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A HISTORICAL OVERVIEW OF TILTROTOR AEROELASTIC RESEARCH AT LANGLEY RESEARCH CENTER

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A Historical Overview of Tiltrotor Aeroelastic Research at Langley Research Center

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Abstract

The Bell/Boeing V-22 Osprey which is being developed for the U. S. Military is a tiltrotor aircraft combining the versatility of a helicopter with the range and speed of a turboprop airplane. The V-22 represents a tiltrotor lineage which goes back over forty years, during which time contributions to the technology base needed for its development were made by both government and industry. NASA Langley Research Center has made substantial contributions to tiltrotor technology in several areas, in particular in the area of aeroelasticity. The purpose of this talk is to present a summary of the tiltrotor aeroelastic research conducted at Langley which has contributed to that technology.

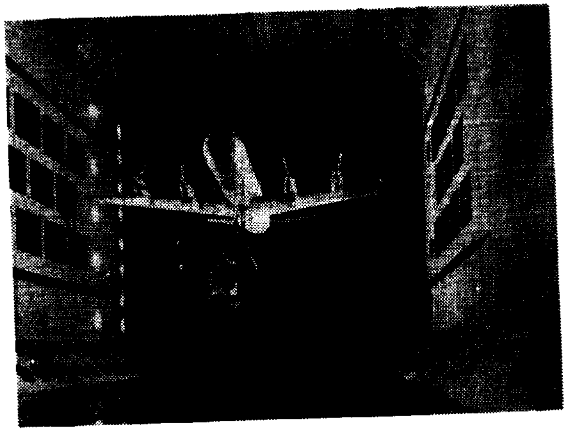
A brief review of early work at Langley which is relevant to the subject area is presented first. This work includes the propeller whirl flutter studies conducted in the early 1960s and the studies carried out during the mid- and late-1960s dealing with the whirl flutter behavior of both propellers having blades with flapping hinges and high-bypass-ratio ducted fan-jet engines. The major portion of the talk addresses the tiltrotor aeroelastic studies which were conducted later, first (1968-1972) in support of the program which led to the XV-15 tiltrotor technology demonstrator and more recently (1984-1985) in support of the V-22 tiltrotor aircraft development program. Illustrative results obtained from wind-tunnel tests of several different tiltrotor models in the Langley Transonic Dynamics Tunnel are presented and discussed. A Langley-developed tiltrotor aeroelastic stability analysis called PASTA is described and correlations with the aforementioned test results are presented. Current and planned tiltrotor aeroelastic research at Langley is described in light of NASA's proposed Advanced Tiltrotor Transport Technology Program.

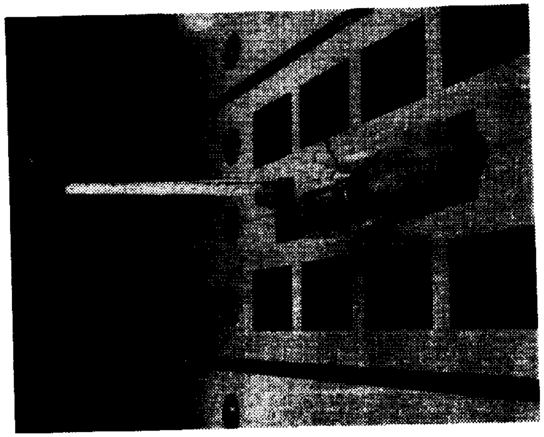
PROPELLER WHIRL FLUTTER STUDIES

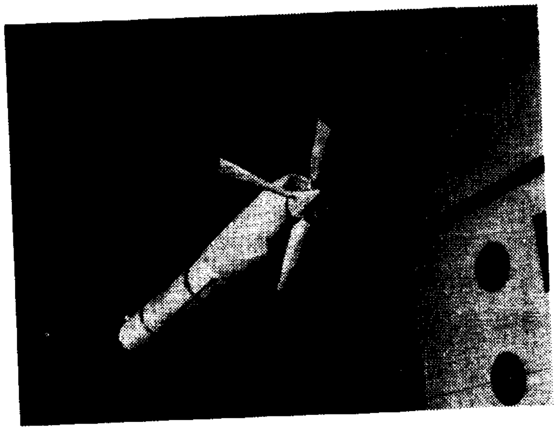
Propeller whirl flutter is a self-excited whirling instability that can occur in a flexibly mounted aircraft propeller-engine combination. The possibility that such an instability might occur was first mentioned in a paper by Taylor and Brown in 1938. However, the very large margins of safety prevalent at that time and in later years resulted in the phenomenon being accorded only academic interest. In particular, the instability was studied extensively at Rensselaer Polytechnic in the early 1950's by Scanlan and his group. The instability remained of academic interest until 1960 when it became of practical concern following the loss of two turboprop aircraft in fatal accidents. Extensive wind-tunnel tests were conducted in the Langley Transonic Dynamics Tunnel on a large, full-span, dynamic and aeroelastic model of the subject aircraft (upper left). These studies showed that propeller whirl flutter was possible if the engine support stiffnesses were sufficiently reduced, say due to damage. Following wind-tunnel tests of that specific configuration, a more general investigation of propeller whirl flutter was initiated with the aim of identifying and studying the pertinent parameters influencing the phenomenon and to obtain data for verifying analyses. The first study involved a model of an isolated propeller/pylon/engine system mounted with flexiblilty in pitch and yaw on a rigid sting support structure (lower left). Studies of this isolated system were followed by tests employing a propeller/pylon/engine system mounted on a cantilever semispan wing (lower right) to determine the effects of a flexible wing on whirl flutter.

Propeller Whirl Flutter Studies

1960 - 1964







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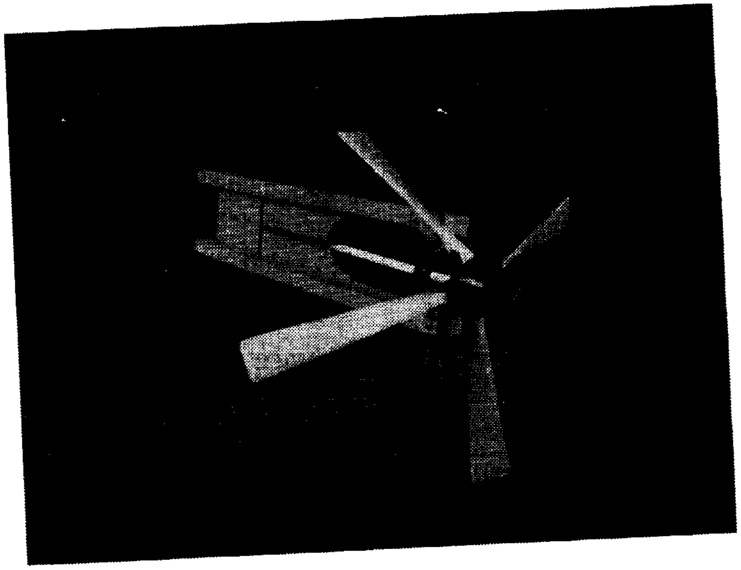
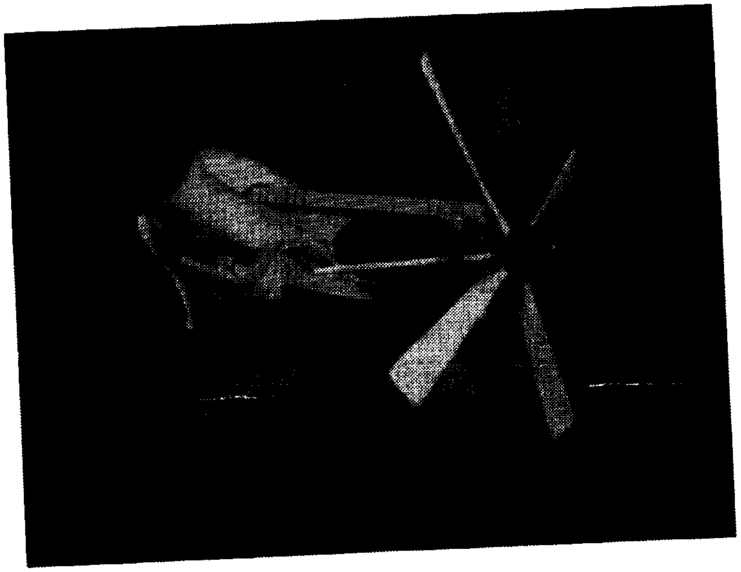
WHIRL FLUTTER STUDIES OF FLAPPING-BLADE PROPELLERS

Several V/STOL aircraft concepts based on the use of propellers having blades which had a hinge at the root to permit flapping motion out of the plane of rotation were proposed as research vehicles in the 1960's, some 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-16B amphibian built for the Navy. Because of the attention which was being directed to propeller whirl flutter, it became of interest to consider the manner in which whirl flutter might be altered by the use of hinged blades. Experimental studies using small models were conducted by government, industry, and academia. These studies showed that either backward or forward whirl flutter could occur when propeller blades have flapping hinges, in contrast to propellers with fixed blades which flutter only in the backward whirl mode. In parallel with these experimental studies, conventional propeller whirl flutter analyses were extended to include the blade flapping freedom. However, none of the analyses which were developed was able to successfully predict the forward whirl instabilities which were obtained experimentally.

A low-speed model tested and studied at Langley is shown in the figure. It consisted of a windmilling propeller mounted on a spring-restrained rod which could rotate in pitch and yaw about a set of gimbal axes behind the propeller. The (symmetric) stiffness could be controlled by varying the tension in a spring connected axially at the other end of the rod. Each blade was attached to the hub by means of two pins, such that when both pins were in position the blades were fixed; and when one of the pins was removed the other pin became a flapping hinge. Analysis predicted the backward whirl flutter which occurred for the rigid and 13% hinge offset cases but failed to predict the forward whirl which occurred for the 8% hinge offset case. As indicated earlier, similar prediction difficulties were experienced by other researchers.

Whirl Flutter Studies of Flapping-Blade Propellers



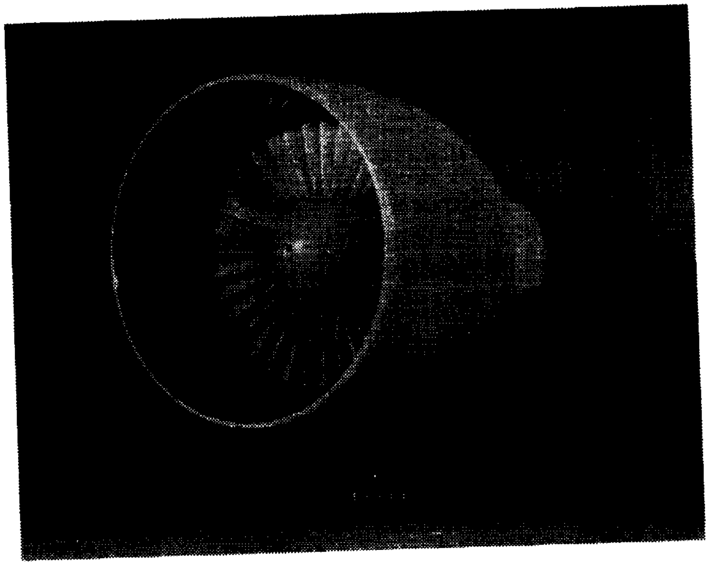


1962 - 64/1969

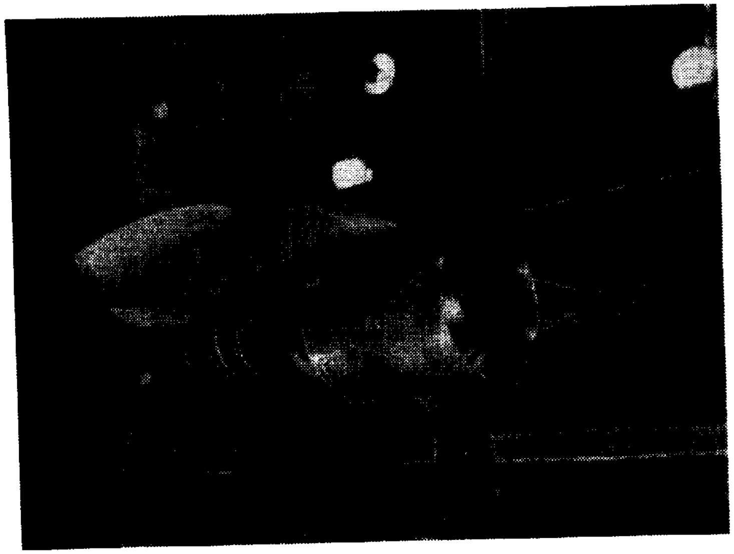
WHIRL FLUTTER STUDIES OF HIGH-BYPASS-RATIO TURBOFAN ENGINES

In the mid-1960's, high-bypass-ratio turbofan jet engines were being developed for the 747 and C5A. These engines are characterized by a large-diameter ducted fan. Because of the large gyroscopic and aerodynamic forces acting on the fan, it was thought that a flexibly mounted engine could be susceptible to a whirl-type instability analogous to propeller whirl flutter. Preliminary studies to explore the possibility of whirl flutter in such engines were conducted at Langley using the low-speed model shown at the left in the figure. The model employed a windmilling fan and was mounted on a sting and elastically restrained with freedom to oscillate in pitch and yaw about a set of gimbal axes located behind the fan. A range of duct chord-to-diameter ratios, restraint stiffnesses, and gimbal axis locations were investigated experimentally and the results compared with analysis. Static and dynamic stability derivatives of importance to whirl flutter were also measured. An existing three-dimensional theory for computing the static derivatives of ducted propellers at angle of attack was extended under contract to include the calculation of the important dynamic derivatives. Some limited studies were also conducted using the high-speed model shown in the lower right in an attempt to measure the static stability derivatives at full-scale Mach numbers.

Whirl Flutter Studies of High-Bypass-Ratio Turbofan Engines



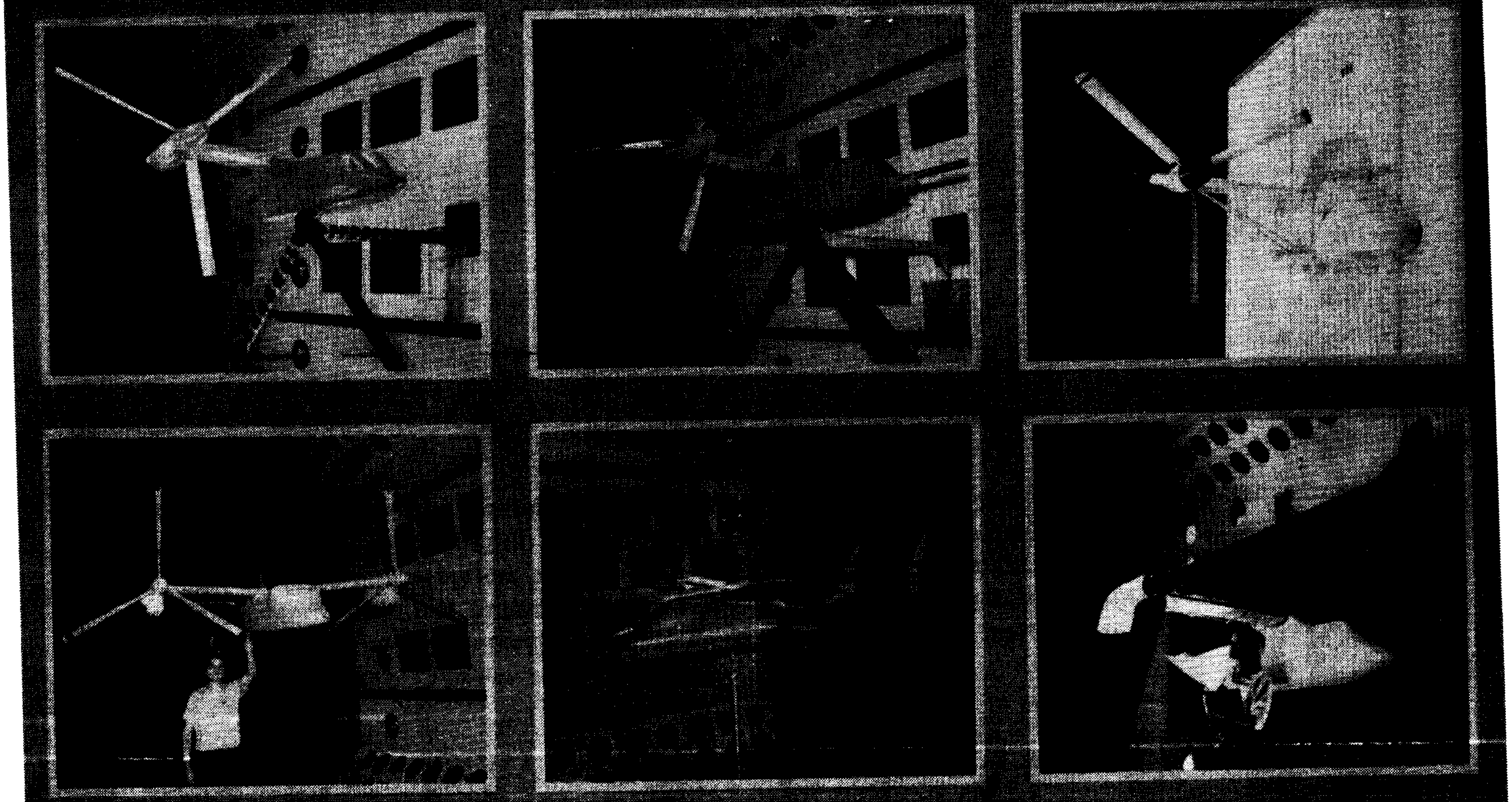
1967 - 1968



TILTROTOR AEROELASTIC RESEARCH
Langley Transonic Dynamics Tunnel

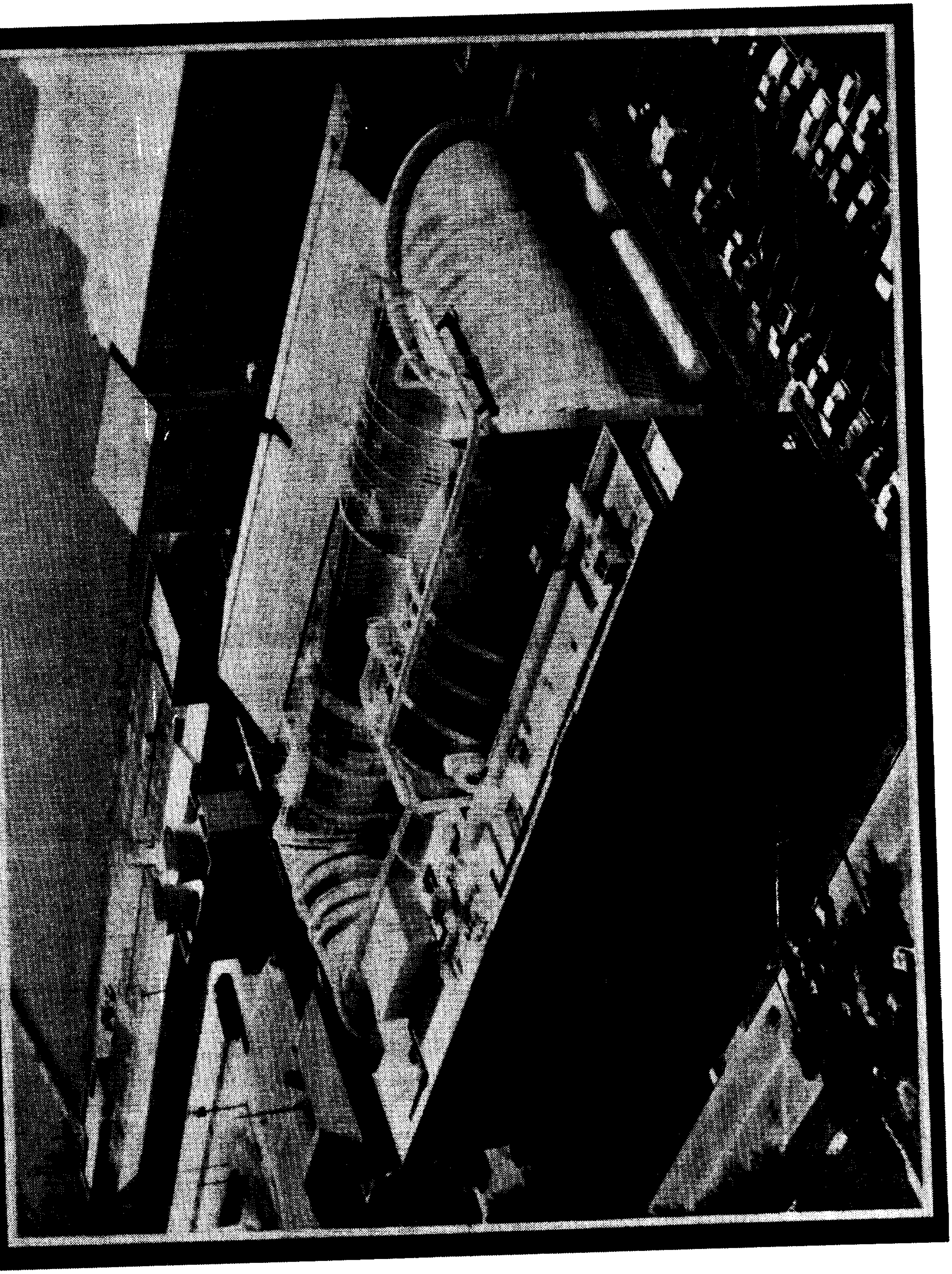
In 1965 the Army started the Composite Aircraft Program with the objective of producing a rotary-wing research vehicle combining the characteristics of an airplane and a helicopter. Bell Helicopter Company proposed a tiltrotor design (designated the Model 266) and was awarded one of the two exploratory definition contracts which were let under the program. A 0.133-scale semi-span dynamic and aeroelastic model of the Model 266 built by Bell in support of their studies was given to Langley by the Army after the program was terminated in 1967. Interest by both NASA and Bell in the tiltrotor 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. This led to a joint NASA/Bell study of proprotor stability, dynamics, and loads using the subject model (upper left in chart) which was conducted in the Langley Transonic Dynamics Tunnel (TDT). Several other cooperative experimental studies were conducted in the TDT following this initial investigation. The models employed in these other studies are also shown in the chart. Briefly, those other studies included: (1) A study of a folding proprotor version of the model used in the first study; (2) A parametric investigation of proprotor whirl flutter using a Grumman model; (3) A stability and control derivative investigation employing an aerodynamic model of the XV-15; (4) A "free-flight" flutter clearance demonstration of the XV-15; and (5) An aeroelastic stability investigation of the JVX (V-22).

TILTROTOR AEROELASTIC RESEARCH
Langley Transonic Dynamics Tunnel



LANGLEY TRANSONIC DYNAMICS TUNNEL

The experimental results to be shown were all obtained from tests which were conducted in the Langley Transonic Dynamics Tunnel (TDT). The TDT is a single-return, variable-pressure, slotted-throat tunnel having a test section 16 feet square (with cropped corners). It is capable of operation at Mach numbers from 0 to 1.2 and at stagnation pressures from near vacuum to slightly above atmospheric. Either air or freon can be used as a test medium. Large windows are provided for closed, unobstructed viewing of the model.



LANGLEY TRANSONIC DYNAMICS TUNNEL

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CHRONOLOGY OF TILTROTOR AEROELASTIC ANALYSIS DEVELOPMENT

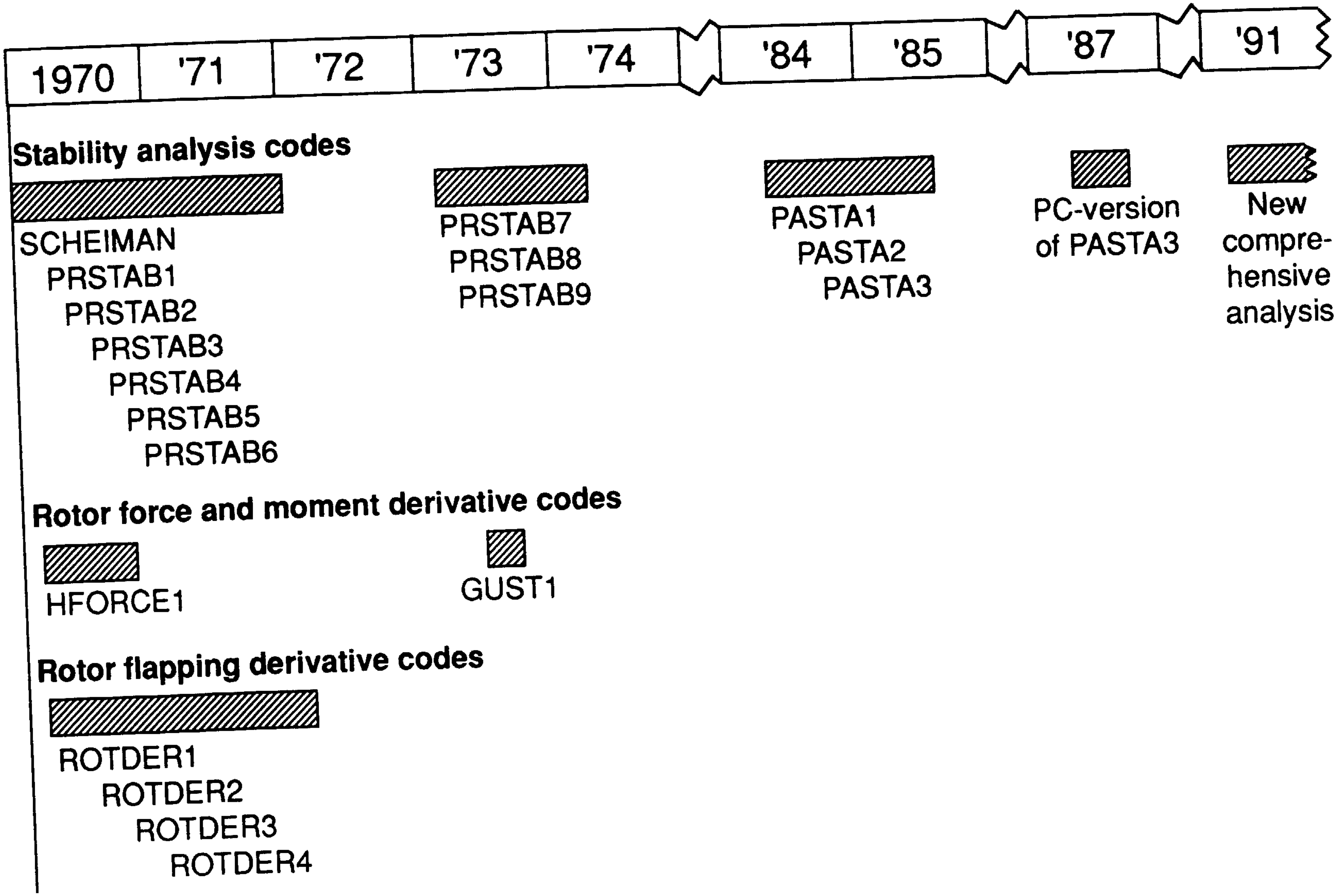
The development of tiltrotor aeroelastic analyses at Langley has proceeded along the three lines indicated in the chart, namely, stability analysis codes, rotor force and moment derivative codes, and rotor flapping derivative codes. As indicated in the chart, the work also occurred in several distinct phases or periods of time. The initial phase ('70-'72) was intended to support the experimental work being conducted in the TDT as well as to serve as a portion of a PhD dissertation by the author. The second phase ('73-'74) involved some enhancements and extensions to the code as a prelude to the phasing out of the activity. Several major extensions and enhancements to the stability code were made in the period '84 to '85 in support of the wind-tunnel tests being conducted on a V-22 flutter model in the TDT. A PC-version of the code was developed in mid-1987. The development of a new and comprehensive tiltrotor code based on UMARC was begun in 1991 for a PhD dissertation.

PRSTAB1 - PRSTAB9 are a series of proprotor stability codes of increasing complexity, all of which are based on a lumped mass and spring representation of the wing structure. The lumped parameter model of the wing in PRSTAB8 was replaced by a modal model in 1984 and the new program called PASTA1. PASTA2 and 3 were extensions of PASTA1 to include first a coning hinge and then an airplane rigid-body stability analysis capability. HFORCE1 is a code for computing rotor oscillatory force and moment derivatives. GUST1 is a version of HFORCE1 which includes a vertical sinusoidal gust. ROTDER1 - ROTDER4 are codes for computing rotor oscillatory flapping derivatives.

The SCHEIMAN program was developed for a PhD dissertation. The analysis was based on a time history solution of the nonlinear equations of motion for a rotor/pylon/wing system in the airplane mode of flight. The author of the code was transferred to a different technical area before the program could be fully validated and so it received only limited use.

The major features of the PASTA3 code are summarized in the next chart.

CHRONOLOGY OF TILTROTOR AEROELASTIC ANALYSIS DEVELOPMENT



THE PROPROTOR AEROELASTIC STABILITY ANALYSIS (PASTA) CODE
(Version 3.1)

PASTA (Proprotor Aeroelastic STability Analysis) is a code for the aeroelastic and rigid-body stability analysis of a tiltrotor aircraft in the airplane mode of flight. The analysis is based on an 11-degree-of-freedom linear mathematical model of the rotor system. The rotor is assumed to be gimballed, windmilling, and in axial flow. The blades are assumed to undergo rigid flapping motion due to both the gimbal action of the hub and an offset coning hinge. The blades are also assumed to execute rigid lead-lag motion about a virtual lag hinge. Quasi-steady strip-theory aerodynamics is employed for the blade airloading. Compressibility effects are introduced using a Ribner Mach number correction which is applied to the blade lift curve slope. A modal representation is employed for the airframe. Either full-span or semi-span configurations can be treated. The aerodynamic forces acting on the airframe rigid-body modes are expressed in terms of stability derivitives. No airloads are assumed to be acting on the wing elastic modes. Stability is determined by examining the eigenvalues which are obtained by solving the system equations as a matrix eigenvalue problem.

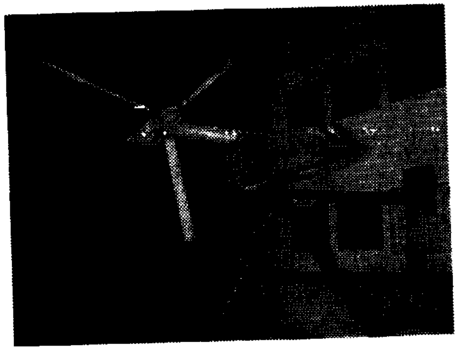
THE PROPROTOR AEROELASTIC STABILITY ANALYSIS (PASTA) CODE
(Version 3.1)

- 11 degree-of-freedom linear math model of rotor system
  - Windmilling (nonthrusting)
  - Axial flow (airplane mode)
  - Gimbaled hub with offset coning hinges
  - Rigid flapping motion of blade due to gimbal action and coning hinge
  - Rigid lead-lag motion of blade about virtual lag hinge
  - Rigid control system
  - Quasi-steady strip-theory aerodynamics for blade airloading
  - Ribner Mach number correction to blade lift curve slope
- Modal representation of airframe structure
- Full-span (“free-free”) or semi-span (cantilevered) configurations
- Provision for support system springs and dampers (full-span model)
- Stability derivative representation of airframe rigid-body aerodynamics
- No airloads on wing elastic modes
- Aeroelastic stability determined by solving equations as a matrix eigenvalue problem

BELL MODEL 266

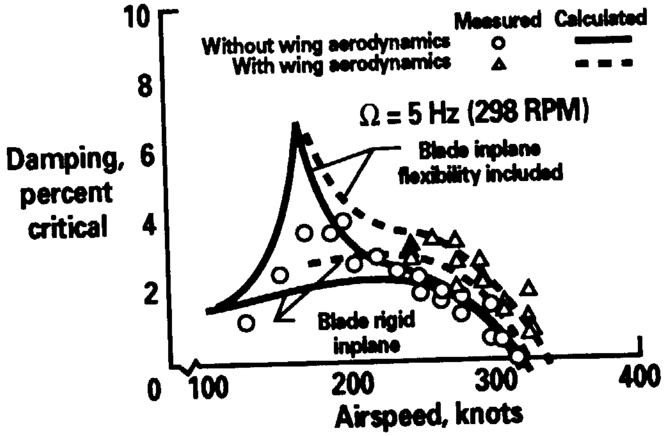
The Model 266 was the tiltrotor design which Bell entered in the Composite Aircraft Program. As mentioned earlier, a 0.133-scale model built by Bell as part of their work under the program was given to Langley by the Army after the program was cancelled. The experimental portion of Langley's tiltrotor research activities was initiated in September 1968 in a joint NASA/Bell study of proprotor stability, dynamics, and loads employing that model. Some results pertaining to stability and gust response are shown in the figure. Equivalent full-scale values are given. An indication of the relative degree to which stability is effected by wing aerodynamics and rotor-induced aerodynamic forces is given in the results shown at the lower left and at the upper right. It is seen that rotor aerodynamic forces predominate in the ultimate balance of forces at flutter and that wing aerodynamic forces have only a slight stabilizing effect. The results in the upper right also show the stabilizing effects of blade inplane flexibility. The sharp rise in the damping at about 170 kt is associated with the coupling of the blade inplane (lag) bending mode with the wing vertical (beam) bending mode. The dynamic response characteristics of the model due to excitation by a vertical sinusoidal gust which was generated by a device in the TDT were also studied. Some results showing the variation of wing vertical bending moment with gust frequency for the rotor-on and rotor-off conditions are shown in the lower right.

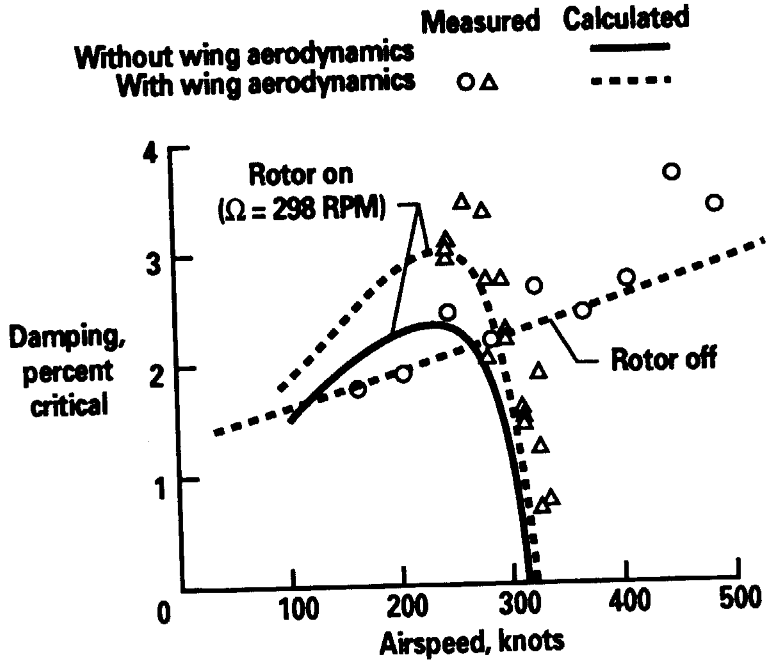
Bell Model 266

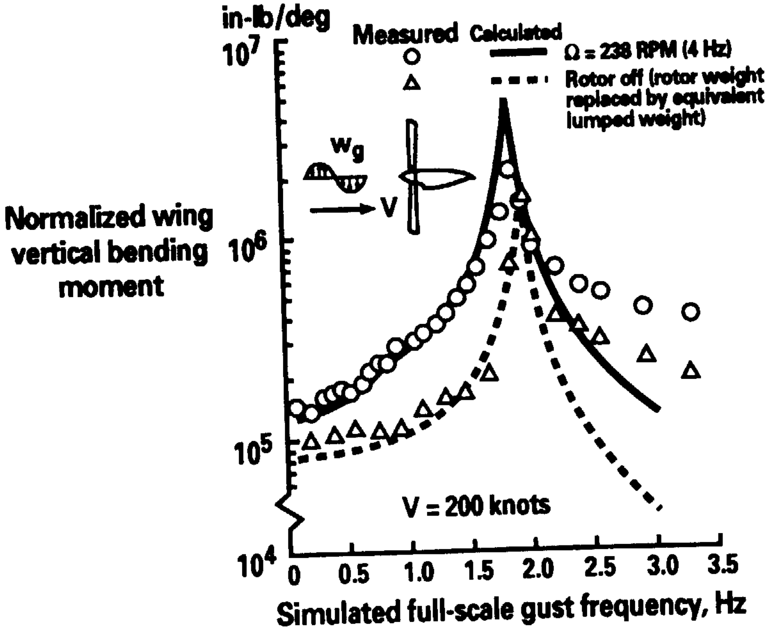


September

1968







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BELL MODEL 266 - FOLDING PROPROTOR VARIANT

A joint NASA/Bell/Air Force test was conducted in the TDT in January 1970 to investigate the stability, dynamics, and loads of a folding proprotor variant of the tiltrotor. The model used in this study was the same model employed in the first investigation but modified to include a collective drive motor which permitted rapid feathering and unfeathering of the rotor blades and a manually adjustable blade folding hinge. The stability boundary obtained for one of the configurations tested is shown in the figure at the right. The variation of flutter airspeed with rpm as it is reduced from its nominal value to zero is shown. As indicated in the figure, the model experienced several different modes of instability as rpm was reduced. The variation of steady-state one-per-rev blade flapping response with rotor rotational speed for a fixed shaft angle of attack is shown in the lower left. The peak in the flapping response occurs when the rotor rotational speed is in resonance with the blade flapping natural frequency.

Bell Model 266 – Folding Proprotor Variant

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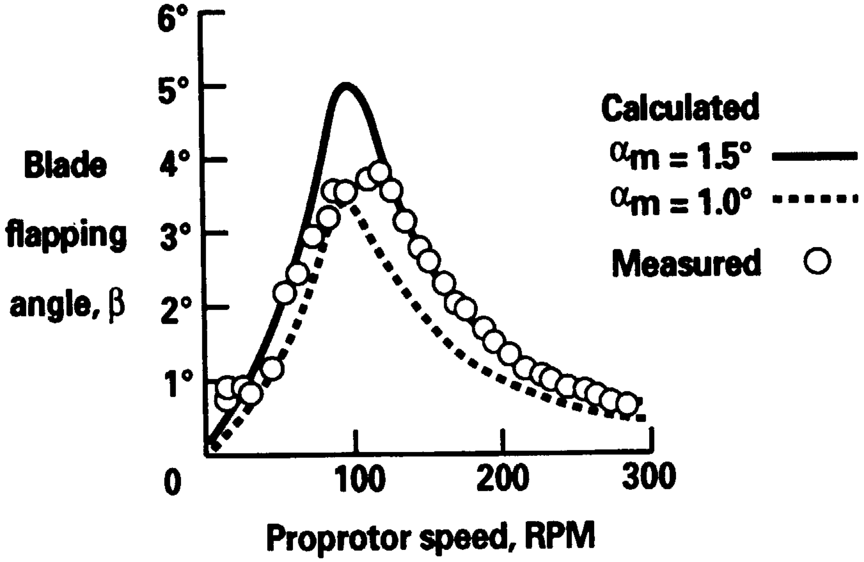
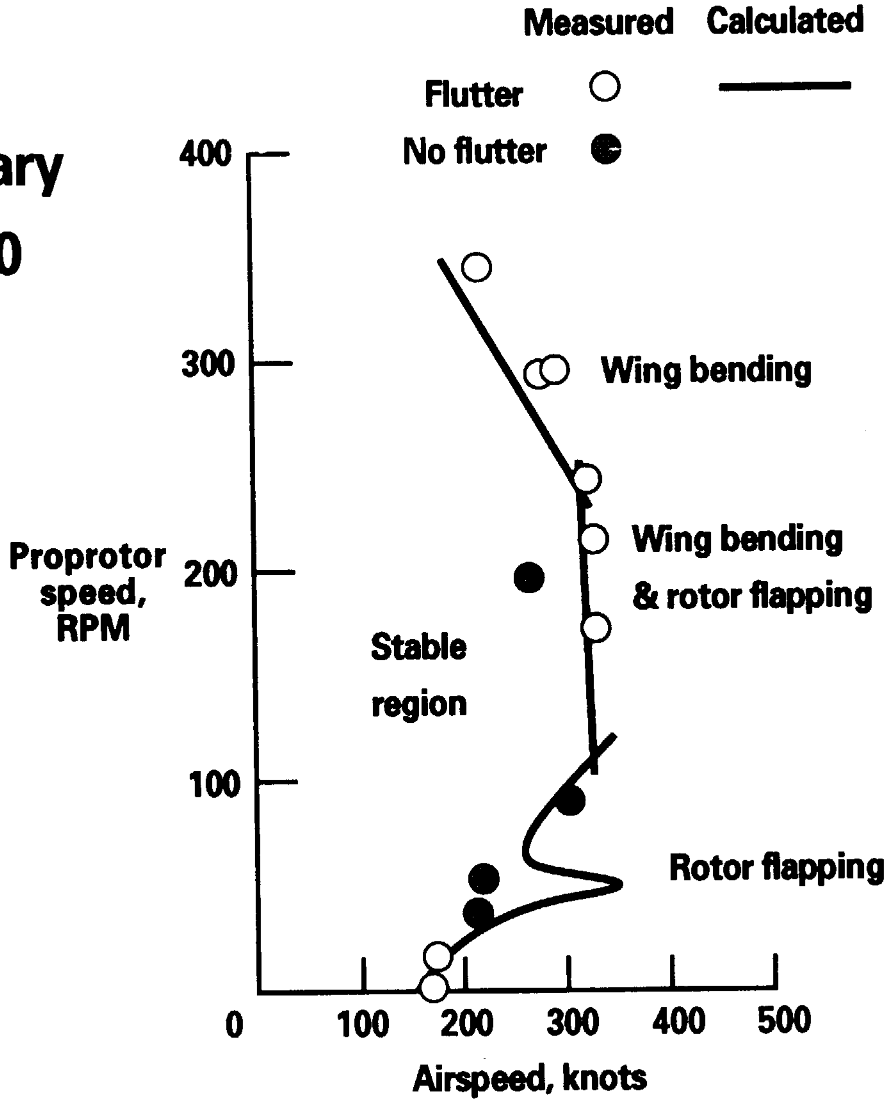
January
1970

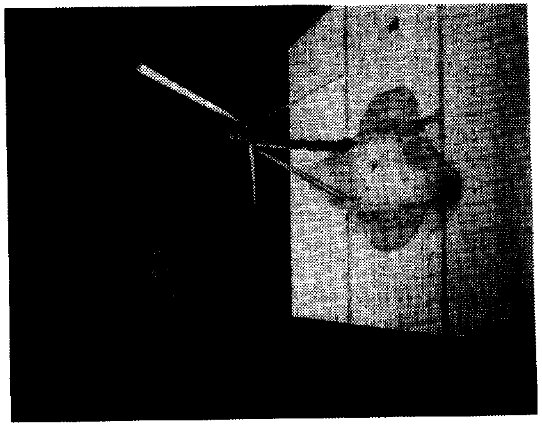




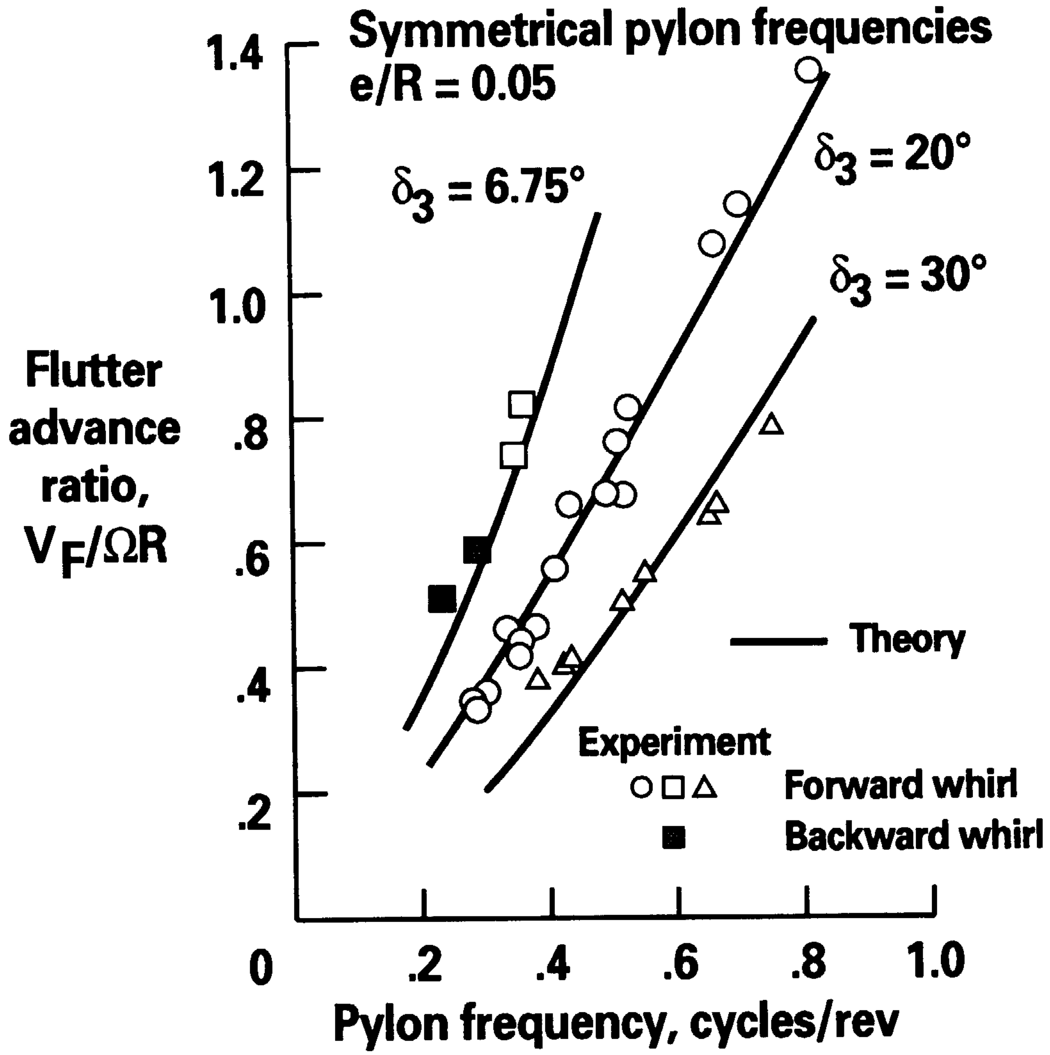
GRUMMAN HELICAT WHIRL FLUTTER STUDIES

Grumman interest in the tiltrotor aircraft concept led to a joint NASA/Grumman investigation in March 1971 of a 1/4.5-scale semi-span model of a Grumman tiltrotor design called Helicat which employed offset flapping hinges. During this entry, an off-design research configuration of the model (see figure) was employed in an extensive investigation of whirl flutter. A range of pylon pitch and yaw stiffnesses, blade hinge offsets, and blade kinematic pitch-flap couplings were investigated over a wide range of windmilling advance ratios. To obtain flutter at low tunnel speeds, a reduced-stiffness pylon-to-wing-tip restraint mechanism which permitted independent variations in pylon pitch and yaw stiffness was employed. The restraint was sufficiently soft so that the wing was effectively rigid. Fifty cases of forward whirl flutter and 26 cases of backward whirl flutter were clearly identified. Some whirl flutter results showing the effect of pitch-flap coupling (δ_3) on stability of a symmetric pylon configuration are given in the figure, where the flutter advance ratio, $V_F / \Omega R$, is plotted versus pylon frequency nondimensionalized by the rotor speed. For the cases shown, all flutter occurred in the forward whirl mode, except for the two points denoted by the solid symbols, which were in the backward whirl mode. The measured whirl flutter characteristics (flutter speed and frequency, direction of pylon whirl, and pylon yaw-to-pitch amplitude ratio and phase angle) were in excellent agreement with predictions from two different four-degree-of-freedom linear stability analyses, both of which employed simple two-dimensional quasi-steady aerodynamics for the blade loading.

Grumman Helicat Whirl Flutter Studies



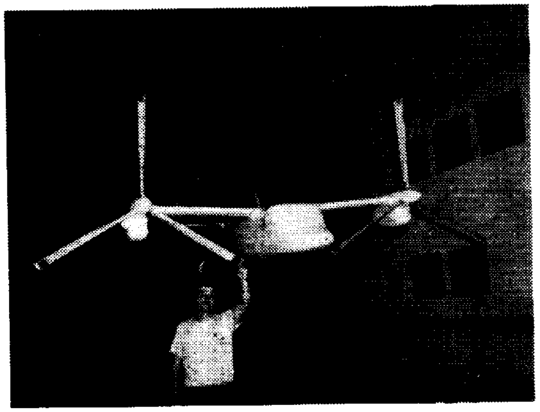
March 1971



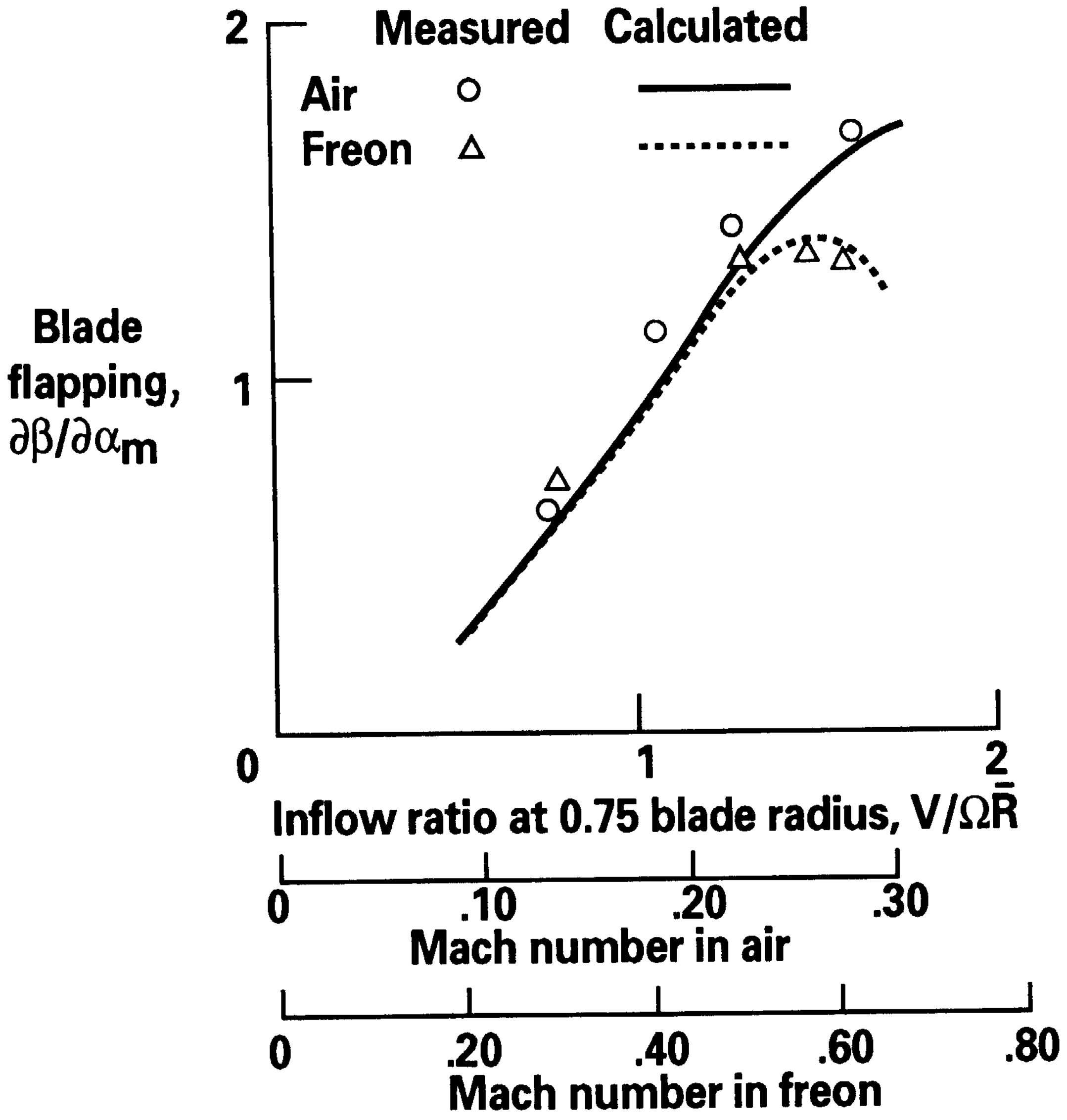
AERODYNAMIC TEST OF BELL MODEL 300 (XV-15)

A joint NASA/Bell investigation employing a 1/5-scale full-span aerodynamic model of the Bell Model 300 (XV-15) was conducted in the TDT in August 1971 for the purpose of determining the longitudinal and lateral static stability and control characteristics and establishing the effect of the proprotors on the basic airframe characteristics. Use of freon permitted testing at full-scale Mach numbers and near full-scale Reynolds numbers. Blade flapping was measured in both air and freon for several values of tunnel airspeed over a range of sting pitch angles. The resulting flapping derivatives are shown in the figure. Since the range of inflow ratios over which the derivatives were measured was the same in air and freon, and the test medium density at the simulated condition was about the same, an indication of the effects of Mach number on the flapping derivatives can be obtained by comparing the air and freon results. The drag rise associated with operating at high Mach numbers is seen to reduce flapping as Mach number is increased.

Aerodynamic Test of Bell Model 300 (XV-15)



August 1971



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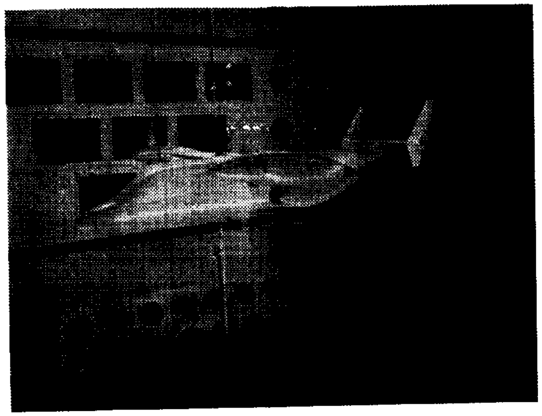
FLUTTER CLEARANCE TEST OF BELL MODEL 300 (XV-15)

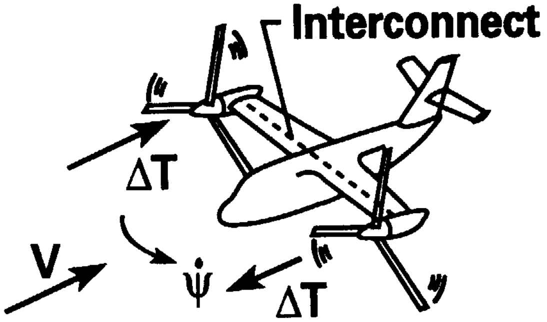
A 1/5-scale full-span dynamic and aeroelastic model of the Bell Model 300 (XV-15) tiltrotor was tested in a "free-flight" configuration in March 1972 to demonstrate that the design had the required flutter margin of safety and to confirm that the aircraft rigid-body modes were adequately damped. During 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 fore-and-aft oscillations of the rotor shaft when operating in the fully-converted airplane mode of flight.

Tiltrotor aircraft employ an interconnect shaft between the two rotor/engine systems so that in the event of an engine failure either engine may drive both rotors. The interconnect shaft also maintains synchronization of the rotor speeds during any aircraft motions. For example, yawing motions of the aircraft generate perturbation lift forces which tend to damp the yawing motion, as depicted in the sketch at the upper right. The effect of thrust damping on the stability of the Dutch Roll mode is illustrated in the figure, which shows the variation in the damping of that mode with tunnel airspeed for the cases in which the interconnect is engaged and disengaged. The substantial contribution of thrust damping to total damping is quite apparent.

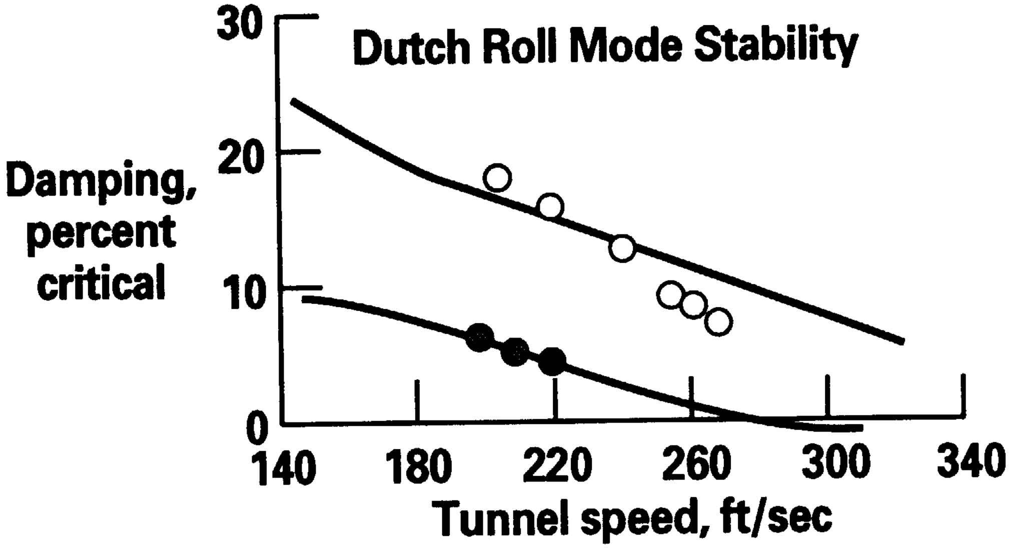
Flutter Clearance Test of Bell Model 300 (XV-15)



March 1972



Rotor interconnect shaft	Measured	Calculated (Bell)
Engaged (ΔT > 0)	○	—
Disengaged (ΔT = 0)	●	—



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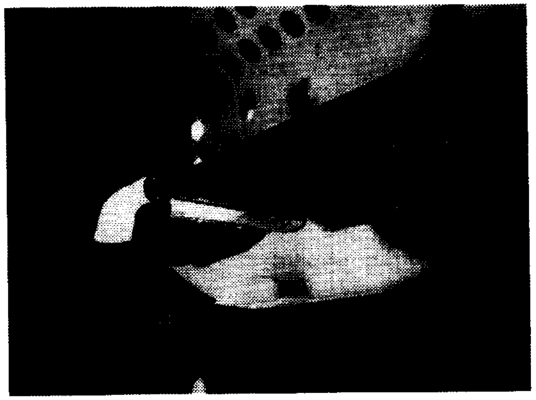
BELL/BOEING JVX (V-22)

A 1/5-scale dynamically and aeroelastically scaled semi-span model of first a preliminary design and then an updated version of the Bell/Boeing JVX (V-22) were tested in two separate entries in the TDT in 1984. The main objective of these tests was to determine the aeroelastic stability of the rotor/wing system in the high-speed airplane mode of flight as depicted in the figure and to correlate these results with analysis. A wide variety of configurations were tested and analyzed. Parameters which were varied included: pylon-to-wing locking (on and off downstop), rotor rpm, blade pitch-flap coupling, hub flapping restraint, and wing and blade stiffness distributions. Several configurations of the model with an updated hub design which had offset flapping hinges in addition to the gimbal were tested in the second entry. Some illustrative results from the first entry are presented in the figure as the variation with airspeed of the calculated and measured damping and frequency of the three lowest wing modes which are of importance to stability of the rotor/wing system. The wing beam mode (primarily wing vertical bending) is seen to be criticial (lowest flutter speed) for the case shown at the right while the wing chord mode (primarily fore-and-aft wing bending) is critical for the case shown in the lower left. The wing torsion mode was not critical for any of the configurations tested in either of the entries. The "peaks" which are evident in the calculated damping curves for the wing beam and chord modes in both of the cases shown are due to the coupling of those modes with the blade lag (inplane bending) mode as velocity is increased, as can be seen by inspection of the plots showing the variation of the modal frequencies with airspeed.

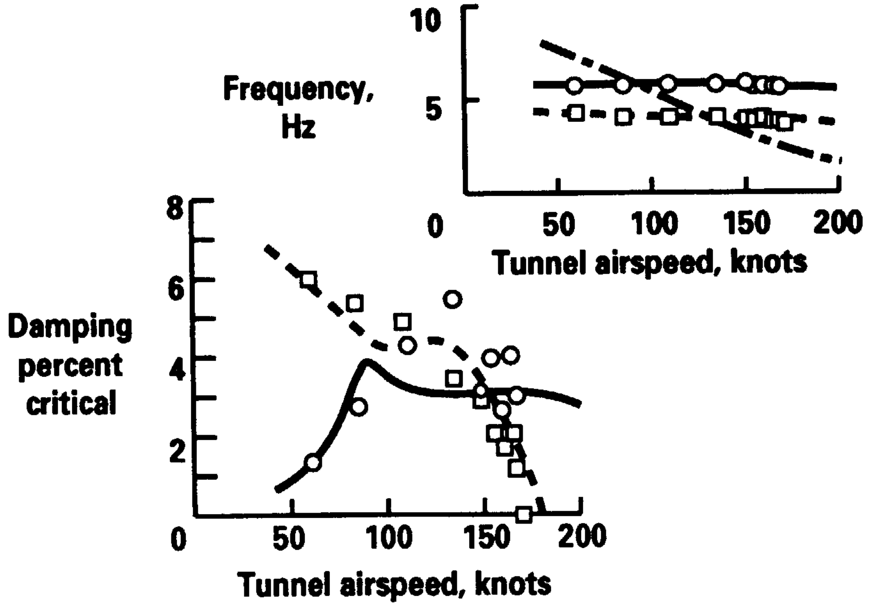
Bell/Boeing JVX (V-22)

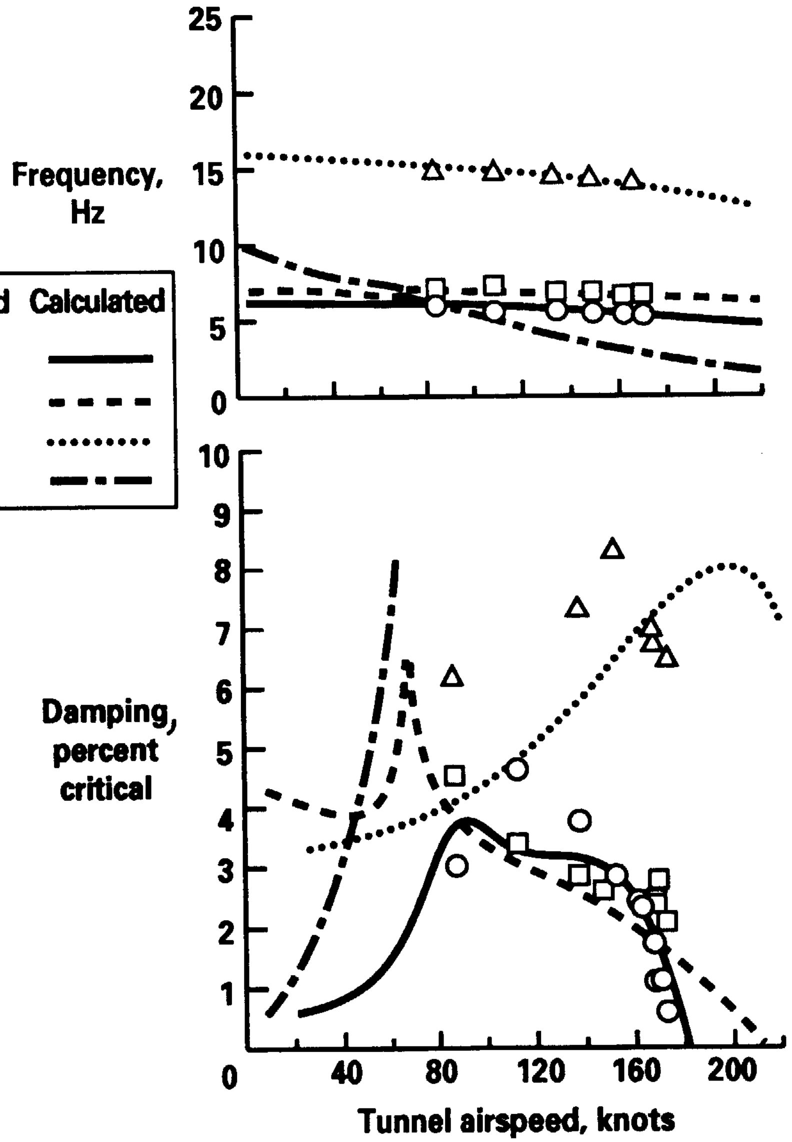


Feb./June

1984

	Measured	Calculated
Wing beam mode	○	───
Wing chord mode	□	- - - -
Wing torsion mode	△	········
Blade lag mode		—·—





CURRENT TILTROTOR AEROELASTIC RESEARCH ACTIVITIES

Langley's current tiltrotor research activities are both experimental and analytical. In a cooperative program between Ames and Langley, a 1/4-size, full-span, Mach-scaled model of the V-22 is being designed and built for the purpose of studying the aeroacoustic characteristics of tiltrotor aircraft. The TRAM (Tilt Rotor Aeroacoustics Model) is to be used as a testbed and tested at several research facilities. Although intended primarily for aeroacoustics research, the model is being designed to incorporate provisions for replacing its structurally-rigid wings by dynamically-scaled wings for aeroelastic studies. Langley has been refocusing its rotorcraft research activities and defining new research thrusts to position itself to better support NASA's planned Advanced Tiltrotor Transport Technology Program. As a result of various planning activities associated with defining Langley's part in this program, it was determined that small-scale aeroelastic models will play an essential role in the new program and that a new generic testbed system would be needed for conducting aeroelastic studies of advanced rotorcraft systems. A Langley conceptual design study has identified the general functional requirements and characteristics of this new system. The name HARTS (High-speed Aeroelastic Rotorcraft Test System) has been given to this new testbed system.

On the analytical side, work continues on the development of a new comprehensive aeroelastic stability analysis for tiltrotor aircraft for a PhD dissertation. The analysis is based on the UMARC (University of Maryland Advanced Rotorcraft Code) code and will incorporate such enhanced features as a finite-element-based formulation of the equations of motion, composite blades, bearingless hub, and advanced aerodynamics. With regard to the PASTA code, several potential enhancements and extensions have been identified which are aimed at making that code a research tool for conducting analytical studies in the area of active control of structural response.

CURRENT TILTROTOR AEROELASTIC RESEARCH ACTIVITIES

- Experimental
    - Tiltrotor aeroacoustics model (TRAM)
    - High-speed aeroelastic rotorcraft test system (HARTS)
- Analytical
    - Comprehensive aeroelastic analysis (based on UMARC)
    - PASTA enhancements

SUMMARY/CONCLUDING REMARKS

The Langley Research Center has a long history of propeller and proprotor aeroelastic research. The research has included a broad range of experimental and analytical studies, all of which have contributed, in one way or another, to the technology base which has led to the successful development of the the XV-15 and V-22 tiltrotor aircraft. In particular, the studies conducted at Langley have contributed substantially to increased understanding of the many unique aeroelastic and dynamic characteristics of tiltrotor aircraft and in the resolution of anomalies. Recently, there has been a resurgence of tiltrotor-related activity at Langley, primarily because of NASA's planned Advanced Tiltrotor Transport Technology Program.

SUMMARY/CONCLUDING REMARKS

- Langley has long history of propeller and proprotor aeroelastic research
- Research has included broad range of experimental and analytical studies
- Work has contributed to understanding of phenomena involved and resolving anomalies
- Recent resurgence of activity

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The Bell/Boeing V-22 Osprey which is being developed for the U.S. Military is a tiltrotor aircraft combining the versatility of a helicopter with the range and speed of a turboprop airplane. The V-22 represents a tiltrotor lineage which goes back over forty years, during which time contributions to the technology base needed for its development were made by both government and industry.
NASA Langley Research Center has made substantial contributions to tiltrotor technology in several areas, in particular in the area of aeroelasticity. The purpose of this talk is to present a summary of the experimental and analytical tiltrotor aeroelastic research conducted at Langley which has contributed to that technology.

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