EXPERIMENTAL AND ANALYTICAL STUDIES IN TILT-ROTOR AEROELASTICITY

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Abstract

An overview of an experimental and analytical research program underway within the Aeroelasticity Branch of the NASA Langley Research Center for studying the aeroelastic and dynamic characteristics of tilt-rotor VTOL aircraft is presented. Selected results from several joint NASA/contractor investigations of scaled models in the Langley transonic dynamics tunnel as well as some results from a test of a flight-worthy proprotor in the NASA Ames full-scale wind tunnel are shown and discussed with a view toward delineating various aspects of dynamic behavior peculiar to proprotor aircraft. Included are such items as proprotor/pylon stability, whirl flutter, gust response, and blade flapping. Theoretical predictions, based on analyses developed at Langley, are shown to be in agreement with the measured stability and response behavior.

Notation

e	Blade flapping hinge offset
H	Rotor normal shear force
$\partial H/\partial \alpha_m$	Rotor normal shear force component in phase with pitch angle
$\partial H/\partial q$	Rotor normal shear force component in phase with pitch rate
R	Blade radius
$\bar{R}$	0.75 blade radius
ΔT	Rotor perturbation thrust
V	Airspeed
$V_F/\Omega R$	Flutter advance ratio
w_g	Vertical component of gust velocity
α_m	Mast angle of attack
α_o	Oscillation amplitude of airstream oscillator
β	Blade flapping angle
$\partial\beta/\partial\alpha_m$	Blade flapping derivative
δ_3	Pitch-flap coupling angle
ϵ_g	Gust-induced angle of attack
ζ_R	Hub damping ratio
$\dot{\psi}$	Aircraft yaw rate
Ω	Rotor rotational speed
ω	Frequency
ω_β	Blade flapping natural frequency
ω_θ	Pylon pitch frequency
ω_ψ	Pylon yaw frequency

The feasibility of the tilt-proprotor composite aircraft concept was established in the mid 1950's on the basis of the successful flight demonstrations of the Bell XV-3 and Transcendental Model 1-G and Model 2 convertiplanes. Flight research conducted with the XV-3 identified several dynamic deficiencies in the airplane mode as technical problems requiring further attention.[1] A more serious proprotor dynamic problem was identified in a 1962 wind-tunnel test of the XV-3. In that test, conducted in the Ames full-scale tunnel, a proprotor/pylon instability similar in nature to propeller whirl flutter was encountered. Clearly, to maintain the viability of the tilt-proprotor concept it remained to demonstrate that neither the whirl flutter anomaly nor the major flight deficiencies were endemic to the design principle. An analytical and experimental research program having this objective was undertaken by Bell in 1962. Results of this research, which defined the instability mechanism and established several basic design solutions, were reported by Hall.[2] Edenborough[3] presented results of subsequent full-scale tests at Ames in 1966 which verified the analytical prediction techniques, the proposed design solutions, and demonstrated stability of the XV-3 through the maximum wind-tunnel speed of 100 m/s (195 kts).

In 1965 the U.S. Army inaugurated the Composite Aircraft Program which had the goal of producing a rotary-wing research aircraft combining the hovering capability of the helicopter with the high-speed cruise efficiency and range of a fixed-wing aircraft. Bell Helicopter Company, with a tilt-proprotor design proposal, was awarded one of two exploratory definition contracts in 1967. The Model 266 was the design resulting from their work (Fig. 1). The research aircraft program which was to have been initiated subsequent to the exploratory definition phase was never begun, however, primarily due to lack of funding.

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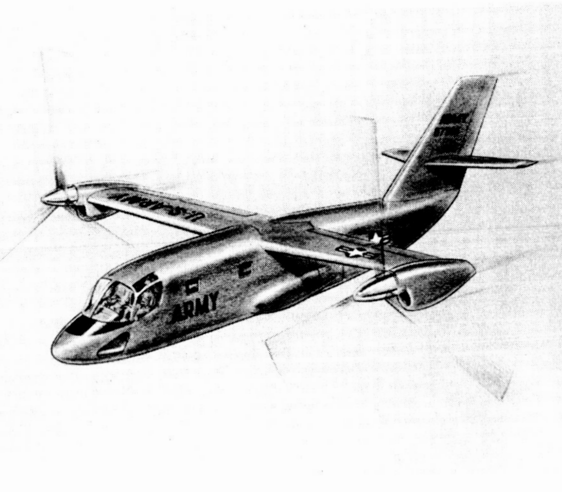

Figure 1. Artist's conception of Bell Model 266 tilt-proprotor design evolved during the Army Composite Aircraft Program.

Concurrent with the developments described above, various VTOL concepts based on the use of propellers having independently hinged blades were proposed with several reaching flight-test status. These included the Grumman proposal in the Tri-Service VTOL Transport competition, the Vertol VZ-2 built for the Army, and the Kaman K-16 amphibian built for the Navy. A vigorous investigation of the whirl flutter phenomenon peculiar to conventional propellers had been initiated in 1960 as a result of the loss of two Lockheed Electra aircraft in fatal accidents. The possibility that hinged blades could adversely affect the whirl flutter behavior of a propeller undoubtedly contributed considerable impetus to examine the whirl flutter characteristics of these flapping propellers. Work related to these efforts was reviewed by Reed.[4]

The foregoing constitutes a résumé of proprotor-related experience through 1967. This paper will present an overview of a research program initiated within the Aeroelasticity Branch of the NASA Langley Research Center. Included in this program are joint NASA/contractor wind-tunnel investigations of scaled models in the transonic dynamics tunnel and the in-house development of supporting analyses. For completeness, motivating factors leading to the work and the scope of the investigation are outlined below.

A 0.133-scale semispan dynamic and aeroelastic model of the Model 266 tilt rotor built by Bell in support of their work pertaining to the Composite Aircraft Program was given to Langley by the Army in 1968. The availability of this model and the interest of both government and industry in the tilt-rotor VTOL aircraft concept suggested the usefulness of continuing the experimental work initiated by Bell with the model to further define the aeroelastic characteristics of proprotor-type aircraft. Because both the XV-3 experience and studies conducted during the Composite Aircraft Program identified certain high-risk areas associated with operation in the airplane mode of flight, specifically proprotor/pylon stability (whirl flutter), blade flapping, and flight mode stability, it was judged that the research effort would be primarily directed to these areas.

The experimental portion of the research program was initiated in September 1968 in a joint NASA/Bell study of proprotor stability, dynamics, and loads employing the 0.133-scale semispan model of the Model 266. Several other cooperative experimental studies followed this investigation. The models employed in these studies are positioned in chronological order in the composite photo given in Figure 2. Briefly, these other studies included: (1) A study of a folding proprotor version of the tilt-rotor model used in the first study, (2) a parametric investigation of proprotor whirl flutter, (3) a stability and control investigation employing an aerodynamic model, and (4) a "free-flight" investigation of a complete tilt-rotor model.

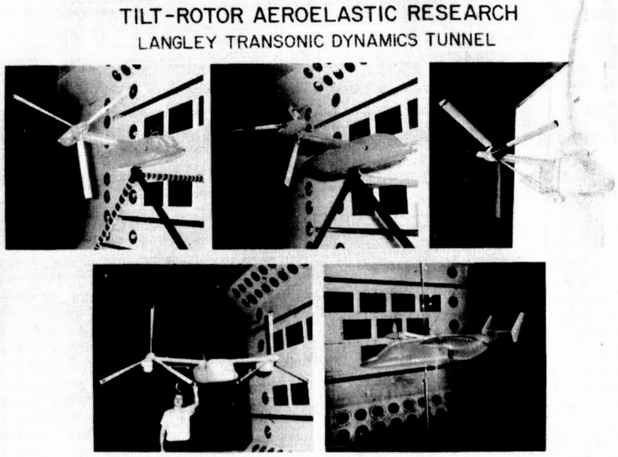

Figure 2. Tilt-rotor models tested in the Langley transonic dynamics tunnel.

The results pertaining to the above-mentioned studies are quite extensive. The particular results to be presented herein have been selected with a view toward highlighting some of the dynamic aspects of proprotor behavior, delineating the effects of various design parameters on proprotor/pylon stability and response, and providing validation of analyses developed at Langley. The results pertaining to investigations conducted in the Langley transonic dynamics tunnel are presented first. These are arranged in chronological order according to Figure 2. To provide additional data for correlation, some experimental results obtained by Bell in tests of a semispan model and a full-scale flight-worthy proprotor are also included. In each case both experimental and analytical results are for the pylon fully converted forward into the airplane mode of operation and the rotors in a windmilling condition. Equivalent full-scale values are given unless noted otherwise.

Model Tests in Langley Transonic Dynamics Tunnel

Bell Model 266

(a) September 1968

Although the 0.133-scale semispan model of the Bell Model 266 was not designed to permit extensive parametric variations, in that it represented a specific design, it did permit a fairly diversified test program. The principal findings of this investigation have been published and are available in the literature.[5,6] Some results adapted from Reference 6 pertaining to stability and gust response are discussed below.

Proprotor/Pylon Stability. To provide an indication of the relative degree to which stability could be affected, and to provide a wide range of configurations for correlation with analysis, several system parameters were varied either individually or in combination with other parameters and the level of stability established.

A baseline stability boundary, based on a reference configuration, was first established. The degree to which stability could be affected was then ascertained by varying selected system parameters (or flight conditions). Stability data were obtained by holding rpm constant as tunnel speed was incrementally increased, transiently exciting the model by means of lightweight cables attached to the model, and analyzing the resulting time histories to determine the damping. The reference configuration consisted of the basic Model 266 parameters with the pylon yaw degree of freedom locked out and the wing aerodynamic fairings removed. A 100% fuel weight distribution was maintained by appropriately distributing lead weights along the wing spar. The hub flapping restraint was set to zero and the δ_3 angle to -0.393 radian (-22.5°). The reference stability boundary as well as changes in this boundary due to several parameter variations are shown in Figure 3.

For the reference configuration instability occurred in the coupled pylon/wing mode in which the pylon pitching angular displacement is in phase with the wing vertical bending displacement. A characteristic feature of this coupled mode is the predominance of wing bending (relative to pylon pitch) and the frequency of oscillation, which is near the fundamental wing vertical bending natural frequency. For descriptive purposes this flutter mode is termed the "wing beam" mode herein. Negligible wing chordwise bending or rotor flapping (relative to space) was observed. The pylon/rotor combination also exhibited a forward whirl precessional motion, the hub tracing out an elliptical path in space. However, because of the large ratio of pylon yaw to pylon pitch stiffness the pylon angular displacement was primarily in the pitch direction. The flutter mode of the model in each of its perturbations from the reference configuration was essentially the same as for the reference configuration.

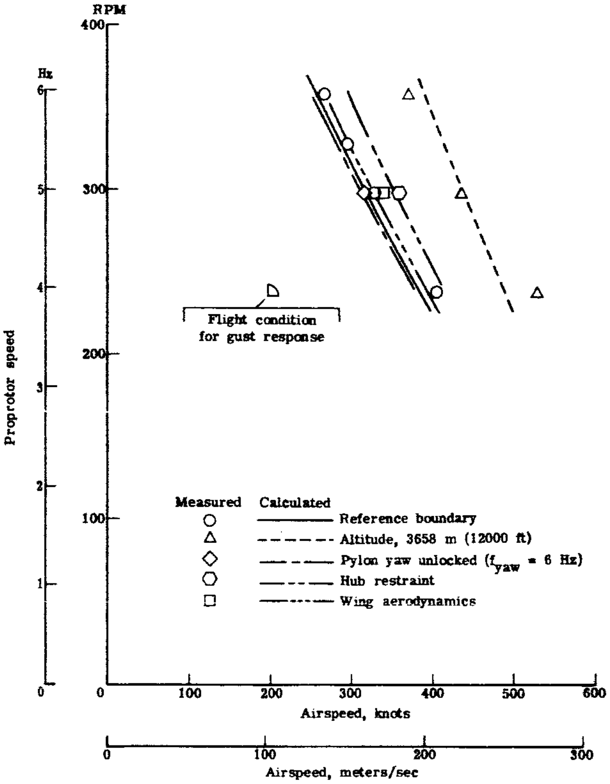

Figure 3. Effect of several system parameters on proprotor/pylon stability.

The proprotor/pylon instability described above is similar in nature to classical propeller whirl flutter. However, because of the additional flapping degrees of freedom of the proprotor the manner in which the precession generated aerodynamic forces act on the pylon is significantly different.[6] Specifically, while aerodynamic cross-stiffness moments are the cause of propeller whirl flutter, the basic destabilizing factors on proprotor/pylon motion are aerodynamic in plane shear forces which are phased with the pylon motion such that they tend to increase its pitching or yawing velocity and, hence, constitute negative damping on the pylon motions.

(1) Altitude – Altitude has a highly beneficial effect on proprotor/pylon stability. This increased stability is a consequence of the fact that the destabilizing rotor normal shear forces decrease with altitude for pylon pitch frequencies near the fundamental wing elastic mode frequencies. This means that a given level of these destabilizing shear forces is attained at progressively higher airspeeds as altitude increases.

(2) Hub Flapping Restraint – A stabilizing effect due to moderate flapping restraint is also indicated in Figure 3. Increasing the flapping restraint increased the flapping natural frequency from its nominal value of about 0.80/rev bringing it closer to the "optimum" flapping frequency in the sense of Young and Lytwyn.[7] They showed that this increased stability because the pylon support

stiffness requirements were reduced as the optimum flapping frequency was approached.

(3) Wing Aerodynamics – Figure 3 indicates that wing aerodynamic forces have a slight stabilizing effect. Now the stiffness of a strength-designed wing for tilt-rotor application is generally sufficiently high to relegate the flutter speed of the pylon/wing combination (with blades replaced by lumped concentrated weights) to speeds well beyond the proprotor mode flight envelope. This suggests that wing aerodynamics will contribute primarily to the damping of any coupled rotor/pylon motions. This is substantiated in Figure 4, which shows the variation of the wing beam mode damping with airspeed through the flutter point for the reference configuration and the corresponding configuration with the wing airfoil segments installed. The damping of the mode is increased; however, the magnitude of the increase is small indicating that proprotor aerodynamic forces are predominant in the ultimate balance of forces at flutter. This provides some justification for neglecting, in this flutter mode at least, wing aerodynamics as a first approximation.

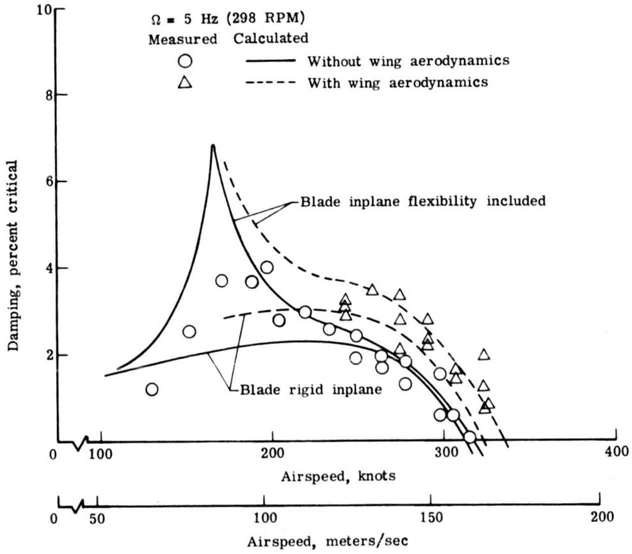

Figure 4. Comparison of measured and calculated wing beam mode damping for reference configuration.

The initial increase in the stability of the wing beam mode before instability occurs is associated with the fact that $\partial H/\partial q$, the component of the normal shear force associated with pylon pitch rate, initially becomes more stabilizing with increasing airspeed until $\partial H/\partial \alpha_m$, the component of the normal shear force in phase with pylon pitch angle, becomes sufficiently large to lower the coupled pylon pitch frequency to a level where $\partial H/\partial q$ becomes increasingly destabilizing with increasing airspeed.[6] The increased damping response at about 103 m/s (200 kts) is due to coupling of the blade first inplane cyclic mode with the wing beam mode. Note, however, that the predicted flutter speed is not sensitive to blade inplane flexibility for the Model 266.

(4) Pylon Restraint – When the pylon yaw stiffness was reduced by unlocking the pylon yaw degree of freedom and soft-mounting the pylon in yaw relative to the wing tip the stability decreased slightly (Fig. 3). The particular yaw flexibility employed in this variation effectively produced a more nearly isotropic arrangement of the pylon support spring rates. Since the region of instability in a plot of critical pylon yaw stiffness against critical pitch stiffness is extended along the line representing a stiffness ratio of unity, the configuration approaching isotropy in the pylon supports is more prone to experience an instability than one in which one of the stiffnesses is significantly less than the other.

The general trend of decreasing stability with increasing rotor speed shown in Figure 3 was found for all values of the adjustable parameters of the model. In each case the predicted flutter mode and frequency were in agreement with the corresponding measured mode and frequency.

Gust Response. Analytical methods for determining aircraft response to turbulence are usually based on power spectral analysis techniques which require the definition of the aircraft frequency response function, that is, the response to sinusoidal gust excitation. A study to assess the feasibility of determining these frequency response functions for fixed-wing aircraft utilizing models in a semi-free-flight condition using a unique airstream oscillator system in the transonic dynamics tunnel has been underway within the Aeroelasticity Branch for several years.[8] This system (Fig. 5) consists of two sets of biplane vanes located on the sidewalls of the tunnel entrance section. The vanes can be oscillated in phase or 180° out of phase to produce nominally sinusoidal vertical or rolling gusts, respectively, over the central portion of the tunnel. The gusts are generated by the cross-stream flow components induced by the trailing vortices from the tips of the vanes. With a

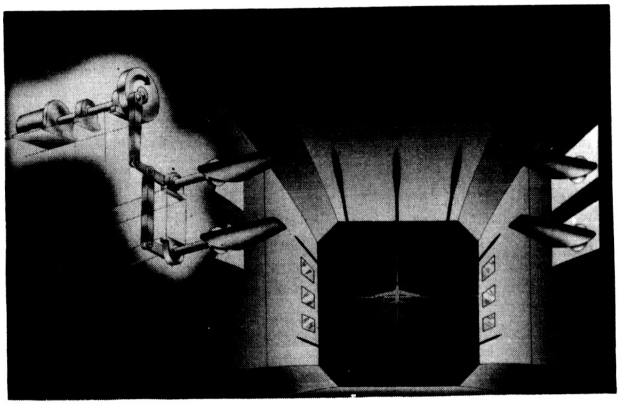

Figure 5. Langley transonic dynamics tunnel airstream oscillator showing cutaway of driving mechanism.

view toward the possible application of this technique to rotary-wing aircraft the airstream oscillator was employed to excite the model for several "flight" conditions below the proprotor stability boundary. Although the model was not "free" the data so obtained did give an indication of the frequency response characteristics of the cantilevered model and permitted the evaluation of the effects of airspeed, rotor speed, and rotor and wing aerodynamics on the overall dynamic response.

A measure of the gust-induced angle of attack (or stream angle) was provided by means of a small balsa vane flow direction transmitter (see Fig. 6) which gave readings proportional to the stream angle. The variation of the vertical component of the stream angle for in phase (symmetrical) oscillation of the biplane vanes is shown in Figure 7. The curve shown is actually an average of data obtained from runs at several tunnel speeds and air densities. The amplitude of the stream angle has been normalized on the maximum amplitude of oscillation of the biplane vanes and plotted against the frequency parameter ω/V, where ω is the frequency of oscillation of the biplane vanes in rad/sec and V is the tunnel speed in m/s (ft/sec). This parameter is proportional to the reciprocal of the wavelength (spacing) between vortices shed from the tips of the oscillating vanes.

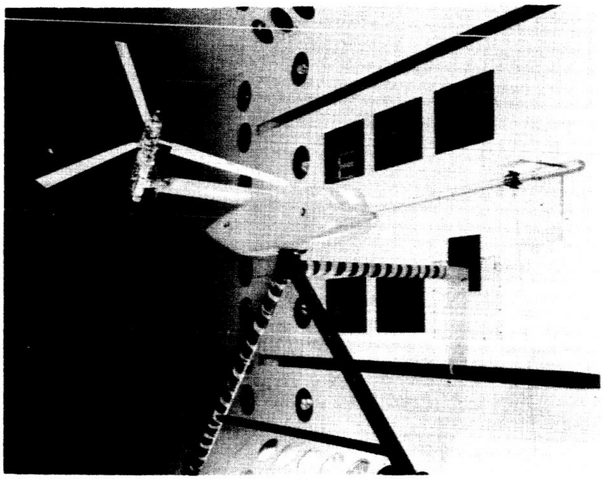

Figure 6. 0.133-scale semispan tilt-rotor model in simulated conversion mode showing boom-mounted flow direction transmitter.

The frequency response of wing vertical bending moment was taken as one measure of system response to vertical gust excitation. To ascertain the relative influence of rotor and wing aerodynamics, three model configurations were employed: wing only, with the rotor blade weight replaced by an equivalent lumped weight; rotor only, with the wing aerodynamic fairings removed; wing and rotor combined. For the "flight" condition indicated in Figure 3 the relative effects of rotor and wing aerodynamics are displayed in Figures 8 and 9. In each of these figures the wing bending moment has been normalized by the maximum amplitude of the stream angle using the curve of Figure 7.

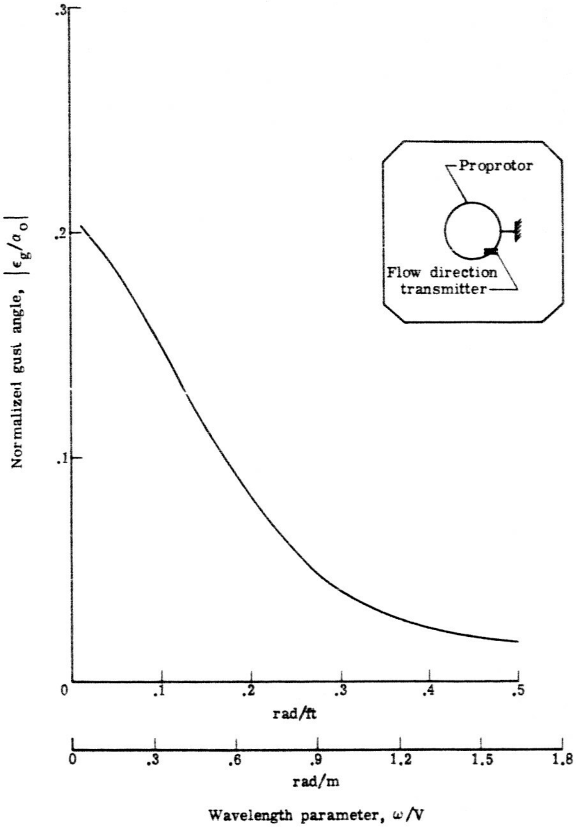

Figure 7. Measured variation of vertical component of gust angle with frequency parameter for vanes oscillating in phase.

Comparison of the rotor-on and rotor-off response curves for the wing panels on configuration is shown in Figure 8. Two proprotor-related effects are indicated: first, the significant contribution of the rotor inplane normal force (H-force) to wing bending response, as indicated by the relative magnitudes of the bending moments; and second, the rotor contribution to wing beam mode damping,* as indicated by the relative sharpness of the resonance peaks. The peak amplitudes occur when the gust frequency is in resonance with the wing beam mode frequency. The peak for the blades-off condition is shifted to the higher frequency side of the rotor-on peak because the rotor H-force decreases the frequency of the wing beam mode. For the rotor-on case the bending moment is considerably larger than for the rotor-off case throughout the range of gust frequencies investigated. The wing chord mode frequency (about 2.8 Hz) is within the gust frequency range but is absent from the response curves because the gust excitation is

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*At this particular airspeed, the rotor was still contributing positive damping to the wing beam mode.

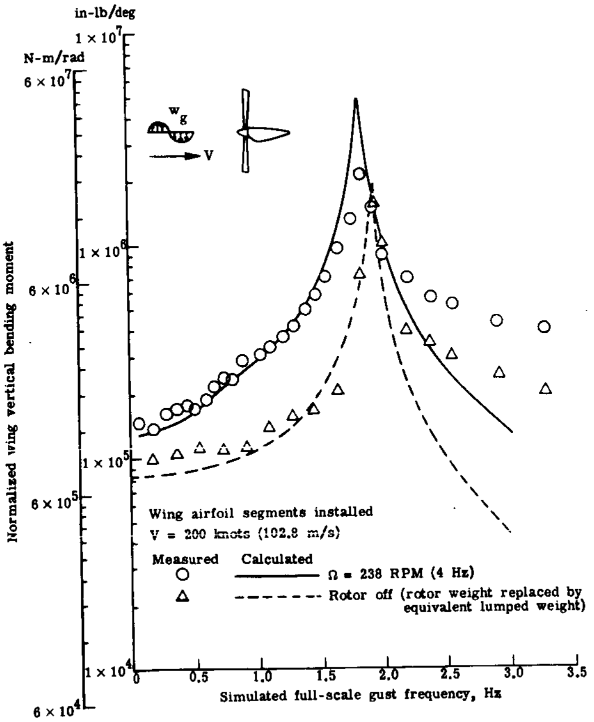

Figure 8. Effect of proprotor aerodynamics on wing root bending moment amplitude response function.

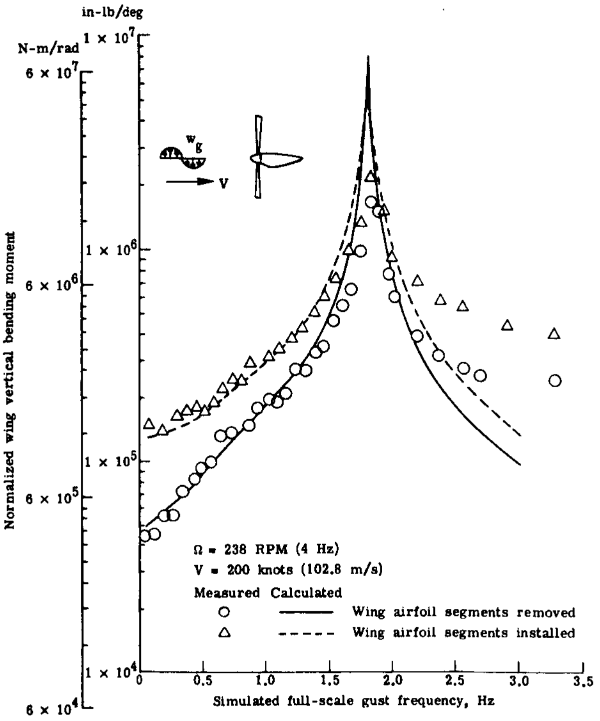

Figure 9. Effect of wing aerodynamics on wing root bending moment amplitude response function.

primarily vertical and there is very little coupling between the wing beam and chord modes.

Figures 8 and 9 quite clearly illustrate that proprotors operating at inflow ratios typical of tilt-rotor operation in the airplane mode of flight are quite sensitive to vertical gusts. This sensitivity is due to the fact that the proprotors, being lightly loaded in the airplane mode of flight, operate at low blade mean angles of attack ($\bar{\alpha}$) and any gust-induced angle of attack is a significant fraction of $\bar{\alpha}$.

Note that good correlation is achieved for frequencies up to about 2 Hz beyond which the calculated responses are much lower than the measured values. This discrepancy is thought to be a consequence of the deviation of the induced gust from its nominally one-dimensional nature to one which is highly two-dimensional (i.e., varies laterally across the tunnel) at the higher frequencies. The analytical results shown are based on the assumption of a one-dimensional gust. Unsteady aerodynamic effects may also be a contributing factor to the discrepancy.

A comparison of the wing panels-on and wing panels-off response curves for the rotor-on configuration is given in Figure 9. As might be expected, the wing response for the case in which the wing airfoil segments are installed is higher than for the rotor alone. The reduced magnitude of the response at resonance for the rotor-plus-wing combination relative to the rotor alone is due to the positive damping contributed by the wing aerodynamics. This increased damping is evident by comparing the widths of the resonance peaks.

Close examination of Figures 8 and 9 reveals a very heavily damped, low amplitude resonance "peak" at a gust frequency of about 0.8 Hz. This resonance is a manifestation of the low-frequency (i.e., $\Omega - \omega_\beta$) flapping mode. Analyses have indicated that the flapping modes are generally well damped for moderate or zero values of flapping restraint.[6] These results constitute an experimental verification.

These results indicate that "free-flight" tilt-rotor models could be used to measure the frequency response functions needed in gust response analyses. This would be a fruitful area for future analytical and experimental research.

(b) January 1970

A joint NASA/Bell/Air Force test program was conducted in the transonic dynamics tunnel in January 1970 for the purpose of investigating any potential problem areas associated with the folding proprotor variant of the tilt-rotor concept. The model used in this study was the same model employed in the first investigation but modified to permit rapid feathering and unfeathering of the proprotor and to include a blade fold-hinge. The main objectives were to investigate stability at low (including zero) rotor rotational speeds, during rotor stopping and starting, and during blade folding. All objectives of the test program were met. No aeroelastic instabilities were encountered during the blade folding sequence of transition, the blade loads and/or the feathering axis loads inboard of the fold hinge being identified as the critical considerations from a design point of view. The stop-start portion of the test indicated that additional flapping restraint would be required to minimize flapping during rotor stopping.* Stability investigations conducted over a wide range of rotor speed identified an apparently new form of proprotor instability involving the rotor at low and zero rotational speeds. The influence of several system parameters on this instability was established both experimentally and analytically.[6]

Proprotor/Pylon Stability. For the stability investigation a reference configuration was again established. This consisted of the basic Model 266 configuration with the pylon locked to the wing tip in both pitch and yaw, a hub restraint of 117,683 N-m/rad (86,800 ft-lb/rad), $\delta_3 = -0.393$ rad (-22.5°), a simulated wing fuel weight distribution of 15%, and the wing aerodynamic fairings installed. The flutter boundary obtained for this configuration and that for $\delta_3 = -0.558$ rad (-32°), are shown in Figure 10 as a function of rotor speed. Open symbols denote flutter points. Excessive vibration resulting from operation near resonances with the pylon/wing or blade modal frequencies often limited the maximum attainable airspeed. These points are indicated by the solid symbols. The annotation to the right of the flutter boundaries indicates that the model experienced several modes of flutter. The predicted flutter modes and frequencies were in agreement with the experimental results. The nature of these flutter modes is discussed below.

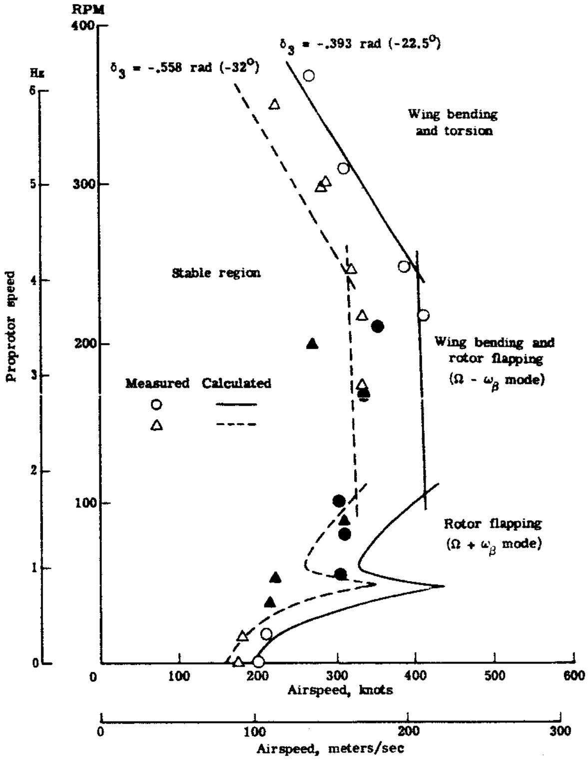

Figure 10. Model 266 flutter boundaries showing variation in character of flutter mode as rpm is reduced to zero.

For Ω greater than about 4 Hz (240 rpm) instability occurred in the wing beam mode and had the characteristics described earlier for the September 1968 test. For Ω between about 2 Hz (120 rpm) and 4 Hz (240 rpm) the motion at flutter was predominantly wing vertical bending and rotor flapping with the hub precessing in the forward whirl direction. Examination of the root loci indicated that this instability was associated with the low-frequency (i.e., $\Omega - \omega_\beta$) flapping mode root becoming unstable. The subcritical response through flutter for $\delta_3 = -0.558$ rad (-32°) and $\Omega = 2.86$ Hz (172 rpm) is shown in Figure 11 where, in addition to the measured wing beam mode damping and frequency, the calculated variation of both the wing beam and low-frequency flapping modes is shown. These results illustrate an interesting modal response behavior similar to that described by Hall.[2] The wing beam mode, being least stable at low airspeeds, is at first dominant. As airspeed increases, however, its damping continually increases. The damping of the $\Omega - \omega_\beta$ flapping mode meanwhile is continually decreasing. Crossover occurs analytically at 144 m/s (280 kts) at a damping of 17% of critical. Beyond 280 knots, the $\Omega - \omega_\beta$ flapping mode is the dominant mode and very abruptly becomes unstable as airspeed is increased. Hence, a transition from a dominant wing beam mode to a dominant flapping mode with an accompanying change in frequency. Since the flapping mode frequency is only slightly less than the wing beam mode in the vicinity of flutter there is only a gradual, albeit distinct, transition in the frequency of the wing beam mode as the flapping mode begins to predominate over the wing mode. Examination of the $\Omega - \omega_\beta$ flapping mode eigenvector indicated that a larger amount of wing vertical motion was evident in this mode than in the wing beam mode eigenvector. This implies that the predominant motion in the flutter mode is not necessarily determined by the root which analytically goes unstable as airspeed is increased but the frequency at which a root goes unstable.

Below about 2 Hz (120 rpm) instability is in the high-frequency (i.e., $\Omega + \omega_\beta$) flapping mode and is characterized by large amplitude flapping, the rotor tip-path-plane exhibiting a precessional motion in the forward whirl direction. The modes of instability at zero rotational speed were similar in character to those at low rotor speeds but with larger amplitudes of flapping. Although the rotor was not turning, the flapping behavior of the blades

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*These aspects of this investigation are given detailed treatment in Reference 9.

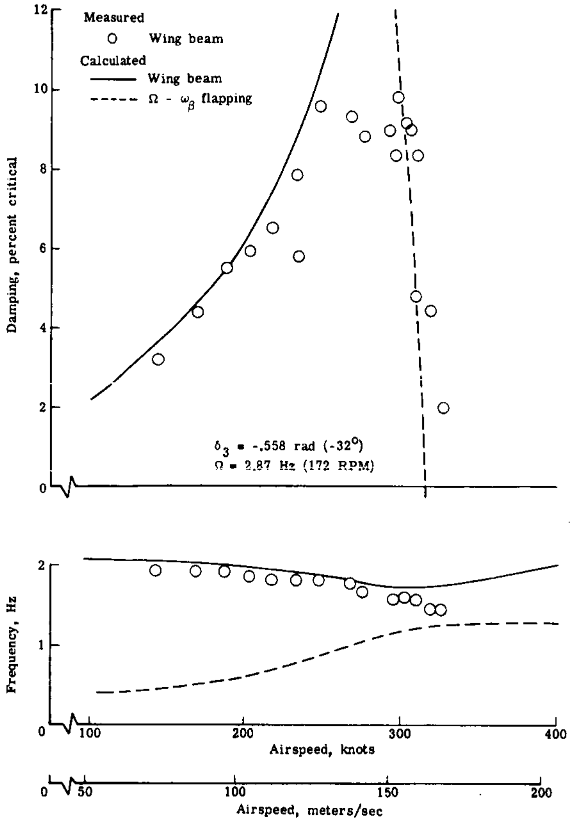

Figure 11. System response characteristics for flutter at $\Omega = 172$ rpm and $\delta_3 = -32°$.

was patterned such that the tip-path-plane appeared to be wobbling or whirling in the forward direction. Negligible wing motions accompanied the flapping motion. Figure 12 shows the variation of flap damping with airspeed. A hub damping of $\zeta_R = 0.015$ was originally used in calculating the stability boundaries, leading to very conservative values for the flutter speed at the low rotor speeds. Based on the results of Figure 12, which indicate that the rotor hub structural damping is closer to $\zeta_R = 0.025$, the stability boundaries were recalculated using $\zeta_R = 0.025$. The predicted boundaries in Figure 10 reflect this change.

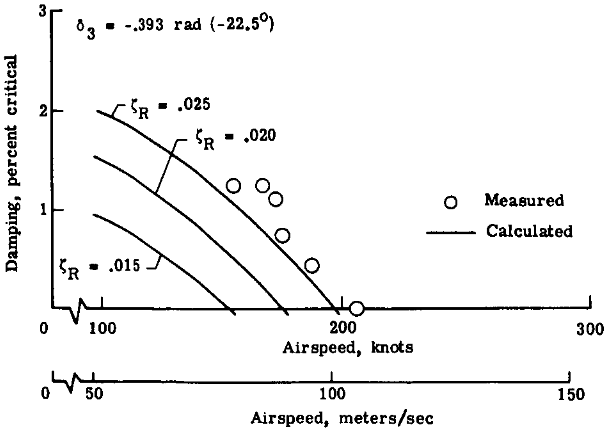

Figure 12. Variation of $\Omega + \omega_\beta$ flapping mode damping with airspeed for zero rpm.

The small region of increased stability in the region of 0.8 Hz (48 rpm) is due to a favorable coupling of the flapping mode with wing vertical bending.

The instabilities encountered at low and zero values of rotational speed were quite mild and had a relatively long time to double amplitude. The necessity of limiting the flapping amplitude during the feathering sequence of transition dictates that significantly increased values of hub restraint are needed as rotor rotational speed is reduced to zero. Since increased flapping restraint was found to stabilize this mode[6] this instability is probably only of academic interest, at least for the configuration tested. However, since it was a new phenomenon and was not understood at the time of the test, attention was directed to assessing the effect of the variation of several system parameters on the flutter speed. Both experimental and analytical trend studies were conducted for this purpose.[6] Based on these studies it was concluded that rotor precone was the primary cause of the instability.

Blade Flapping. In the feathering sequence of transition flapping sensitivity to a given mast angle of attack varies with rotor rotational speed. A typical variation of steady-state one-per-rev flapping response is given in Figure 13. These data were taken to establish a steady-state flapping response baseline for evaluating the transient

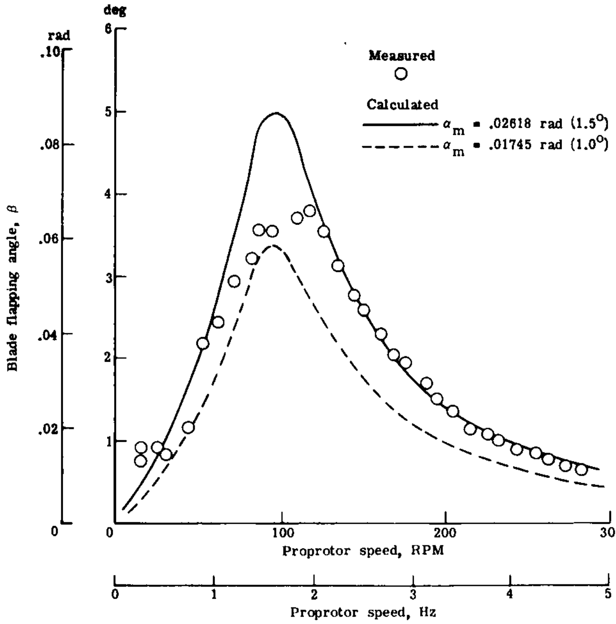

Figure 13. Variation of blade flapping with rotor rpm.

flapping response during the feathering portion of the test. Since the proprotor mast was not affixed to a rigid backup structure the wind-on mast angle of attack was not known (it was nominally 1°). The important conclusion following from Figure 13 is that the measured trend is predicted correctly. The peak in the flapping response occurs when the rotor rotational speed is in resonance with the flapping natural frequency in the rotating system.

Grumman Helicat (March 1971)

A wide variety of technical considerations confront the structural dynamicist in the design of a proprotor VTOL aircraft. Perhaps the most celebrated consideration has been that of proprotor/pylon whirl flutter, having been the concern of many investigators in both government and industry. Several years ago Baird[10] raised the question of whether proprotor whirl flutter, in particular forward whirl flutter, could be predicted with confidence. His skepticism was prompted by the lack of agreement between the experimental results obtained with several small models of flapping-blade propellers and the corresponding theoretical predictions.[4] To provide a large data base from which to assess the predictability of proprotor whirl flutter, a joint NASA/Grumman investigation was conducted in the transonic dynamics tunnel employing an off-design research configuration of a 1/4.5-scale semispan model of a Grumman tilt-rotor design designated "Helicat" (Fig. 14). This design is characterized by a rotor which incorporates offset flapping hinges in contrast to the Bell rotor in which the blades are rigidly attached to the hub which is in turn mounted on the drive shaft by a gimbal or universal joint housed in the hub assembly. The Helicat model was specifically designed to permit rather extensive parametric changes in order to provide a wide range of configurations. These variations included pylon pitch and yaw stiffness and damping, hinge offset, and pitch-flap coupling. To obtain flutter at low tunnel speeds, a reduced-stiffness pylon-to-wing-tip restraint mechanism which permitted independent variations in pitch and yaw stiffness was employed. The resulting pylon-to-wing attachment was sufficiently soft to insure that the wing was effectively a rigid backup structure. Details concerning this model as well as a summary of results are contained in Reference 11.

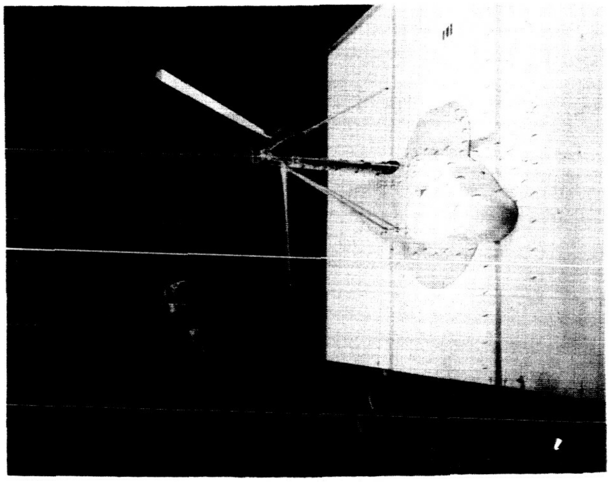

Figure 14. Grumman "Helicat" tilt-rotor model in whirl flutter research configuration.

Some whirl flutter results are given in Figures 15 to 17, where flutter advance ratio $V_F/\Omega R$ is plotted versus pylon frequency nondimensionalized by the rotor speed. The effect of δ_3 on stability is shown in Figure 15 for the case in which the pylon pitch and yaw frequencies are identical and e/R set to 0.05. Many of the configurations were not exactly symmetrical in the frequencies. These data were adjusted to reflect a symmetric frequency support condition using Figure 18 of Reference 11. The results show a strong increase in flutter advance ratio (and hence flutter speed for a fixed rpm) with increasing pylon support stiffness and decreasing δ_3. All flutter was in the forward whirl mode except for the two points denoted by the solid symbols, which were in the backward mode. The analytical results shown assumed a symmetric frequency configuration and, since the structural damping varied somewhat, an average value of damping of $\zeta = 0.01$ in pitch and $\zeta = 0.02$ in yaw. The analytical results shown were obtained using the theory of Reference 6 which is based on the assumption of a gimbaled rotor. For analysis purposes the restoring centrifugal force moment from the offset flapping hinge was represented by introducing an

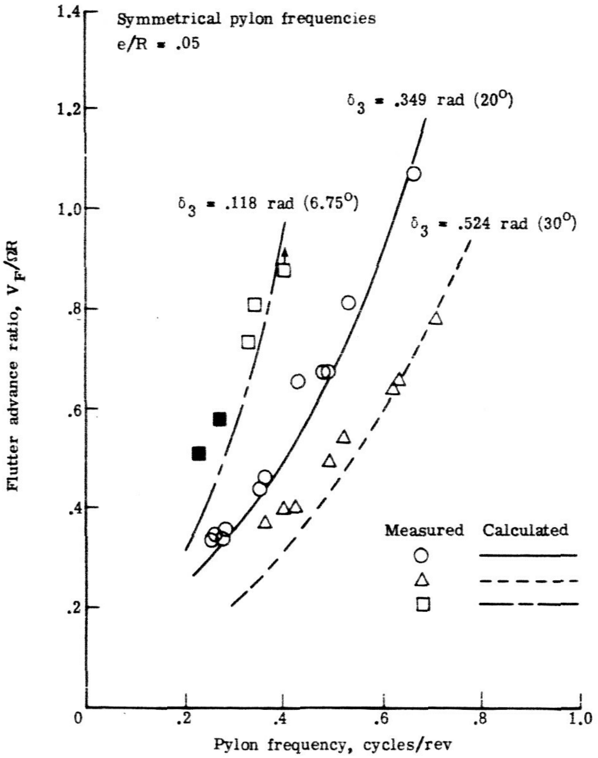

Figure 15. Effect of pitch-flap coupling on whirl flutter.

equivalent hub spring which preserved the blade in-vacuum flapping natural frequency in the manner indicated in Appendix B of Reference 6.

The beneficial effect of increased hinge offset is demonstrated in Figure 16. The results for the 13% hinge offset are particularly noteworthy in that both forward and backward whirl motions were found to occur simultaneously; in effect, the flutter was bimodal. Theory also predicted this bimodal behavior, the forward and backward whirl modes being within a few knots of each other analytically.

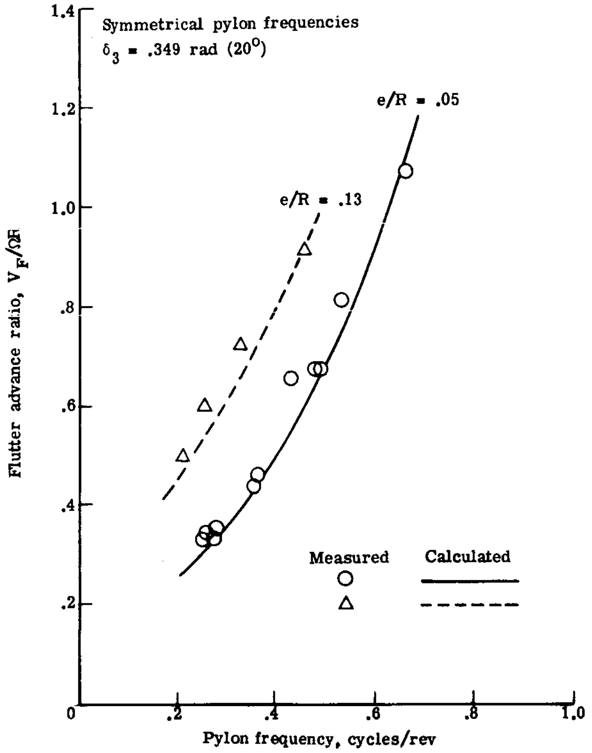

Figure 16. Effect of hinge offset on whirl flutter.

The effect of asymmetry in the pylon support stiffness is shown in Figure 17. Again the symmetric frequency data reflect adjustments to true symmetry for configurations which were nearly, but not exactly, symmetric. The nonsymmetric results reflect actual measured values, the lower of either the pitch or yaw frequencies being plotted. It was analytically shown[6] that for sufficient asymmetry in the pylon support stiffness increasing the asymmetry more does not increase the flutter speed. The data for the nonsymmetric frequencies are an experimental demonstration of this fact. Flutter in all the asymmetric conditions was in the backward whirl mode.

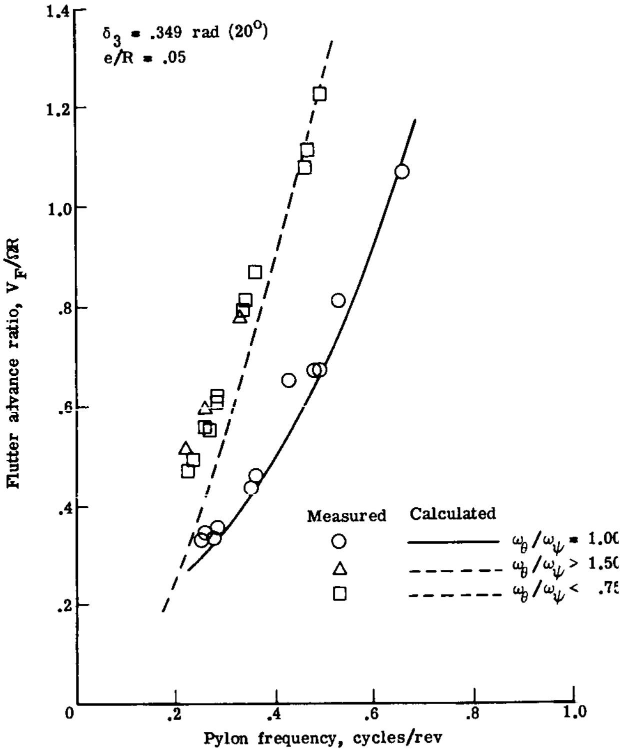

Figure 17. Effect of pylon support stiffness on whirl flutter.

Bell Model 300

(a) August 1971

A joint NASA/Bell investigation employing a 1/5-scale aerodynamic model of a Bell tilt-rotor design designated the Model 300 was conducted in the transonic dynamics tunnel in August 1971 for the purpose of providing the longitudinal and lateral static stability and control characteristics and establishing the effect of proprotors on the basic airframe characteristics in both air an freon. Use of freon permitted testing at full-scale Mach numbers and near full-scale Reynolds numbers. Flapping was measured in both air and freon for several values of tunnel speed over a range of sting pitch angles. The resultant flapping derivatives, obtained by evaluating the slop of the flapping amplitude versus pitch angle curv are shown in Figure 18. Since the range of inflo ratios over which the derivatives were measured w the same in air and freon and the test medium densities at the simulated conditions were about the same, an indication of the effects of Mach number on the flapping derivatives can be obtaine by comparing the air and freon results. The spee of sound in freon is approximately half that in air so that for a given tunnel speed (or inflow ratio) the Mach number in freon is about twice th in air. The calculated results reflect the

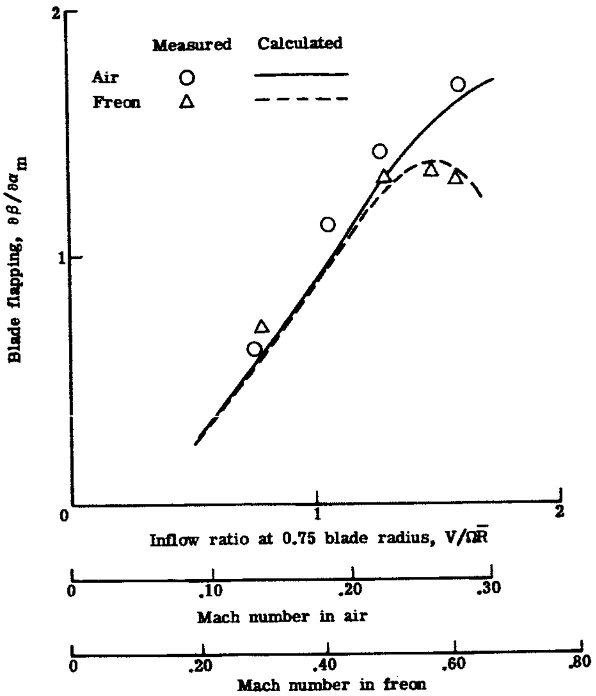

Figure 18. Effect of Mach number on proprotor flapping.

variation of δ_3 with blade pitch. Drag was neglected in the calculated results shown for air but was accounted for, in an approximate manner, in the results shown for freon.[6] The drag rise associated with operation at high Mach numbers is seen to reduce flapping as Mach number is increased and suggests that calculations based on the neglect of blade drag will predict conservative values of flapping at Mach numbers where drag is important.

These data are believed to be the first which provide an indication of the effects of Mach number on blade flapping.

(b) March 1972

The most recent investigation conducted in the transonic dynamics tunnel utilized a 1/5-scale dynamic and aeroelastic "free-flight" model of the Bell Model 300 tilt rotor for the purpose of demonstrating the required flutter margin of safety and to confirm that the aircraft rigid-body flight modes are adequately damped.[12] During this test the importance of rotor thrust damping on stability of the Dutch roll mode was investigated. This damping is associated with rotor perturbation thrust changes which can be generated during axial oscillations of the rotor shaft and constitutes a positive damping force on aircraft yawing motions.

The rotors of tilt-rotor aircraft are generally designed to have an interconnecting shaft between the two rotor/engine systems to provide synchronization of the rotor speeds and to insure that in the event of an engine failure either engine may drive both rotors. Interconnect shafting is also employed in wind-tunnel models. The availability of thrust damping to provide a stabilizing force for yawing motion is dependent on the structural integrity of this cross-shafting and has implications which are pertinent to both full-scale flight and model testing. Consider the case of a windmilling "free-flight" model. A fully effective interconnect maintains synchronization of the rotor speeds during any motions. A yawing motion of the model to the left, say, as might occur during a disturbance, generates blade angle-of-attack changes which decrease the lift of blade elements on the right rotor and increase the lift of blade elements on the left rotor. This produces resultant perturbation thrust changes which tend to damp the yawing motion, as depicted in the sketch in the right-hand portion of Figure 19. If the interconnect is absent, the rotors are able to maintain their inflow angle and, hence, angle of attack by increasing or decreasing rotor speed. The perturbation thrust changes thus go to zero and the stabilizing contribution of this damping to the aircraft yawing motion is lost. The effects of thrust damping on the stability of the Dutch roll mode was investigated by measuring the Dutch roll mode damping as a function of tunnel speed for the cases in which the model interconnect was engaged and disengaged. Some typical results are shown at the left of Figure 19 along with the damping levels predicted by Bell. The substantial contribution of thrust damping to total damping is quite apparent. It is of interest to point out that for the rotors contrarotating in the direction indicated in the sketch at the right of Figure 19 (inboard up) the perturbation thrust changes accompanying an aircraft rolling angular velocity are destabilizing on Dutch roll motion. For contrarotating rotors turning in the opposite direction (inboard down) the ΔT due to both yawing and rolling motion are stabilizing on Dutch roll motion.

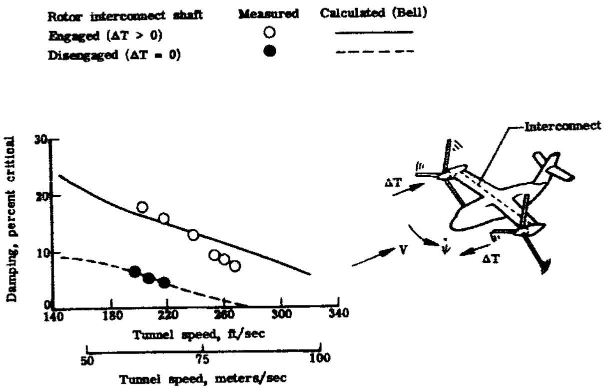

Figure 19. Thrust damping effects on tilt-rotor Dutch roll mode stability.

Rotor rpm governors of the type which maintain rpm by blade collective pitch changes while maintaining constant torque are being considered for use on full-scale tilt-rotor aircraft. With the interconnect engaged, full thrust damping is available (assuming a perfect governor). However, in the event of an interconnect failure, the governors would respond to any rpm changes by varying blade collective pitch in a manner which tends to maintain the original blade angle-of-attack distribution and hence torque. This is aerodynamically equivalent to the windmilling case with no interconnect. It is axiomatic that tilt-rotor aircraft must be designed to have stable Dutch roll characteristics should an interconnect failure occur anywhere within the flight envelope.

Some Additional Results Applicable to the Bell Model 300 Tilt Rotor

A dynamic test of a flight-worthy proprotor for the Bell Model 300 tilt-rotor aircraft was conducted in the NASA Ames full-scale wind tunnel in July 1970 (Fig. 20). Two different test stands were used. One duplicated the actual stiffness characteristics of the Model 300 wing; the other was one-fourth as stiff. By using the reduced stiffness spar and operating the proprotor at one-half its design rotational speed it was possible to preserve the per-rev natural frequencies of the wing and simulate, at any given tunnel speed, the inflow of flight at twice that speed. This expedient did not, however, maintain the blade per-rev elastic mode frequencies or simulate compressibility effects on rotor aerodynamics.

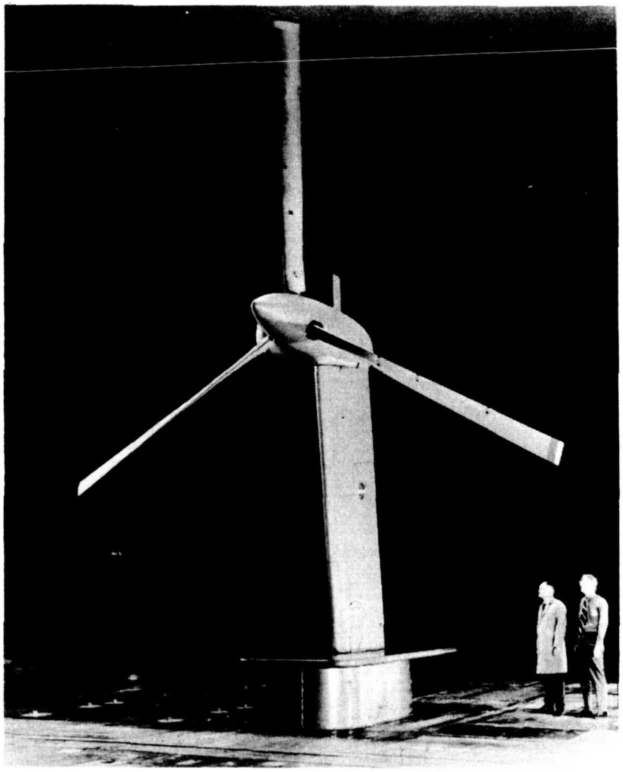

Figure 20. Bell 25-foot flight-worthy proprotor in NASA Ames full-scale tunnel for dynamic testing.

Some results from the full-scale test are compared with data obtained from a test of a 1/5-scale model and theory in Figure 21. Note that the calculated results are based on the use of the design stiffness test stand characteristics. To provide for an indication of the effect of blade inplane flexibility on stability, the predicted results for the case in which the blades are assumed to be rigid inplane are also shown. The predicted increase in damping at about 103 m/sec (200 kts) for the case in which blade inplane flexibility is included is associated with coupling of the blade first inplane cyclic mode with wing vertical bending. For the range of tunnel speed over which full stiffness test stand data are available, the results are in good agreement with theory assuming flexible blades. Note that a significant stabilizing effect is predicted for the Model 300 as a consequence of blade inplane flexibility. This trend is in contrast to that predicted for the Model 266. The data for the quarter-stiffness test stand are in agreement with theory assuming rigid blades because operation at half the design rpm has effectively stiffened the blades by a factor of 4. The 1/5-scale model data are also seen to be in better agreement with analysis based on the assumption of rigid blades. This is because the model hub employed at the time the data were obtained was too stiff. If this increased stiffness is taken into account the predicted damping is in agreement with theory (Fig. 22). The model/full-scale comparisons shown in Figure 21 indicate that assessment of full-scale stability can be made on the basis of results of small-scale model tests.

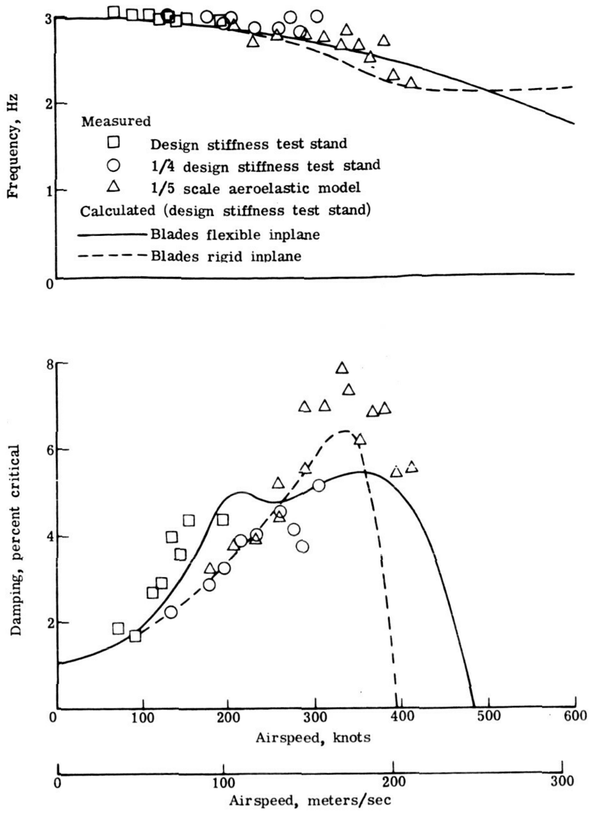

Figure 21. Model/full-scale comparisons of wing beam mode damping and frequency variation with airspeed for Bell Model 300.

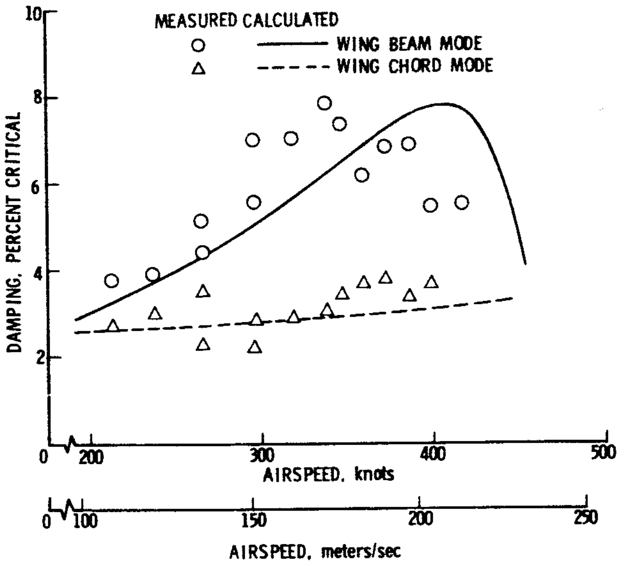

Figure 22. Variation of wing beam and chord mode damping with airspeed for 1/5-scale aeroelastic model of Bell Model 300.

Conclusions

An overview of an experimental and analytical proprotor research program being conducted within the Aeroelasticity Branch of the NASA Langley Research Center has been presented. On the basis of the particular results shown herein the following basic conclusions can be drawn:

(1) A proprotor/pylon/wing system can exhibit a wide variety of flutter modes depending on the degree of fixity of the pylon to the wing, rotor characteristics, and rotor rotational speed. In particular, for pylons which are rigidly affixed to the wing tip, the instability can occur in coupled pylon/wing, pylon/wing/rotor, or rotor modes; for pylons which are soft-mounted to the wing, a true whirl instability akin to classical propeller whirl flutter can occur.

(2) Lightly loaded proprotors operating at inflow ratios typical of tilt-rotor operation in the airplane mode of flight exhibit a marked sensitivity to gust excitation.

(3) Blade inplane flexibility can have a significant effect on stability.

(4) A significant contribution to aircraft lateral-directional (Dutch roll) stability arises from rotor thrust damping. Since the availability of this thrust damping is dependent on the integrity of the rotor interconnect shaft, tilt-rotor aircraft must be designed to have acceptable lateral-directional response characteristics should an interconnect failure occur anywhere within the operating envelope.

(5) Proprotor whirl flutter, both backward and forward, can be predicted with simple linearized perturbation analyses using quasi-steady rotor aerodynamics.

(6) For strength designed wings, wing aerodynamics have only a slight stabilizing effect on proprotor flutter speeds.

(7) The drag rise associated with proprotor operation at high Mach numbers reduces blade flapping and suggests that calculations based on the neglect of blade drag will predict conservative values of flapping at Mach numbers where drag is important.

The analytical portion of this research program is continuing. Attention is presently being directed toward refining the existing stability and response analyses and extending them by including additional degrees of freedom.

Acknowledgments

The author acknowledges the assistance provided by Bell and Grumman in preparing and testing the models employed in the investigations conducted in the transonic dynamics tunnel. Particular thanks are extended to Troy Gaffey of Bell for his general advice and assistance since the initiation of this research program and to Jerry Kohn of Grumman for performing the correlations with the data obtained during the whirl flutter investigation using the Helicat model.

References

1. Deckert, W. H., and Ferry, R. G., LIMITED FLIGHT EVALUATION OF THE XV-3 AIRCRAFT, Air Force Flight Test Center, Report TR-60-4, May 1960.

2. Hall, W. E., PROP-ROTOR STABILITY AT HIGH ADVANCE RATIOS, Journal of the American Helicopter Society, June 1966.

3. Edenborough, H. K., INVESTIGATION OF TILT-ROTOR VTOL AIRCRAFT ROTOR-PYLON STABILITY, Journal of Aircraft, Vol. 5, March-April 1968.

4. Reed, W. H., III., REVIEW OF PROPELLER-ROTOR WHIRL FLUTTER, NASA TR R-264, July 1967.

5. Gaffey, T. M., Yen, J. G., and Kvaternik, R. G., ANALYSIS AND MODEL TESTS OF THE PROPROTOR DYNAMICS OF A TILT-PROPROTOR VTOL AIRCRAFT, presented at the Air Force V/STOL Technology and Planning Conference, Las Vegas, Nevada, September 1969.

6. Kvaternik, R. G., STUDIES IN TILT-ROTOR VTOL AIRCRAFT AEROELASTICITY, Ph. D. Dissertation, Case Western Reserve University, June 1973.

7. Young, M. I., and Lytwyn, R. T., THE INFLUENCE OF BLADE FLAPPING RESTRAINT ON THE DYNAMIC STABILITY OF LOW DISK LOADING PROPELLER-ROTORS, Journal of the American Helicopter Society, October 1967.

8. Gilman, J., Jr., and Bennett, R. M., A WIND-TUNNEL TECHNIQUE FOR MEASURING FREQUENCY-RESPONSE FUNCTIONS FOR GUST LOAD ANALYSIS, Journal of Aircraft, Vol. 3, November-December 1966.

9. Yen, J. G., Weber, G. E., and Gaffey, T. M., A STUDY OF FOLDING PROPROTOR VTOL AIRCRAFT DYNAMICS, AFFDL-TR-71-7 (Vol. I), September 1971.

10. Baird, E. F., CAN PROP-ROTOR STABILITY BE PREDICTED?, presented at the Aerospace Flutter and Dynamics Council Meeting, San Francisco, California, November 12-14, 1969.

11. Baird, E. F., Bauer, E. M., and Kohn, J. S., MODEL TESTS AND ANALYSIS OF PROP-ROTOR DYNAMICS FOR TILT-ROTOR AIRCRAFT, presented at the Mideast Region Symposium of the American Helicopter Society, Philadelphia, Pennsylvania, October 1972.

12. Marr, R. L., and Neal, G. T., ASSESSMENT OF MODEL TESTING OF A TILT-PROPROTOR VTOL AIRCRAFT, presented at the Mideast Region Symposium of the American Helicopter Society, Philadelphia, Pennsylvania, October 1972.