figure 4 shows the variation of damping with δ_3 for the XV-15 with the unmodified rotor. The airspeed is 300 knots, the design maximum. The damping predicted by CAMRAD II becomes negative between –20° and –25° δ_3. The actual aircraft must have a margin of stability, so the design magnitude of δ_3 must be less than the zero-damping value. Figure 4 indicates that –15° is a reasonable value, which is consistent with XV-15 experience. Damping for positive δ_3 is not shown because certain rotor modes, principally blade lag modes coupled with wing modes, are always unstable.

When the example swept blade of Fig. 2 was combined with doubled control-system pitch stiffness, whirl-mode damping remained positive for δ_3 = –45°. (Fig. 5). This value of δ_3 was the maximum studied because no further increase is necessary for a four-bladed rotor.

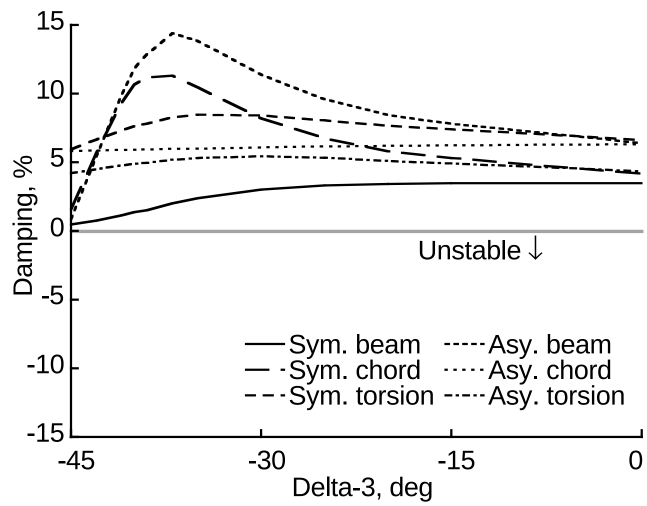

Fig. 5. Variation of damping with δ_3 for the XV-15 with swept blades and twice the baseline pitch stiffness at 300 knots.

V-22 WHIRL-MODE RESEARCH

The logical next step in the research was to apply these concepts to the V-22. A CAMRAD II model of the V-22 was accordingly developed. Figure 6 illustrates the V-22, which has a short, thick wing similar in layout to the XV-15 (Fig. 1), with similar effects on performance.

Simplified V-22 Model

For the purposes of the present research, a simplified CAMRAD model was adequate. The blade, airframe, and aerodynamic models were all simplified, and a simplified trim model was used. Stability predictions by Aeroelastic Stability Analysis of Proprotors (ASAP) — the stability analysis used by Bell Helicopters and validated against flight-test data (Ref. 13) — was used as the reference for checking CAMRAD predictions of the unmodified V-22.

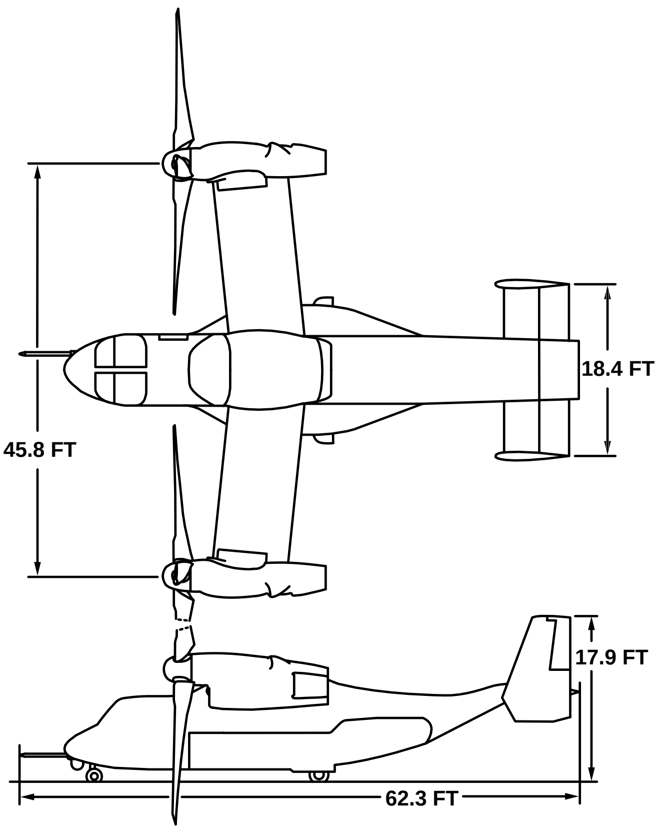

Fig. 6. V-22 aircraft layout.

Figure 7 shows the CAMRAD II model of the V-22 rotor. Rotor airfoils are shown merely to better reveal the blade twist; CAMRAD actually derives its aerodynamic data from external look-up tables (C81 format).

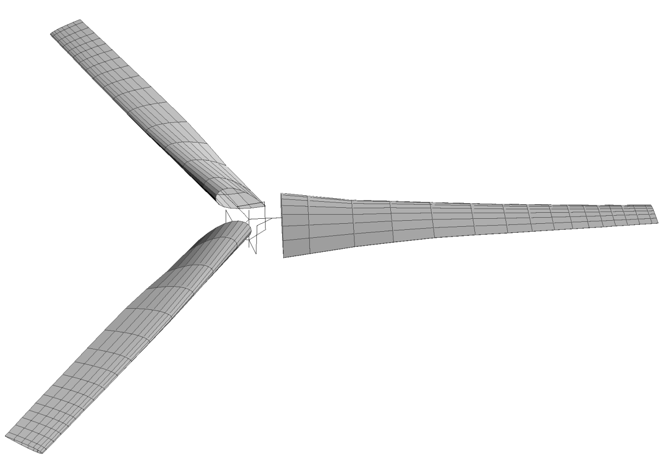

Fig. 7. CAMRAD II model of the V-22 rotor.

Like the XV-15 rotor, the V-22 rotor is stiff-in-plane with a gimbaled hub and –15° δ_3. In contrast to the XV-15, the V-22 rotor structure is mostly composite, with a coning flexure and blade-fold hinges. The aerodynamic sections start with a 36-in chord at 5% radius, linearly tapering to a 22-in chord at the tip. The taper is interrupted by a bump over the blade-fold hinge. Total effective blade twist is 47.5° over a 228.5-in radius. The quarter-chord locus is swept about 1° aft, with the quarter-chord line intersecting the pitch axis at 75% radius, similar to the XV-15.

The actual rotor has a multiple-load-path hub where the centrifugal loads and flap and lag moments are carried by a composite yoke, but pitching moments (hence control loads) are carried by a hollow pitch case ("grip") that surrounds the yoke and pitches with the blade. The yoke does not pitch with respect to the hub. The yoke is less stiff in flap than in lag, such that the yoke constitutes a coning flexure; the at-rest precone is 2.75°. This assembly was modeled in CAMRAD II by a rigid hub and pitch case, connected by a flap/lag joint with very stiff flap and lag springs. The model had a gimbal, three bending modes, one torsion mode, and flexible pitch links. The spring stiffnesses were adjusted to get the blade frequencies predicted by CAMRAD to match predictions by a Myklestad analysis (as used by ASAP).

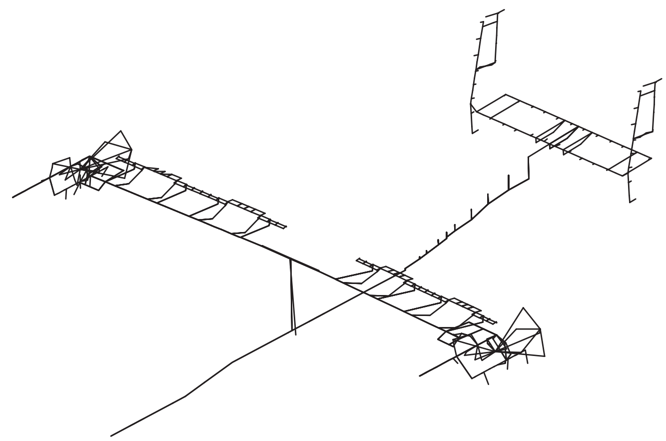

Fig. 8. Elastic-line NASTRAN model of the V-22.

The wing/pylon modes were generated by a 1309-element elastic-line NASTRAN model (Fig. 8), whereas Bell's ASAP predictions were based on a much more complex three-dimensional NASTRAN shell model (about 68,000 elements). Both the ASAP and CAMRAD models used implicit aerodynamic damping for the wing modes, whereby the structural damping of each mode was increased by a constant value to approximate the effects of aerodynamic damping. The drive-train model included drive-shaft modes but no governor.

Both ASAP and CAMRAD were trimmed to zero power (windmill state). The V-22 has a flapping controller that minimizes flapping in flight; this was modeled in CAMRAD simply by assuming axisymmetric, axial flow and by trimming to zero power with collective. This automatically yielded zero flapping. A further simplification was to trim only the rotor; given the assumptions of axisymmetric flow and zero power, there was little to be gained by explicitly trimming the airframe. Accordingly, the automatic flight control system was not modeled. The rotor was trimmed to 332 rpm at 7500 ft altitude to match the reference ASAP predictions.

An incompressible aerodynamic model was used, which always took the values from C81 aerodynamic tables at zero Mach number. This was done in anticipation of tests in a low-Mach-number wind tunnel, for which a full compressible-flow model would be an unnecessary complication.

Despite these simplifications, the stability trends predicted by CAMRAD were generally similar to those predicted by ASAP. To improve the match to the ASAP predictions, the CAMRAD model added additional damping to the symmetric wing torsion mode. The symmetric wing bending mode was less stable than predicted by ASAP, but this serendipitously proved useful for evaluating design modifications and was left unchanged. While not completely rigorous, the simplified CAMRAD model was adequate to investigate the effects of rotor design changes on whirl-mode stability, which is the purpose of the present research.

V-22 Blade Modifications

Following the same logic as the XV-15 research, the V-22 blade model was modified to have 10° of blade sweep over the outer 20% radius. (In contrast to the XV-15 swept blades, the V-22 model swept the elastic axis the same amount as the aerodynamic and mass loci.) Figure 9 shows unmodified and swept V-22 blades.

Figure 10 shows the effects of blade sweep on predicted stability. The reference flight condition was 332 rpm at 400 knots and 7500 ft altitude. The wing beam-bending modes, both symmetric and antisymmetric, are strongly affected by sweep. Because the antisymmetric beam mode is already very stable, Fig. 10(b) was truncated at 30% critical damping. The torsion modes are weakly affected, with stability slowly decreasing as sweep increases. The remaining modes are sufficiently stable to be of no concern.

The mass was sized to balance the additional mass moment (first-order) added by the sweep. Figure 11 shows the stability for the swept blade with varying chord-balance mass. Compared to Fig. 10, all modes become stable at a much lower value of sweep (about 4°). Furthermore, torsion-mode damping declines very little with sweep, and even increases at high sweep values for antisymmetric torsion. The rate of increase in damping begins to decline above about 12° of sweep, most evidently for the symmetric beam mode, so the analysis was stopped at 14°.

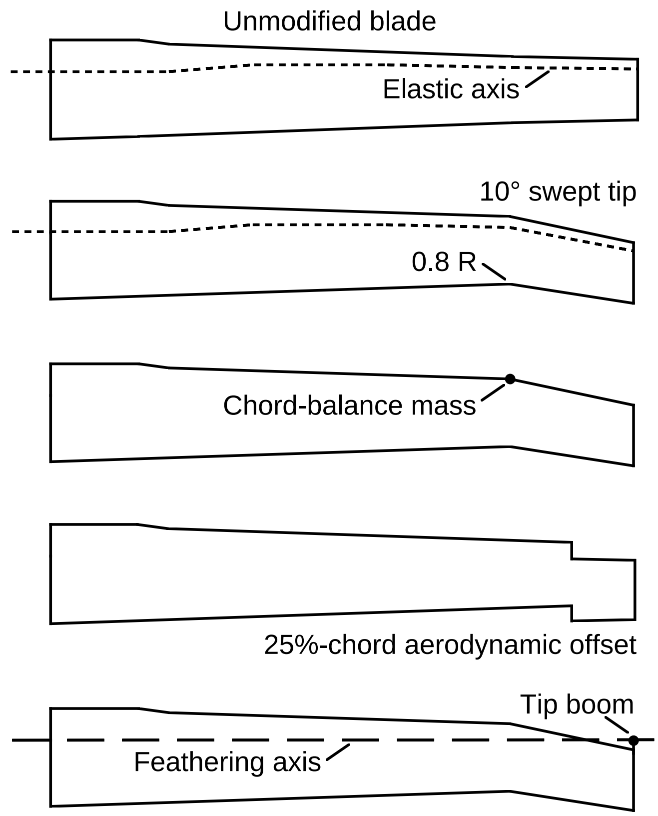

Fig. 9. V-22 rotor blade planform (47.5° twist not shown).

The effects of control-system stiffness were also investigated. Only a slight improvement in stability was seen, even for very large (factor of 20) increases in stiffness. This contrasts sharply with the results of XV-15 analyses (Ref. 6). The reason is that the coning flexure reduces the elastic precone that causes pitch-lag coupling. (Reference 2 has a concise description of the relationship between precone and pitch-lag coupling; see also Ref. 14.) Stiffening the control system reduces the adverse effects of pitch-lag coupling on stability. The V-22 coning flexure provides the same benefit as a stiffer control system, so further increases in stiffness are of little additional benefit. Control-system stiffness was retained at the nominal design value for all V-22 predictions illustrated herein.

Although clearly helpful, blade sweep had a less powerful effect on V-22 stability than on the XV-15. To determine why, the effects of pure mass and aerodynamic offsets were examined. The outer 50% of the blade was analytically divided into five equal sections, and either the center of gravity (CG) or aerodynamic center (AC) was offset chordwise by 25% of local chord. AC offsets were modeled by shifting the entire airfoil with respect to the blade structure (Fig. 9). CG offsets were towards the leading edge, and AC offsets were towards the trailing edge. Only one type of offset at one radial station was applied at a time.

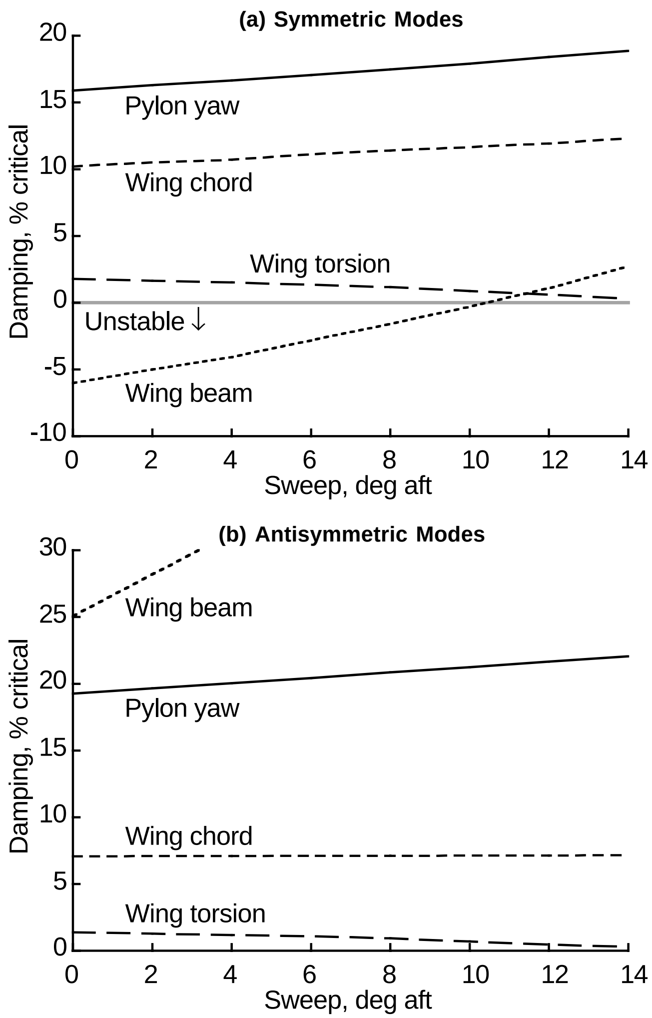

Fig. 10. Variation of damping with sweep at 400 knots.

The results are shown in Fig. 12 for the symmetric beam mode. Both types of offset show strong nonlinearities near the tip. AC offsets were more beneficial than CG offsets, implying that, as for the XV-15, sweep would provide a net benefit. However, the nonlinearities reduced the benefit at the tip, where the offset created by sweep was largest. Hence sweep was necessarily less beneficial for V-22 stability than for the XV-15. It is possible that re-optimizing sweep, with less sweep starting further inboard, could provide a greater net increase in stability. However, design optimization was beyond the scope of this research.

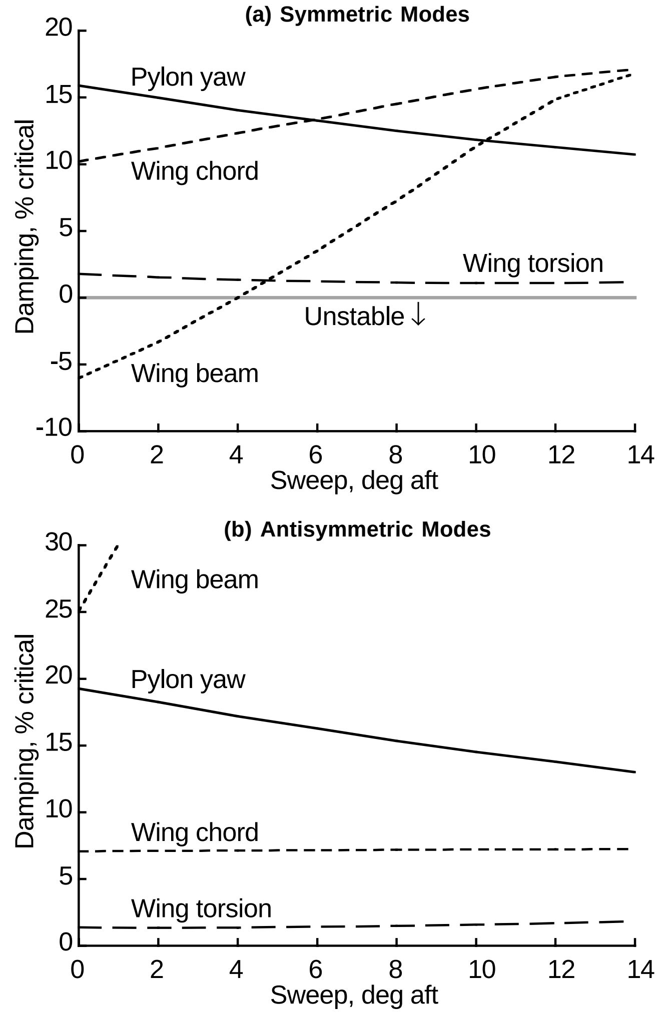

Fig. 11. Variation of damping with sweep 400 knots, with chord-balance weights at 80% radius.

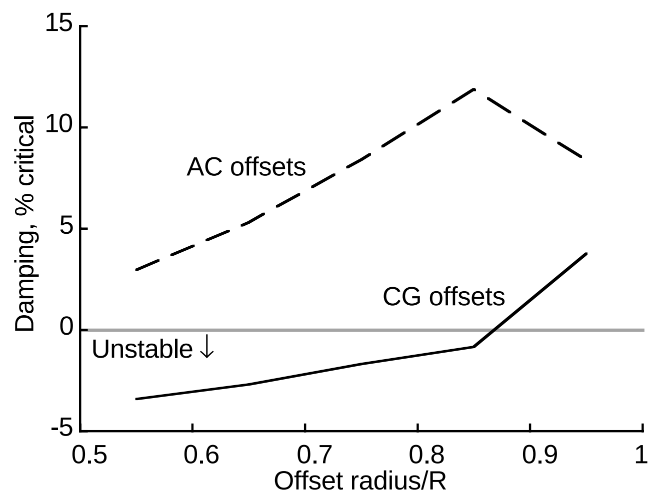

Fig. 12. Variation of symmetric wing beam-bending mode damping with aerodynamic and mass offset radial position; all offsets are 25% of chord.

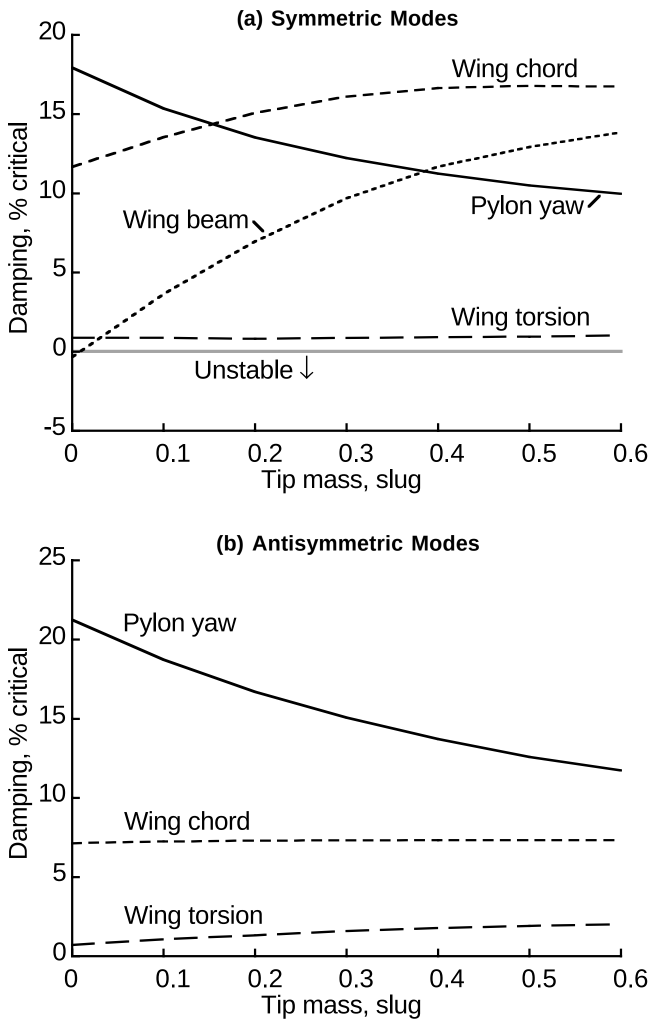

Fig. 13. Variation of damping with tip mass for the 10° swept tip; the mass is located on the feathering axis.

Although they partially negate the effects of sweep, the nonlinearities of Fig. 12 suggest a different design solution: a weighted tip boom, similar to those used on some swept-wing aircraft. Figure 13 shows the trends in stability for a tip mass added to the 10° swept rotor. The mass is positioned at the feathering axis (pitch-change axis) in the local chord plane, which is about 3.6 in ahead of the leading edge (Fig. 9). The tip mass has a strong positive effect on the symmetric beam mode. (The antisymmetric beam mode was always extremely stable and was well off the top of the plot.) Less than a pound of mass is enough to completely stabilize the system. This is less than the nominal values of tip weights used to balance the rotor. The pylon yaw modes are adversely affected, but they are already so stable as to be of no concern.

The effects of a tip mass alone, without blade sweep, are shown in Fig. 14. Here, the mass is extended ahead of the leading edge by the same amount as for Fig. 13, but the absence of blade sweep places the mass about 8 in ahead of the feathering axis. The trends of stability with mass value are similar to those of Fig. 13, except for the antisymmetric pylon mode, where the (negative) slope is reduced. Nearly 6 lb of mass are needed to stabilize the rotor.

The tip-mass analyses bring the present research full circle to its starting point, which was a balsa wood model of a teetering rotor with adjustable tip masses (Refs. 5, 6, and 15). Analyses of the XV-15 rotor with a tip boom yielded poor results. It was not until the tip boom was combined with blade sweep on the V-22 rotor that the original promise of the concept was fulfilled.

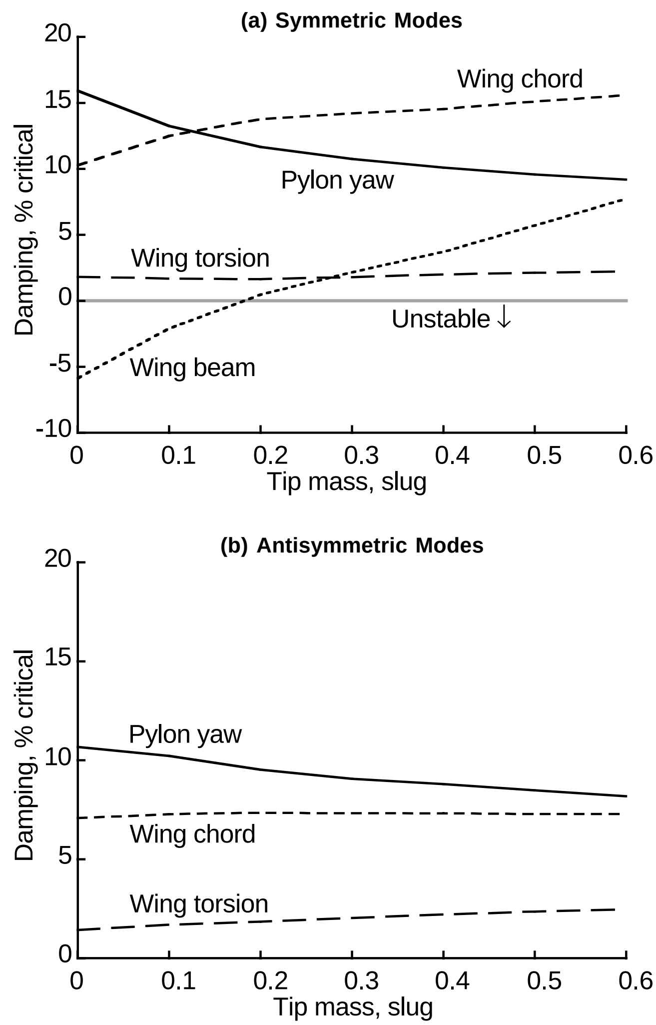

Fig 14. Variation of damping with tip mass for the unswept blade; the mass is located 3.6 in ahead of the leading edge.

"SPAR" EXPERIMENTAL CONCEPT

The most significant limitation to the XV-15 research reported above is the near-total lack of experimental verification. An extremely simple, balsa-wood model, driven by an ordinary box fan, provided much of the initial impetus for the present research (Refs. 5 and 6). However, that model was far too crude to reliably validate the analytical predictions.

The premier proprotor whirl-flutter research facility is the Wing and Rotor Aeroelastic Test System (WRATS), operated in the Transonic Dynamics Tunnel (TDT) at the NASA Langley Research Center. This is a 1/5-scale, semi-span aeroelastic model of the V-22 (Fig. 15). Although the TDT is the preferred test facility for proprotor aeroelasticity tests, its size, complexity and cost preclude routine use for conceptual studies of the sort suggested herein. It is planned to eventually use WRATS to test the advanced rotor concepts described herein, but it is highly desirable to preselect the most promising designs with simpler experiments.

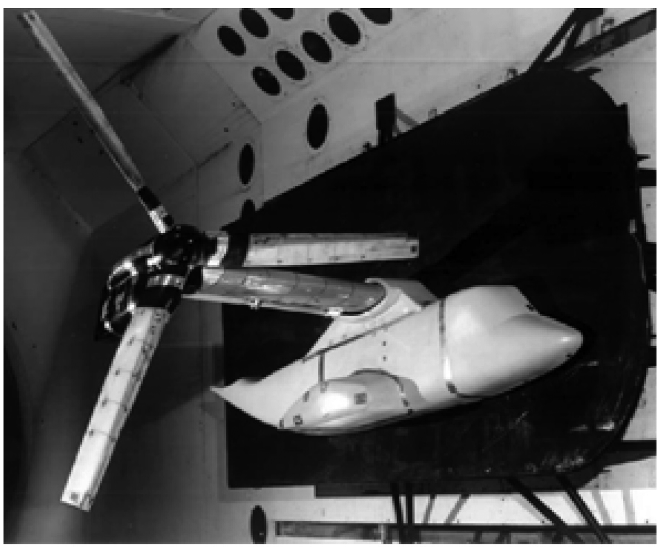

Fig. 15. WRATS 1/5-scale aeroelastic V-22 model mounted in the Langley TDT.

The desire for a simpler and cheaper test facility led to a proposal for a 1/10-scale XV-15 semi-span model, dubbed Small-scale Proprotor Aeroelastics Rig (SPAR). New rotor design concepts could be tested on SPAR relatively quickly and cheaply; the most promising designs could then be scaled up to WRATS for definitive evaluation.

Intended for use in the NASA Ames Research Center 7x10-ft Wind Tunnel, SPAR will be a scaled-down version of the Dynamic Test Stand operated in the Ames 40x80-ft Wind Tunnel in the 1970's (Refs. 1 and 16). To minimize cost, as much of SPAR as possible will be assembled from off-the-shelf hardware originally designed for radio-controlled (R/C) helicopter models. The increasing popularity and sophistication of R/C models makes such an approach much more technically feasible and affordable than heretofore.

SPAR will be a 1/10-Froude-scale XV-15 rotor and wing. Froude scaling is not actually necessary, but the resulting characteristics are well-suited to the 7x10-ft wind tunnel. Far more important is frequency scaling, whereby all rotor and wing frequencies are maintained at the same ratios to the rotor rotational rate (Ω). Advance ratio $V/\Omega R$ (tunnel velocity divided by rotation rate times rotor radius) must also be matched. Wind tunnel operational limits determine maximum allowable V, and test-section dimensions determine maximum practical R, hence the scale factor. If Froude scaling is used to determine Ω, advance ratio then determines V at the stability boundary. 1/10 Froude scaling yields a stability boundary comfortably within the 7x10-ft wind-tunnel operating range. Figure 16 is a conceptual sketch of SPAR installed in the 7x10-ft test section.

Although conceptually based on the Dynamic Test Stand with idealized 1/10 Froude scaling, SPAR will be simplified as much as possible to keep costs down. A conventional swashplate will be used below the rotor instead of a scaled XV-15 "spider" above the rotor. Delta-three and effective control-system stiffness will not be matched exactly, but the effects of these deviations from perfect scaling are readily analyzable, so the validity of the test data will not be compromised.

The blades will have constant chord — a very minor compromise for an XV-15 model. If possible, the blade design will be further simplified to have constant section properties. Linear twist will also be studied in hopes of additional cost savings. As with the control system design, it is critical that stability analyses be performed to ensure that aeroelastic tests remain valid. The point is not to perfectly model the XV-15 or any other rotor, but to reliably demonstrate the effects of rotor design modifications on whirl flutter.

Although generally well-sized for SPAR, available R/C hardware must be modified for use with an aeroelastic stability model. Compared to a perfectly-scaled XV-15 hub, the hub and pitch hinges are slightly oversized, and there is no gimbal or precone. A new hub centerblock with a gimbal and precone will be built. Because the rotor will operate in windmill state, the gimbal will carry negligible torque loads, so a very small gimbal bearing set is feasible.

The pylon, a scaled half-span wing, is conceived as a simple, welded aluminum box beam with a floating airfoil. The air-

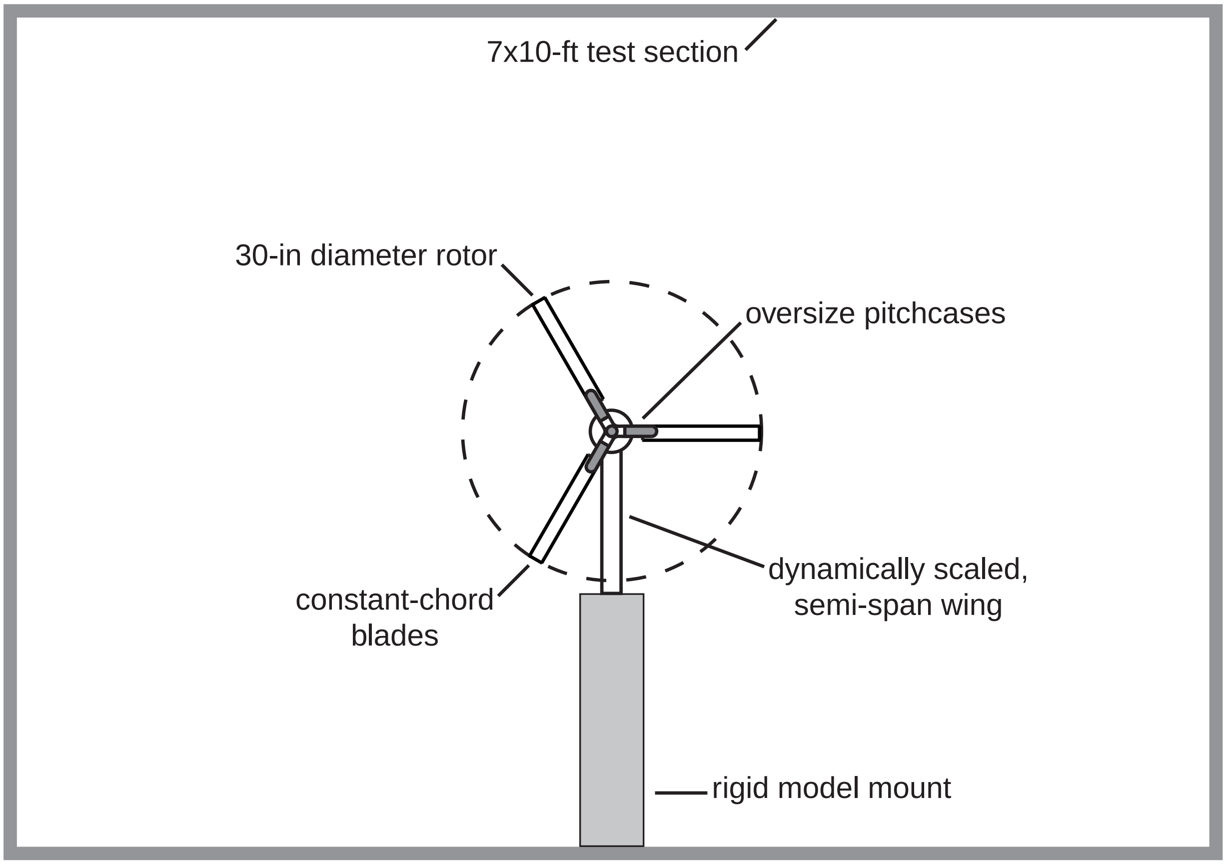

Fig. 16. SPAR model mounted in the 7x10-ft test section (rotor and test section drawn to scale).

foil will be structurally independent of the box beam. This will allow the beam to be more easily modified to match the dynamic characteristics of other aircraft wings, such as the V-22. The entire wing/pylon assembly will be mounted on a very stiff (effectively rigid) model support to elevate the rotor to the center of the test section (Fig. 16).

An obvious question is, why model the XV-15 and not the V-22? The inboard portion of the V-22 rotor uses a hollow pitch case (grip) to transfer pitch-link forces to the rotor; inside the pitch case is a yoke that carries the flap and lag loads. The yoke includes a coning flexure. In contrast, the XV-15 uses a conventional pitch hinge that carries all flap and lag loads through its spindle; there is no coning hinge or flexure.

Modeling the dual-load-path grip and yoke system at small scale is much more difficult than modeling the XV-15 pitch hinge. The XV-15 can be modeled by modifying readily available R/C model hardware, whereas the V-22 would require a completely custom hub, at much greater cost. An XV-15 model would be completely adequate to demonstrate the design concepts discussed herein, so there is no justification for a more expensive V-22 model. However, SPAR is designed to allow substitution of different hubs and blades in the future, should modeling the V-22 or other rotor concepts become desirable.

CONCLUDING REMARKS

Based on previous XV-15 research, the V-22 was analyzed with CAMRAD II to evaluate the effects of blade sweep and other design changes on aeroelastic stability (whirl flutter). Modest amounts of blade sweep (10°) at the tip (outer 20% radius) substantially increased the stability of the least stable modes, especially the symmetric wing beam mode. However, other modes, notably the wing torsion modes, were little affected.

The effects of sweep were considerably enhanced by adding either a chord-balance mass to compensate for the aft shift in tip center of gravity with sweep, or by adding a tip mass on a boom extended slightly ahead of the leading edge. A tip mass smaller than the standard tip weights and located less than a quarter-chord ahead of the leading edge was enough to stabilize the rotor with a 10° swept tip.

Several avenues of future analytic research present themselves, most obviously further refinements of the V-22 CAMRAD model and true design optimization of blade sweep, tip masses, etc. This would logically follow on to redesigns of the wing and rotor to take advantage of the performance improvements enabled by the increased stability margins.

However, much higher priority should be given to acquiring experimental data to confirm the existing analyses. A design effort is underway to produce a small-scale wind-tunnel model of the XV-15 rotor and pylon. The challenge is to keep the cost low while maintaining representative dynamics. The use of radio-controlled model hardware, modified for use in a wind tunnel, will greatly help to achieve this goal.

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