# A Review of Some Tilt-Rotor Aeroelastic Research at NASA-Langley

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**An overview of an experimental and analytical research program conducted 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 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.**

## Nomenclature

| | |
|---|---|
| $e$ | = blade flapping hinge offset |
| $H$ | = rotor normal shear force |
| $R$ | = blade radius |
| $\bar{R}$ | = 0.75 blade radius |
| $\Delta T$ | = rotor perturbation thrust |
| $V$ | = airspeed |
| $V_F/\Omega R$ | = flutter advance ratio |
| $w_g$ | = vertical component of gust velocity |
| $\alpha_m$ | = mast angle of attack |
| $\beta$ | = blade flapping angle |
| $\partial\beta/\partial\alpha_m$ | = blade flapping derivative |
| $\delta_3$ | = pitch-flap coupling angle |
| $\zeta_R$ | = hub damping ratio |
| $\dot{\psi}$ | = aircraft yaw rate |
| $\Omega$ | = rotor rotational speed |
| $\omega_\beta$ | = blade flapping natural frequency |

## Introduction

SEVERAL rotary-wing concepts have been proposed over the years for an advanced VTOL transportation system which combines the hover efficiency of a helicopter with the speed and cruise efficiency of a fixed-wing aircraft. One example of this concept is the tilt rotor which is characterized by wing-tip mounted rotors which tilt forward from the vertical position, employed for helicopter flight, to the horizontal position, in which they function as tractive propellers for high-speed airplane flight (Fig. 1). The feasibility of the tilt-rotor 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. However, extensive flight and wind-tunnel research conducted with the XV-3 identified several dynamic deficiencies as technical problems requiring further investigation.[2-4] Subsequent studies by Bell, related to solving the XV-3 deficiencies and to their tilt-rotor design, (Fig. 1) developed during the Army Composite Aircraft Program in 1966-1967, pointed out the need for establishing a firm dynamics technology base to support the design of a tilt-rotor aircraft. An experimental and analytical tilt-rotor research program for the purpose of contributing to this dynamics technology base was initiated within the Aeroelasticity Branch at NASA Langley several years ago. Included in this program were joint NASA/contractor investigations of scaled models in the transonic dynamics wind tunnel and the in-house development of supporting analyses. 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 decided that the research effort would be directed primarily to these areas. The purpose of this paper is to present a review of this program.

The experimental portion of the research program was initiated in September 1968 in a joint NASA/Bell study of proprotor stability, dynamics and loads in the helicopter, conversion, and airplane modes of operation. Primary attention was directed to assessing the effect of several system design parameters on proprotor/pylon stability and gust response in the airplane mode of flight. The model employed in this study was a semispan model of the Bell model 266 tilt-rotor design shown in Fig. 1. Several other cooperative experimental studies followed this investigation. The models employed in these studies are positioned in chronological order in the composite photograph given in Fig. 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. The results pertaining to these 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 are arranged in chronological order according to Fig. 2. 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.

## Bell Model 266

**September 1968**

The principal findings of this first investigation have been published and are available in the literature.[5,6] Some results adapted from Ref. 6, pertaining to stability and gust response, are discussed below.

### *Proprotor/Pylon Stability*

A baseline stability boundary, based on a reference configuration, first was established. The degree to which stability

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Index categories: VTOL Aircraft Design; Structural Stability Analysis.

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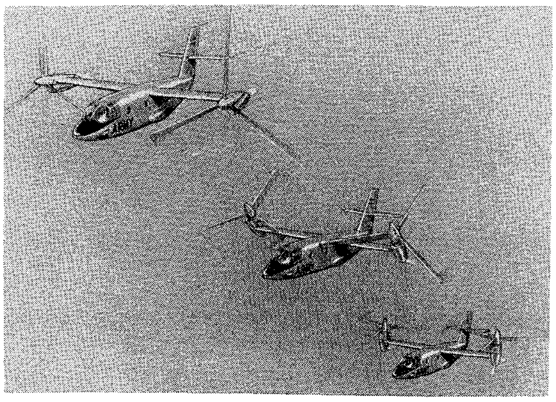

Fig. 1 Artist's conception of Bell Model 266 tilt-rotor design evolved during the Army Composite Aircraft Program.

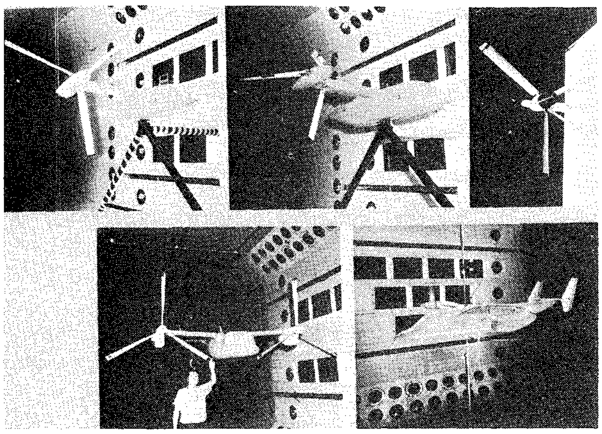

Fig. 2 Tilt-rotor models tested in the Langley transonic dynamics tunnel.

could be affected then was ascertained by varying selected system parameters (or flight conditions). The reference configuration consisted of the basic model 266 parameters with the pylon yaw degree of freedom locked out and the wing airfoil segments removed. The hub flapping restraint was set to zero and the $\delta_3$ angle to $-0.393$ rad $(-22.5°)$. The reference stability boundary, as well as changes in this boundary caused by several parameter variations, are shown in Fig. 3.

For the reference configuration, instability occurred in the coupled pylon/wing mode where 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 herein, this flutter mode is termed the "wing beam" mode. 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 proprotor/pylon instability just described 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, whereas 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.

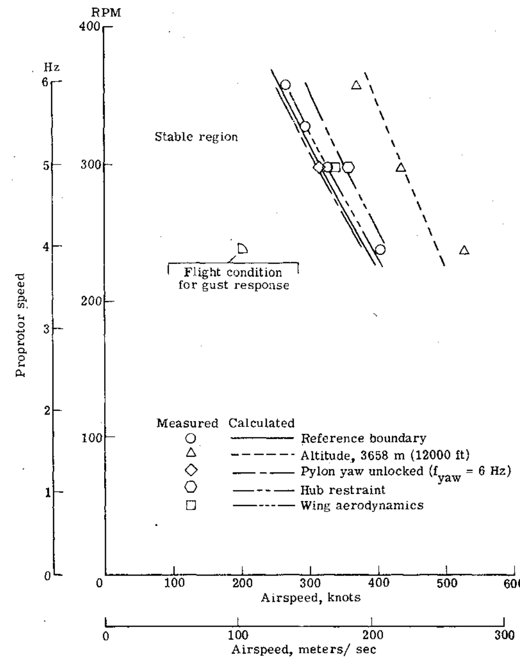


Fig. 3 Effect of several system parameters on proprotor/pylon stability.

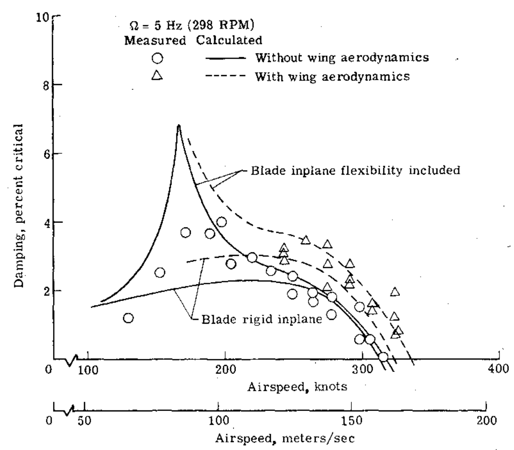


Fig. 4 Comparison of measured and calculated wing beam mode damping for reference configuration and for configuration with wing airfoil segments installed.

The stability of the model in several other configurations representing perturbations from the reference configuration also are shown in Fig. 3. The flutter mode in each case was essentially the same as for the reference configuration:

1) Altitude. Altitude has a strong stabilizing effect on proprotor/pylon stability, and the increase in stability is approximately inversely proportional to the air density.

2) Hub flapping restraint. A stabilizing effect caused by moderate flapping restraint also is indicated in Fig. 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 procedure increased stability because the pylon support stiffness requirements were reduced as the optimum flapping frequency was approached.

3) Wing aerodynamics. The effect of wing aerodynamics was assessed by installing the wing airfoil segments. Figure 3 indicates that wing aerodynamic forces have a slight stabilizing effect. Figure 4 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. To provide for an indication of the effect of blade in-plane flexibility on stability, the predicted results for the case in which the blades are assumed rigid in-plane also are shown in Fig. 4. Note that the predicted flutter speed is not sensitive to blade in-plane flexibility for Model 266. It should be emphasized, however, that the effects of blade in-plane flexibility are not always small. For example, for the Bell Model 300 proprotor, a significant stabilizing effect is predicted as a consequence of blade in-plane flexibility.[1] The large increase in damping predicted at about 85 m/sec (175 knots), for the case in which blade in-plane flexibility is included, is associated with coupling of the blade first in-plane cyclic mode with wing vertical bending.

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.

### *Gust Response*

A study to assess the feasibility of determining 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 in the Aeroelasticity Branch for several years. This system 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 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.

For the "flight" condition indicated in Fig. 3 the effect of rotor aerodynamics on the frequency response of wing vertical bending moment is indicated in Fig. 5, where a comparison of the rotor-on and rotor-off response curves for the configuration having wing airfoil segments installed is shown. The wing bending moments have been normalized by the maximum amplitude of the gust-induced stream angle, which was measured by means of a small balsa vane flow direction transmitter located approximately two rotor diameters upstream of the model. Two proprotor-related effects are indicated: first, the significant contribution of the rotor in-plane 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 primarily vertical, and there is very little coupling between the wing beam and chord modes.

Figure 5 quite clearly illustrates 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 because 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 isa 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.

Close examination of Fig. 5 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 generally are well damped for moderate or zero values of flapping restraint.[6] These results constitute an experimental verification.

### 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 it was 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. 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 were identified

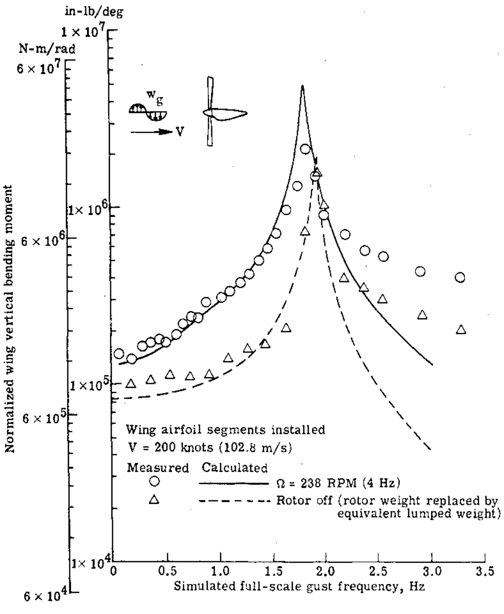


**Fig. 5 Effect of proprotor aerodynamics on wing root bending moment amplitude response function.**

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

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 speeds, identified an apparently new form of proprotor instability involving the rotor at low and zero rotational speeds.

Proprotor/Pylon Stability. For the stability investigation, a reference configuration again was 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 ($-22.5°$), and the wing airfoil segments installed. The flutter boundary obtained for this configuration and that for $\delta_3 = -0.558$ rad ($-32°$) are shown in Fig. 6 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 notation 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 subsequently.

For $\Omega$ 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 $\Omega$ 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 Fig. 7, 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.[3] 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 decreasing continually. Crossover occurs analytically at 144 m/sec (280 k) 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, there is 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 eignevector. This implies that the predominant motion in the flutter mode is not determined necessarily by the root which analytically goes unstable as airspeed is increased, but by 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 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 8 shows the variation of flap damping with airspeed. A hub damping of $\zeta_R = 0.015$ originally

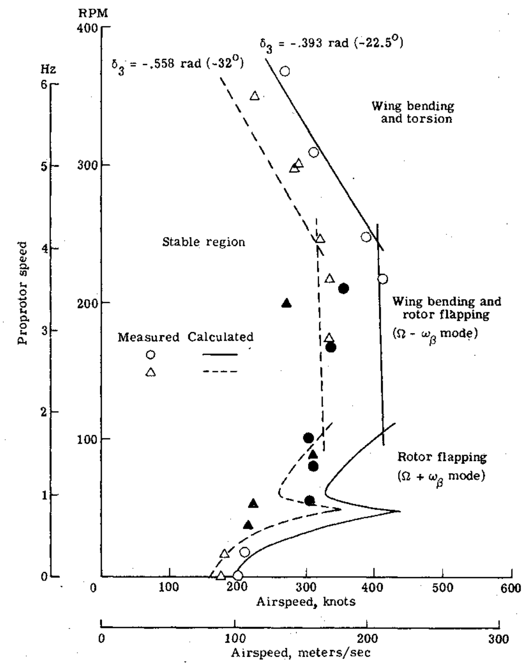


**Fig. 6 Model 266 flutter boundaries showing variation in character of flutter mode as rpm is reduced to zero.**

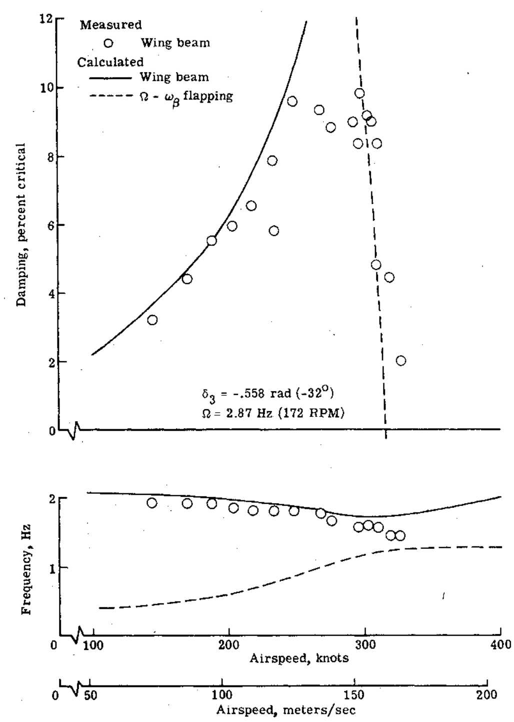


**Fig. 7 System response characteristics for flutter at $\Omega = 172$ rpm and $\delta_3 = -32°$.**

was 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 Fig. 8, 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 Fig. 6 reflect this change. 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

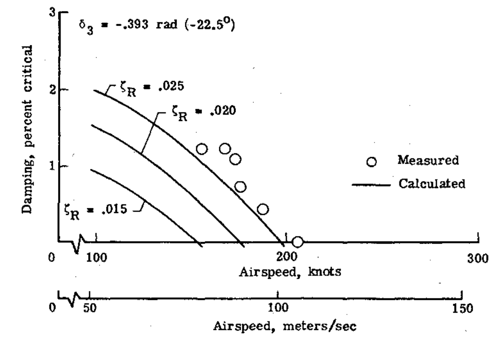


**Fig. 8 Variation of $\Psi + \omega_\beta$ flapping mode damping with airspeed for zero rpm.**

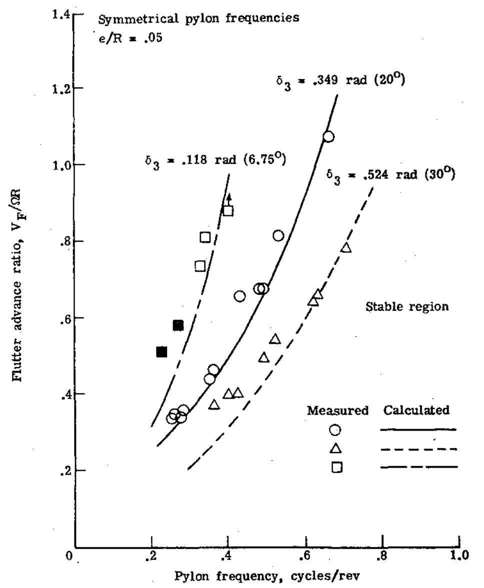


**Fig. 9 Effect of pitch-flap coupling on whirl flutter.**

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.

## Grumman Helicat (March 1971)

Several years ago Baird[8] 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.[9] 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". 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. 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. The principal findings of this particular investigation are summarized in Ref. 10.

Some whirl flutter results adapted from Ref. 10 are given in Fig. 9, where flutter advance ratio $V_F/\Omega R$ is plotted vs pylon frequency, nondimensionalized by the rotor speed. The effect of $\delta_3$ on stability is shown for the case in which the pylon pitch and yaw frequencies are identical, and $e/R$ is 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 Fig. 18 of Ref. 10. 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 $\delta_3$. 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 Ref. 6 which is based on the assumption of a gimbaled rotor. For purposes of analysis the effects of the offset flapping hinge were represented by establishing an equivalent hub spring which preserved the blade flapping natural frequency in the manner suggested in Appendix B of Ref. 6.

## Bell Model 300

### August 1971

A joint NASA/Bell investigation employing a 1/5-scale aerodynamic model of a Bell tilt-rotor design, designated 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 and 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 slopes of the flapping amplitude vs pitch angle curves, are shown in Fig. 10. Since the range of inflow ratios over which the derivatives were measured was 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 could be obtained by comparing the air and freon results. The speed 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 that in air. The calculated results reflect the variation of $\delta_3$ with blade pitch. Drag was neglected in the calculated results shown for air but was accounted for in the results shown for freon. The drag rise associated with operation at high Mach numbers is seen to reduce flapping as the Mach number is increased.

### 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 confirming that the aircraft rigid-body flight modes are damped adequately. During this test, the importance of rotor thrust damping on stability of the Dutch

‡This design is the basis for the current XV-15 NASA/Army research aircraft.

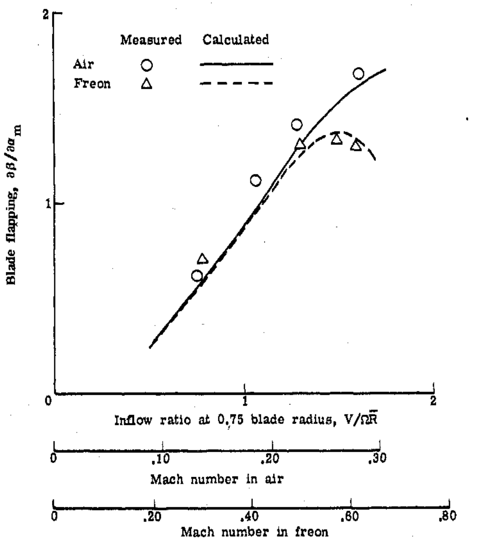


**Fig. 10 Effect of Mach number on proprotor flapping.**

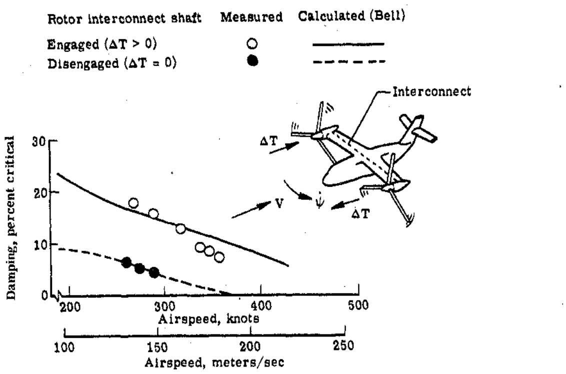


**Fig. 11 Thrust damping effects on tilt-rotor Dutch roll mode stability.**

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 generally are 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 also is 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 Fig. 11. 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 were 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 Fig. 11, 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 Fig. 11 (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 $\Delta T$ caused by both yawing and rolling motion are stabilizing on Dutch roll motion.

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.

## Conclusions

An overview of an experimental and analytical tilt-rotor research program conducted in 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 in-plane flexibility can have a significant effect on stability of the proprotor/pylon/wing system.

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 quasisteady rotor aerodynamics.

6) For strength-designed wings, characteristic of tilt-rotor aircraft, wing aerodynamics have only a slight stabilizing effect on the stability of the proprotor/pylon/wing system.

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.

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