A REVIEW OF RECENT ROTORCRAFT INVESTIGATIONS IN THE LANGLEY TRANSONIC DYNAMICS TUNNEL

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ABSTRACT

A review of recent rotorcraft investigations conducted in the NASA Langley Transonic Dynamics Tunnel (TDT) is presented. The paper begins with a brief description of the TDT and the rotorcraft testbeds used at the facility. A unique characteristic of the TDT is the use of a heavy gas test medium, so a brief discussion of the beneficial effects of this test medium for model-scale rotorcraft testing is presented. The paper concludes with a discussion of results obtained during recent TDT tests of an active twist helicopter rotor, and stiff- and soft-inplane tiltrotor configurations.

INTRODUCTION

The Langley Transonic Dynamics Tunnel (fig. 1) has a long and substantive history of experimental aeroelastic research, which has made credible contributions to rotorcraft technology and development. The efforts conducted at the TDT, extending from shortly after the tunnel's inception to the present, have included a wide range of experimental investigations using a variety of scale models and testbeds. TDT research results have made substantial contributions to the technology base needed by industry to design and build advanced rotorcraft systems. This body of work has contributed to supporting rotorcraft research and development programs through the fundamental understanding of phenomena involved, and the introduction of new concepts. For convenience of discussion, the rotorcraft research conducted at the TDT may be divided into two general categories: helicopter research and tiltrotor research.

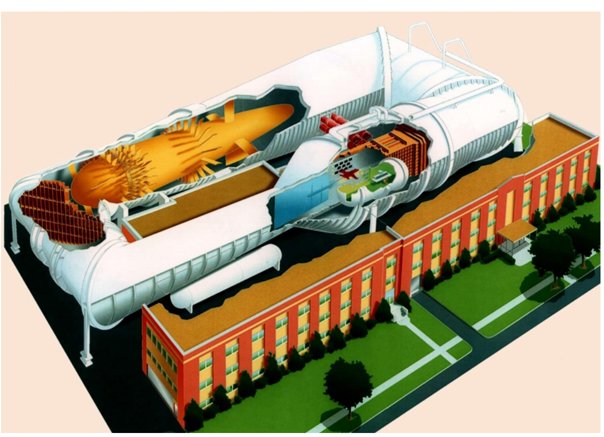


Figure 1. The Langley Transonic Dynamics Tunnel (TDT).

Helicopter testing has been conducted in the TDT almost since the inception of the facility in 1960, and has generally taken the form of research testing as compared to testing in support of any particular aircraft. Several testbeds have been used for helicopter testing in the TDT and the current testbed, referred to as the Aeroelastic Rotor Experimental System or ARES (figs. 2 - 3), has been in use since 1977. The ARES testbed has been used for investigations involving rotor performance, loads, stability and acoustics. Examples of these investigations are documented in references 1 – 11.

In recent testing, the ARES testbed has been used to evaluate rotors incorporating technologies that may be utilized to meet future needs for increased rotorcraft mission effectiveness. A model rotor system utilizing piezoelectric active fiber composite actuators to produce controlled, strain-induced blade twisting (refs. 12 - 13) has been tested open loop to determine the effect of the active blade twist on rotor-produced vibratory loads and noise. This concept is attractive because it offers an efficient way to achieve rotor individual blade control without the need for hydraulic power in the rotating system. The results of these tests (refs. 14-19) have been encouraging, and have demonstrated that active twist rotor (ATR) designs offer the potential for significant load and noise

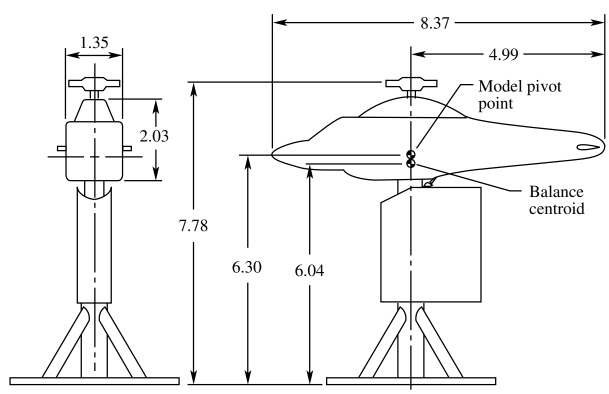


Figure 2. Schematic of the Aeroelastic Rotor Experimental System (ARES) helicopter testbed. All dimensions are in feet.

Figure 3. The ARES testbed in the TDT test section.

reductions in future helicopter rotor systems. An additional series of tests have been conducted with the ATR to investigate the use of closed loop controls in conjunction with the active blade twist to improve the reduction of vibratory loads.

Tiltrotor aeroelastic research in the TDT has been equally divided between supporting both research and development programs, and has its roots in the propeller whirl flutter studies conducted in the early 1960s (refs. 20-26). Tiltrotor aeroelastic studies began in 1968 in an exploratory parametric investigation of stability, dynamics, and loads using a model of a proposed Bell Helicopter Company tiltrotor design. Aerodynamics and flutter clearance tests were conducted in the 1970s in support of the development program that resulted in the NASA/Army XV-15 tiltrotor research aircraft. In 1984 tests were conducted in the TDT in support of the V-22 tiltrotor aircraft development program. These tests used a 1/5-size model designed and built by Bell Helicopter and Boeing-Vertol Company (ref. 27). In 1994, a new tiltrotor research program was initiated at the TDT using a refurbished version of the 1/5-size semispan model of the V-22 (fig. 4). The refurbished model has been incorporated into a tiltrotor research testbed now known as the Wing and Rotor Aeroelastic Testing System (WRATS). In collaboration with Bell Helicopter, studies under the current research program are focusing on a range of aeroelastic technical areas that have been identified as having the potential for enhancing the commercial viability of tiltrotor aircraft. In particular, considerable emphasis is being directed to

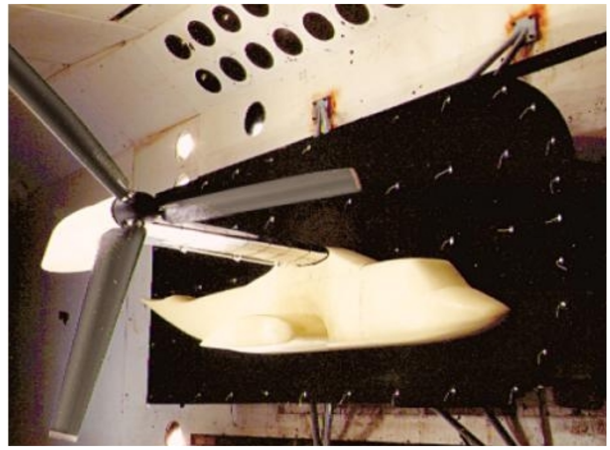


Figure 4. The Wing and Rotor Aeroelastic Testing System (WRATS) tiltrotor testbed.

the development and evaluation of modern adaptive control techniques for active vibration control and stability augmentation of tiltrotor aircraft (refs. 28-36). Attention has also been given to the use of passive design techniques to enhance aeroelastic stability and aerodynamic performance of tiltrotor aircraft (refs. 37-41). The most recent tiltrotor test at the TDT used the WRATS testbed to investigate the stability characteristics of a soft inplane, semi-articulated rotor for possible use on a future quad tiltrotor aircraft.

This paper will present results of recent helicopter and tiltrotor tests in the TDT and indicate how these results are contributing to rotorcraft technology and development. The paper will begin with a brief description of the TDT, will address model scaling for use in the TDT, and describe how the scaling process is aided by virtue of the TDT heavy gas test medium. The recent rotorcraft tests will be discussed in separate sections and illustrative results will be provided for each test.

TRANSONIC DYNAMICS TUNNEL CHARACTERISTICS

The Langley Transonic Dynamics Tunnel (TDT) was originally designed as a 19-foot diameter subsonic pressure tunnel (ref. 42). In the late 1950s, the facility was converted to the Transonic Dynamics Tunnel to satisfy the need for a transonic facility capable of testing dynamic models of a size large enough to allow simulation of important structural properties of aircraft. This new aeroelastic testing capability was made possible by using the high-molecular-weight gas R-12 as the test medium (ref. 43). In the late 1980s, environmental concerns were raised regarding the continued use of R-12, and a decision was made to replace R-12 with the environmentally acceptable

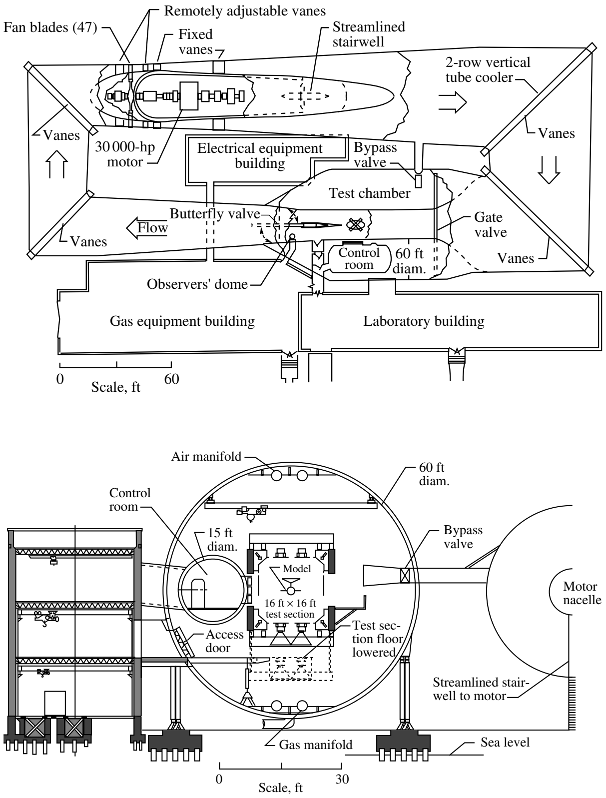


Figure 5. Schematics of the Transonic Dynamics Tunnel (TDT).

refrigerant R-134a. In terms of the benefits for aeroelastic model scaling, R134a is essentially equivalent to R-12. Conversion of the TDT heavy gas test medium from R-12 to R-134a was completed in 1997 and is described in references 44-45.

The TDT is a single-return, closed-loop, continuous-flow, variable-pressure, slotted-throat wind tunnel having a test section 16-feet square with cropped corners. Schematics depicting the general arrangement of the tunnel are shown in figure 5. The tunnel uses air or R-134a as the test medium and can operate at total (stagnation) pressures from near vacuum to atmospheric. The tunnel operates over a Mach number range from near zero to about 1.2, with attendant maximum Reynolds numbers of about three million per foot in air to about ten million per foot in R-134a. Both Mach number and pressure are independently controllable.

Since its inception the TDT has been a unique national facility for testing aeroelastic models of a variety of aircraft, spacecraft, and launch vehicles (refs. 46-47). The heavy gas feature of the tunnel, in combination with the large test section size, offers several advantages over air with respect to the design, fabrication, and testing of aeroelastic models. For example, improved model-to-full-scale similitude, eased fabrication requirements, lower model vibration frequencies, reduced test section flow velocities, higher test Reynolds numbers, and reduced tunnel and model power requirements are all advantages offered by the TDT heavy gas test medium. For rotorcraft testing, the test section easily accommodates model rotors up to 10 feet in diameter. More detailed descriptions of the TDT and its capabilities may be found in references 44-45.

TRANSONIC DYNAMICS TUNNEL ROTORCRAFT TESTBEDS

ARES Model Helicopter Rotor Testbed

The Aeroelastic Rotor Experimental System (ARES) model helicopter rotor testbed shown in figures 2 and 3 is used for all helicopter rotor testing in the TDT. The ARES is powered by a 47-hp electric motor through a two-stage, belt-driven transmission system. Rotor control is achieved by a conventional hydraulically actuated rise-and-fall swashplate using three independent actuators. Similarly, a single hydraulic actuator controls rotor-shaft angle of attack.

Instrumentation on the ARES testbed permits continuous display of model control settings, rotor speed, rotor forces and moments, fixed-system accelerations, blade loads and position, and pitch-link loads. All rotating-system data are transferred through a 30-channel slip ring assembly to the testbed fixed system. An additional slip ring permits the transfer of high-voltage power from the fixed system to the rotating system for actuation of the Active Twist Rotor blades. A six-component strain-gage balance placed in the fixed system 20.88 inches below the rotor hub measures rotor forces and moments. The strain-gage balance supports the rotor pylon and drive system, pitches with the model shaft, and measures all of the fixed-system forces and moments generated by the rotor model. A streamlined fuselage shape encloses the rotor controls and drive system; however, the fuselage shape is isolated from the rotor system such that its forces and moments do not contribute to the loads measured by the balance.

WRATS Tiltrotor Testbed

The Wing and Rotor Aeroelastic Testing System (WRATS) is a semi-span 1/5-size aeroelastic tiltrotor model based on the V-22. This tiltrotor model has been used in several aeroelastic experimental efforts beginning in 1984 as part of the Navy's JVX program, and more recently has been on loan to NASA LaRC. Since 1994, Bell Helicopter and NASA LaRC have had an ongoing cooperative research agreement in place to perform experimental aeroelastic investigations involving the WRATS model with several associated modifications. Some of the more notable investigations include stability augmentation using a composite tailored wing (refs. 37 - 39), vibration reduction using an active flap (ref. 28), and vibration reduction using an active swashplate (refs. 29 - 30).

Important general features of the model are listed as follows: an aeroelastically-scaled wing with removable airfoil panels, a dynamically-scaled pylon with a downstop spring tuned to provide elastic mode shapes and frequencies close to those associated with the full-scale conversion actuator (different springs are used for different conversion actuator positions), a gimballed 3-bladed hub with a constant-velocity joint (the baseline hub system), and a set of aeroelastically-scaled rotor blades.

Another notable feature of the WRATS tiltrotor model is the hydraulically controlled swashplate, which has high bandwidth controller capability. Three oil cylinder actuators are used to position the swashplate, each controlled by a Moog servo valve using an attached linear variable displacement transducer (LVDT) for position feedback. The WRATS pilot control console has three inputs for AC/DC signals (active control commands) that may be summed with the pilot DC input commands before being sent to the swashplate actuators.

ROTORCRAFT MODEL SCALING CONSIDERATIONS

The use of scaled rotor models to investigate aeroelastic events can be best justified through considerations of cost, safety, and ease of design changes. When compared to full-scale flight studies, model tests are also advantageous in that the basic aeroelastic parameters and test conditions can be controlled (ref. 48). The response of a model rotor blade is influenced by aerodynamic, elastic, inertial, and gravitational loads acting on the blades (refs. 48-49). For a model rotor blade to be a dynamically scaled version of a full-scale blade, the relative magnitudes of these four forces must be the same between the model and full-scale blade. This is usually accomplished through the use of appropriate non-dimensional similarity parameters. For complete scaling of a model rotor blade, the ratio of the model to full-scale non-dimensional similarity parameters must be unity. In actual usage, particularly when testing in air, it is virtually impossible for these ratios to all have a value of unity. For this reason, attempts are made to match the most important parameters, depending on the test results desired. Model advance ratio and Lock number are usually matched to full-scale values to simulate basic blade relative velocities with respect to the test medium. Three additional non-dimensional parameters usually considered are Mach number, Froude number, and Reynolds number. Since full-scale rotor tip speeds are generally in the near-sonic range where compressibility effects are important, duplicating Mach number is necessary. Testing of aeromechanical instabilities involves coupling between blade motions and body degrees-of-freedom, making gravity effects important, and so Froude numbers should be matched. Rotor performance testing, involving airfoil evaluation, makes matching Reynolds number important. In addition, elastic and mass simulation requires duplicating rotating natural frequencies on a per-rev basis. This is necessary for blade loads and vibration studies.

The design of a scale model rotor that matches the five similarity parameters mentioned above is not possible due to conflicting requirements. However, the design task is made more manageable if the aerodynamic test medium can be tailored. The capability to tailor the test medium for aeroelastic model studies is greatly enhanced by the use of a heavy gas such as the R-134a used in the TDT. The properties of R-134a enable a model-scale rotor to achieve larger Reynolds numbers, and a better match of Froude number and Mach number, all at a lower rotational speed than the same size model in air. The use of R-134a as a test medium also results in a reduction in model power required to match tip Mach number and advance ratio. Model construction for operation in R-134a is benefited by lower centrifugal loads and the allowance of heavier structural designs than those of an air-scaled model. Additionally, lower rotor speeds permit the use of control actuators at lower frequencies during active control applications. The benefits of using the R-134a test medium in the TDT for the testing of aeroelastic rotor models are considered significant. The ability to accurately simulate rotor dynamics as well as operate at increased Reynolds numbers produces test results more comparable to real world conditions than would be possible with a similar test conducted in air.

RECENT TDT ROTORCRAFT INVESTIGATIONS

Active Twist Rotor

The Active Twist Rotor (ATR) program is a cooperative effort among NASA, the U.S. Army Research Laboratory (ARL), the Massachusetts Institute of Technology (MIT), and, more recently, the University of Michigan and Sikorsky Aircraft Corporation. The goal of the program is to explore the effects and potential benefits of an active-blade-twist helicopter rotor system. Potential advantages of such a system include fixed-system (fuselage) vibration reduction, rotor noise reduction, rotor performance and maneuverability improvements, and active blade tracking. Initial program efforts began in the mid-1990s using solely analytical methods (refs. 12 - 14). These studies were followed in 1998 and 1999 by experimental investigations of a single active-twist prototype blade on the benchtop and in hovering flight on the ARES testbed (refs. 15 - 16). A full four-bladed active-twist rotor system was fabricated in 2000 and tested on the ARES in hovering and forward-flight conditions in the TDT using open-loop control methods. This test confirmed that the ATR offered 4P fixed-system component load reductions of as much as 60% to 100%, and could be used to reduce rotor noise by as much as 3 dB (refs. 17 - 19). In the spring of 2002, a second test of the ATR was conducted in the TDT to explore the use of closed-loop control methods to minimize fixed-system vibrations. This section of the paper will present an overview of the vibratory loads reduction results obtained with the Active Twist Rotor.

ATR Blade Description

Each Active Twist Rotor blade utilizes 24 commercially available Active Fiber Composite (AFC) actuators to achieve active twist control. The AFC actuators, shown conceptually in figure 6, are embedded directly in the structure of each blade D-spar, spanning a section of uniform blade structure from 0.30R (30% blade radius) to 0.98R. The AFCs are placed in four layers through the blade thickness and are oriented such that the active strain is applied at ±45° relative to the blade spanwise axis to generate maximum torsional control of the blades. Four dedicated high-voltage amplifiers, one for each blade, are used to generate high voltage, low current power for the independent actuation of each blade.

The ATR blades are of a simple design having a rectangular planform with a chord of 4.24 inches, radius of 55.0 inches, a NACA-0012 airfoil, and a linear pretwist of -10° from the center of rotation to the blade tip. To the extent possible, uniform mass and blade stiffness distributions were used throughout the blade to minimize fabrication complexity. ATR testing was conducted on a four-bladed articulated hub with coincident flap and lag hinges, and trailing pitch links. A constant rotor speed of 688 rpm was used throughout testing, resulting in a blade hover tip Mach number, M_{tip}, of 0.60.

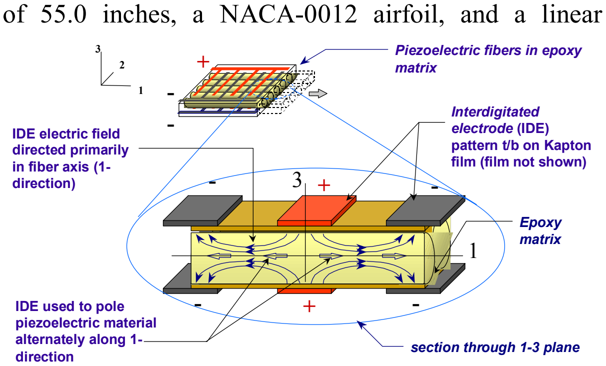


Figure 6. Active Fiber Composite (AFC) piezoelectric actuator concept.

Open-Loop Control System

Open-loop active-twist control of the ATR blades is achieved with a computer control system that permits the user to prescribe either: 1) the amplitude and frequency of collective twist mode actuation, useful for sine dwell excitation for the development of system frequency response functions; or 2) the amplitude, control phase, and harmonic frequency of actuation. With this second type of actuation, the active-twist commands are synchronized to the rotation of the rotor system such that proper actuation frequency and control phase are achieved, regardless of rotor speed. For this type of control, either "collective" twist mode or "individual blade control (IBC)" twist mode actuation may be selected. In the collective twist mode of actuation each blade is sent the same twist commands simultaneously, resulting in all of the blades twisting the same way at the same time in a "collective" fashion. For the IBC mode of actuation, each blade is sent twist commands according to a prescribed schedule associated with its own position in the rotor azimuth.

Closed-Loop Control Systems

Three different closed-loop control systems have been implemented for fixed-system vibratory loads reduction using the ATR. The first is a multi-harmonic vibration reduction controller developed jointly by the University of Michigan and MIT. The second is a single-harmonic vibration controller developed by the Sikorsky Aircraft Coroporation. It is designed to reduce specifically the primary fixed-system vibration frequency at four times the operating frequency of the rotor, or four-per-revolution (4P). The third controller is also a single-harmonic vibration controller designed to minimize 4P fixed-system vibratory loads. It was developed jointly by NASA and the Army Research Laboratory. Each of the controllers utilizes the identical or similar computer control hardware as that used for the open-loop control of the ATR blades.

ATR Results

Representative results from the forward-flight ATR tests conducted in the TDT in 2000 and 2002 are

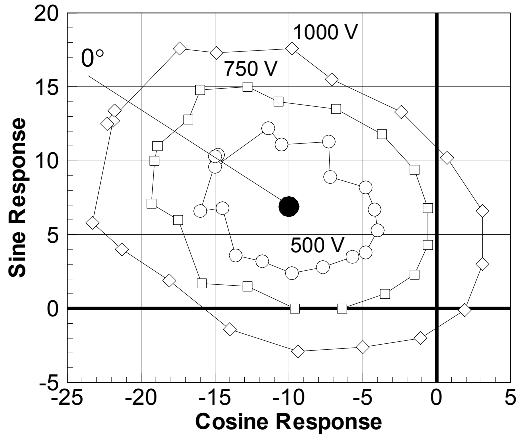
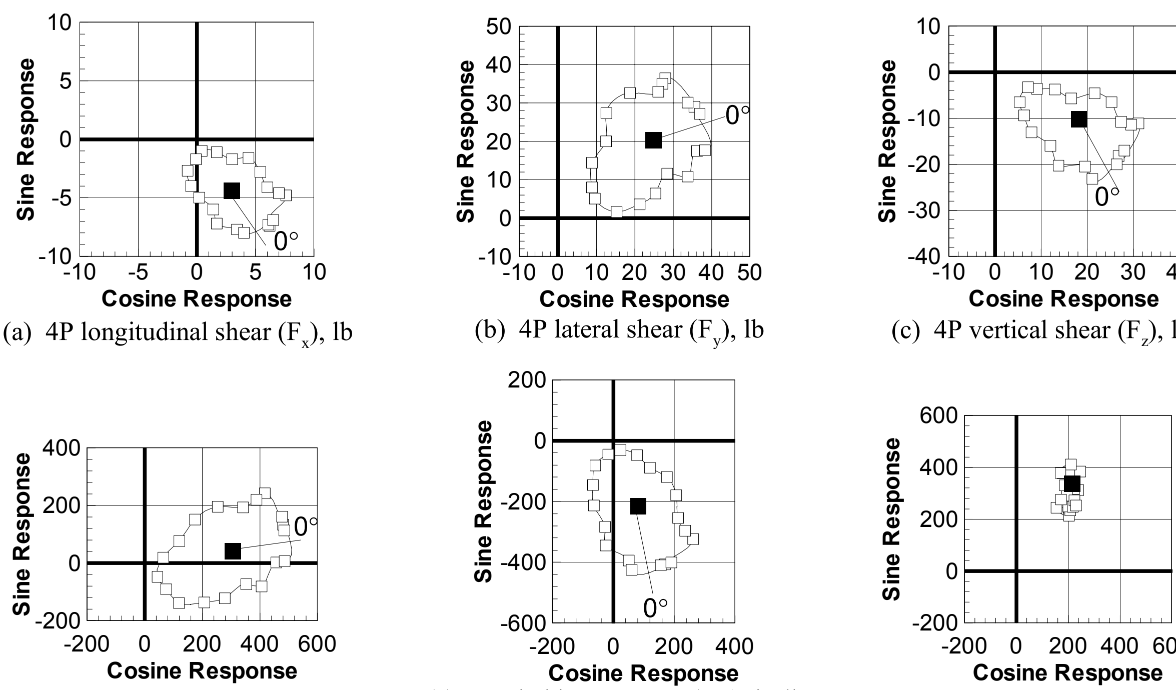


Figure 7. Sample response map of blade flapwise bending moment (0.29R) for 3P IBC control at a low-speed flight condition (0.14 advance ratio).

presented in figures 7 to 10. During the open-loop testing conducted in 2000, 3P IBC twist control was determined to be generally the most effective mode of actuation for reducing 4P fixed-system loads. During the testing conducted in 2002, each of the closed-loop vibration controllers further verified that 3P IBC twist control was the most effective and emphasized its use in minimizing 4P fixed-system vibratory loads.

Figure 7 presents a reduced data format that is of particular use during the analysis of open-loop control effectiveness. The rotating-system 3P blade flapping moment response is presented in a response map format for the baseline (no control) condition and 3P active twist actuation voltages of 500 V, 750 V, and 1000 V. Results are presented for an advance ratio of 0.14, a typical low-speed forward-flight condition in which helicopter vibratory loads tend to be high. The plot presents the 3P sine component of the response as a function of the 3P cosine component of the response, so that both response magnitude and response phase are evident in the results. The solid circle represents the baseline condition, while the open symbols represent the response measured during 3P IBC twist actuation at the three different voltage amplitudes. A radial line is presented on the plot to reference the location of the response due to 0° control phase. Control phase angles advance around the plots counterclockwise. The advantage of this plot type is that it directly shows the relationship between the baseline response, the response for varying actuation voltage amplitudes, and the zero harmonic load condition represented by the origin of the plot. A plot in which the circle of response points encompasses the origin represents a condition for which sufficient control authority exists to eliminate that particular harmonic load. For this particular example, the load may be "zeroed" at an approximate voltage amplitude of 900 V and control phase of 180°.

In the fixed-system, the 3P IBC twist actuation is shown to produce large variations in the 4P shears and moments. Figure 8 presents the 4P fixed-system loads



(a) 4P longitudinal shear (F_x), lb

(b) 4P lateral shear (F_y), lb

(c) 4P vertical shear (F_z), lb

(d) 4P rolling moment (M_x), in-lb

(e) 4P pitching moment (M_y), in-lb

(f) 4P yawing moment (M_z), in-lb

Figure 8. Fixed-system response maps for low-speed flight (0.14 advance ratio) and 3P, 1000 V IBC actuation.

corresponding to the 1000 V, 3P IBC twist actuation conditions presented in figure 7 for the rotating-system. As shown, the 4P fixed-system loads are generally reduced the most using 1000 V 3P IBC twist actuation at about 180° control phase. One exception to this was for the 4P yawing moment, which was shown to be generally insensitive to almost all twist control conditions.

Figures 9 and 10 present some representative vibration reduction results from the closed-loop control test conducted in 2002. Figure 9 presents results obtained using the University of Michigan/MIT vibration reduction controller. The results are presented for a typical cruising forward flight advance ratio of 0.267, a condition in which the vibration control capacity of the ATR is particularly effective. The upper plot in figure 9 presents the power spectral density of the vertical fixed-system shear for both the baseline (control off) and the closed-loop active-twist control. The controller was optimized to minimize vertical fixed-system shear at both 1P and at 4P. The lower plot presents the ratio between the closed-loop response and the baseline response. As shown, the controller is effective in reducing the 1P and 4P vertical fixed-system loads by approximately 30 dB and 50 dB respectively, effectively eliminating both harmonic loads.

Figure 10 presents the overall effectiveness of the

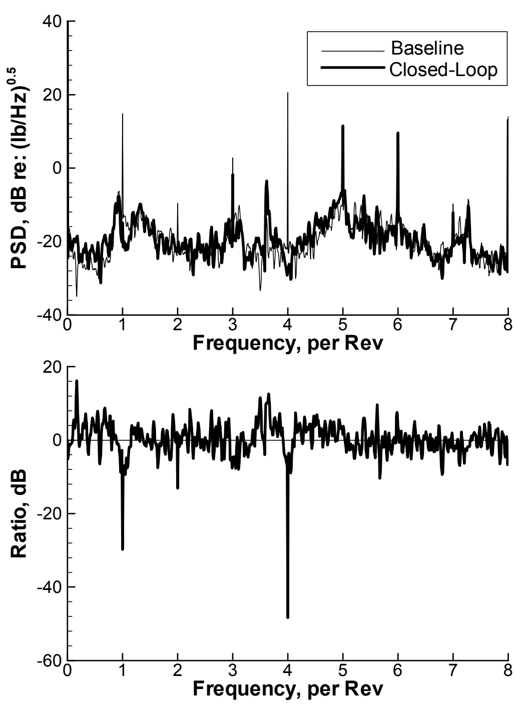


Figure 9. University of Michigan/MIT vibration reduction controller results showing vertical fixed-system load reduction. Cruising-speed flight (0.267 advance ratio).

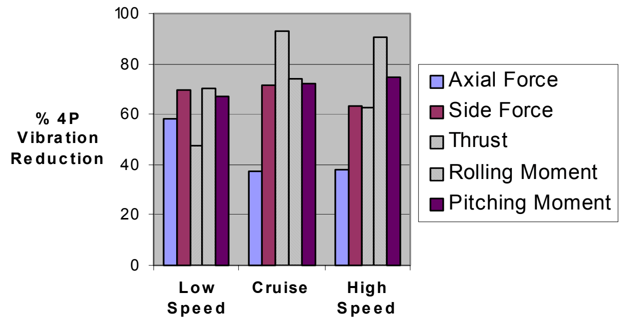


Figure 10. Sikorsky Aircraft Corporation vibration reduction controller results showing 4P fixed-system vibration reduction.

Sikorsky Aircraft Corporation vibration reduction controller across the flight speed range. The figure presents 4P fixed-system loads for three different flight speeds of advance ratios 0.14, 0.267, and 0.33, representing low-speed, cruise-speed, and high-speed flight, respectively. For these results, the objective function of the controller was set to provide an equally weighted minimum of each of the five-presented components of the fixed-system loads. Yawing moment was omitted from the objective function because open-loop control results indicated little sensitivity of this load to active-twist control. As shown in the figure, the controller was able to reduce the 4P fixed-system loads by a minimum of 35%, and by as much as 90%.

Future research in the area of active-twist rotor configurations will focus on the development of an Advanced Active Twist Rotor (AATR) blade design. This rotor will be used to demonstrate the improvements available using modern rotor blade design parameters (tip droop, sweep, and taper), non-uniform mass and stiffness distributions, and advanced piezoelectric actuators. Initial forward-flight wind tunnel testing of the AATR is expected to commence in 2004.

Soft-Inplane Tiltrotor Testing

A new four-bladed soft-inplane semi-articulated rotor system, designed as a candidate for future heavy-lift rotorcraft, was tested at model scale on the Wing and Rotor Aeroelastic Testing System (WRATS). The WRATS is a 1/5-size aeroelastic tiltrotor wind-tunnel model based on the V-22. The experimental investigation included both a hover test with the model in helicopter mode subject to ground resonance conditions, and a forward flight test with the model in airplane mode subject to whirl-flutter conditions. The experiment was conducted as part of a cooperative

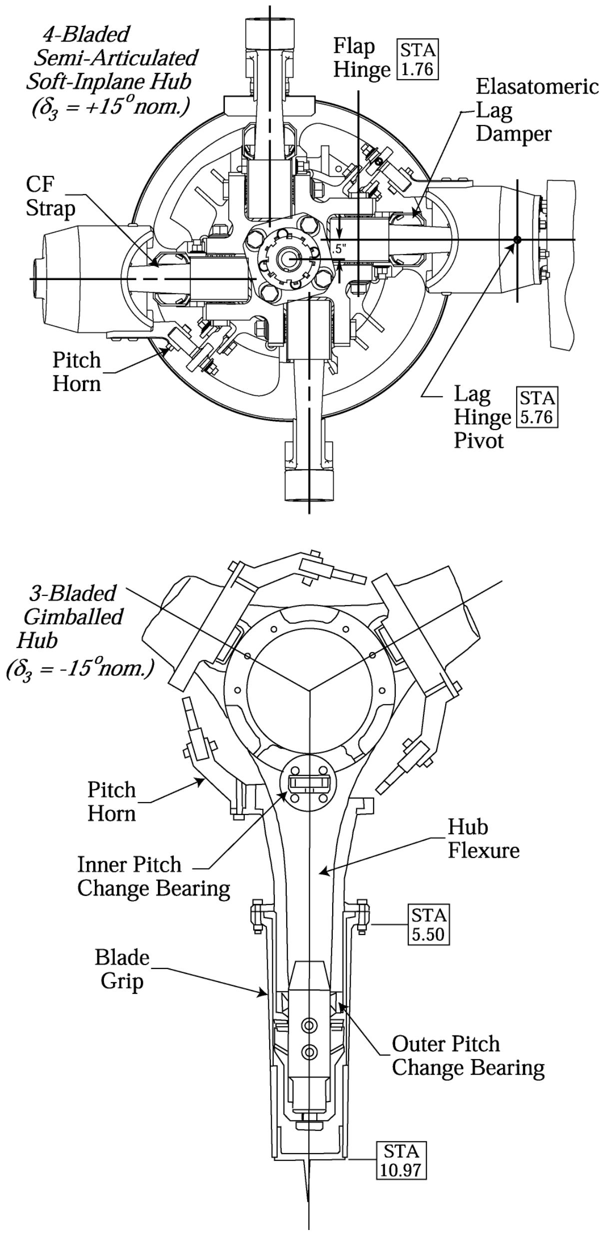


Figure 11. Schematics of the two hub types tested.

agreement among the U.S. Army Research Laboratory (ARL), NASA Langley Research Center (LaRC), and Bell Helicopter. The objective of the investigation is to determine the damping margins and load reduction factors associated with a soft-inplane rotor as compared to the current baseline stiff-inplane rotor system.

Also included as part of this investigation was testing of a three-bladed stiff-inplane gimballed rotor system, and assessment of an active control system designed to augment system damping. The three-bladed stiff-inplane rotor system used in several past investigations (refs. 29, 32-33, 38-39) was examined under the same conditions as the four-bladed soft-

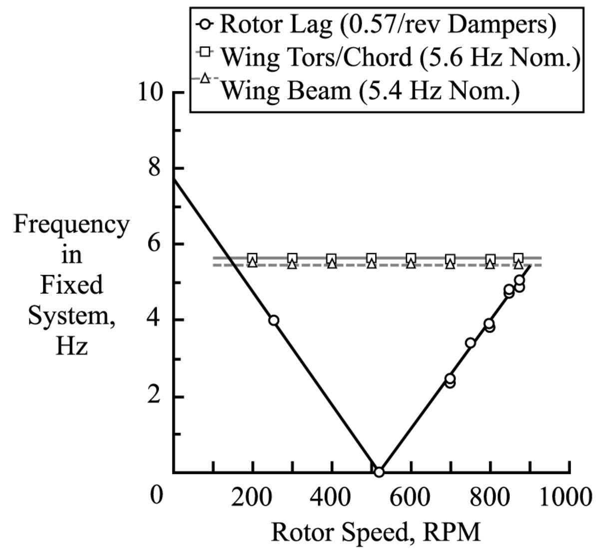


Figure 12. Important system frequencies as a function of rotor speed (0.57/rev damper set).

inplane hub to provide a baseline for comparison. Schematics of the two hubs tested are shown for comparison in figure 11. The active control system examined in this study incorporates wing-root bending measurements (strain gages) for feedback and applies control signals to three independent swashplate hydraulic actuators. The active control algorithm application for rotorcraft was developed cooperatively between Bell Helicopter and NASA LaRC, and is based on the Generalized Predictive Control theory presented in references 35 and 36. Past studies that have successfully demonstrated the stability augmentation capability of the GPC control theory for tiltrotors are documented in references 30 and 31.

The four-bladed soft-inplane rotor system had two sets of elastomeric dampers that were used in the tests so that effects of frequency placement could be examined. The elastomeric dampers provide both damping and stiffness to the hinge so they also served as the hinge springs. The softer set of dampers produced a nominal lag mode frequency of 0.57/rev while the stiffer set of dampers produced a lag mode of 0.63/rev (nonrotating based on 888 rpm design rotor speed). Only the soft damper set was used in the hover test, while both damper sets were used in the wind-tunnel test.

Hover Testing

For the four-bladed soft-inplane rotor system, frequencies of three key modes are plotted as a function of rotor speed in figure 12. The three modes are the rotor lag mode (with the 0.57/rev damper set installed),

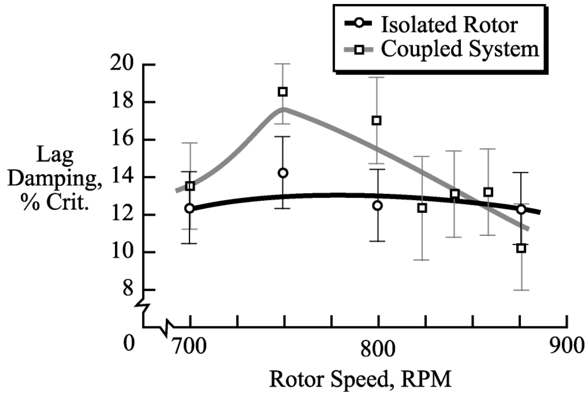


Figure 13. Rotor lag mode damping as a function of rotor speed (0.57/rev damper set).

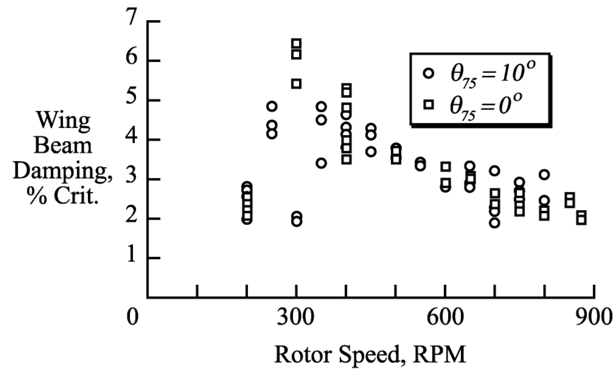


Figure 15. Wing beam mode damping as a function of rotor speed (0.57/rev damper set).

the wing beam mode, and the wing torsion/chord (WTC) mode. Coupling between the rotor lag and WTC modes occurs as the lag mode frequency approaches the WTC frequency at the upper rotor speed range. Without sufficient damping, this condition will generally result in an aeromechanical instability. The damping associated with these three modes is shown in the plots of figures 13 through 15, and as indicated there is not an instability associated with any of the modes within the rotor speed range considered. A likely reason for these results is the high value of lag mode damping provided by the elastomeric damper as indicated in figure 13. The nominal value for damping is about 12% for the isolated rotor, and for the coupled system the nominal value rises to about 14%. The frequency and damping measurements of the rotor lag mode are in close proximity to those expected for full-scale applications to soft-inplane tiltrotor systems.

The frequency of the WTC mode, which is the key mode associated with aeromechanical stability in hover, is about 5.6 Hz and remains steady with respect to rotor speed as shown in figure 12. Damping of this crucial mode is shown in figure 14 for two collective pitch settings, 0° and 10° as measured at the 75% radial station. As shown, the damping begins at about 2% critical in the lower rotor speed range, and then falls as rotor speed increases to a minimum of about 1% at 800 rpm, and then begins to rise again. The soft-inplane system did not encounter a ground resonance or other aeromechanical instability under normal operating conditions. In previous studies with a soft-inplane gimballed rotor system (ref. 32) this mode was found to become unstable. Thus, it appears that the new semi-articulated hub design with use of highly damped elastomeric materials provides adequate damping to avoid aeromechanical instability over the design rotor speed range.

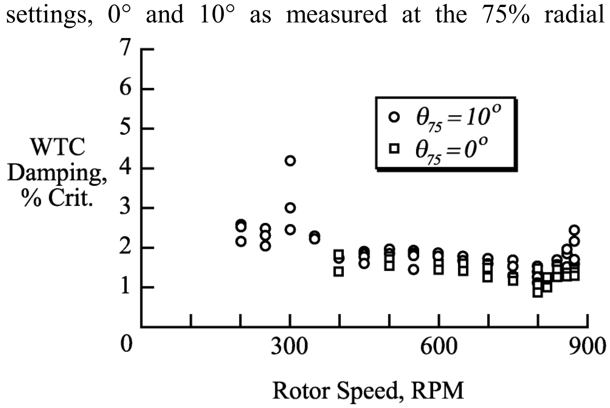


Figure 14. Wing torsion/chord mode (WTC) damping as a function of rotor speed (0.57/rev damper set).

The wing beam mode in hover is not highly coupled with the rotor lag mode, and previous studies indicate it is not a concern to become unstable. However, as this is a lower energy mode (5.4 Hz natural frequency) it was monitored carefully throughout the testing. The plot of figure 15 shows the damping associated with the beam mode as a function of rotor speed, and indeed this mode is more highly damped than the WTC mode. The damping does, however, decrease with rotor speed from about 5% critical at the peak to about 2% critical at the upper end of the rotor speed spectrum. Both the WTC and wing beam modes show only small changes in damping with collective pitch. The blade pitch was found to have a significant impact on damping behavior of the key modes for the gimballed rotor system as discussed in reference 32.

Wind-Tunnel Testing

The new four-bladed soft-inplane rotor system, oriented in airplane mode for high-speed wind tunnel testing, is shown in figure 16 mounted on the WRATS model in the TDT. The basic dynamics of the wing/pylon/rotor system shifts substantially with conversion to airplane mode, as the mass offset of the

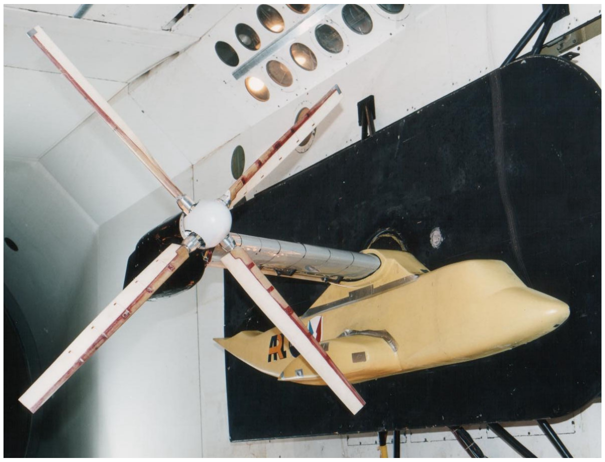


Figure 16. The 4-bladed soft-inplane rotor mounted on the WRATS model for airplane-mode testing in the TDT.

pylon/rotor moves from above to forward of the elastic axis, and now creates a significant coupling between the wing beam and torsion modes and the rotor lag mode. The wing chord mode becomes predominantly isolated from these modes.

For airplane-mode aeroelastic stability testing, the rotor system is normally operated windmilling (unpowered), with the collective blade pitch used to adjust the rotor speed, and there is no torque at the rotor shaft. This represents the most conservative manner to test the stability of the system because there is no damping from the drive system. Under windmilling operation, damping of the key mode associated with system stability (the wing beam mode) was determined to be significantly less for the new four-bladed soft-inplane hub than for the three-bladed stiff-inplane (baseline) system, as shown in figure 17. Damping of

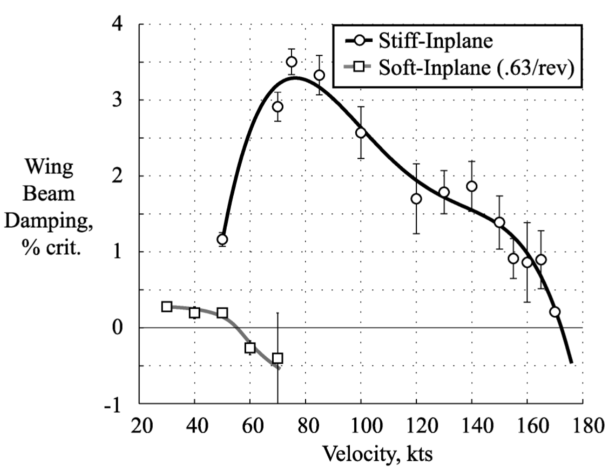


Figure 17. Comparison of wing beam mode damping between the soft-inplane (0.63/rev dampers) and the stiff-inplane rotor systems (742 rpm, off-D/S, windmilling).

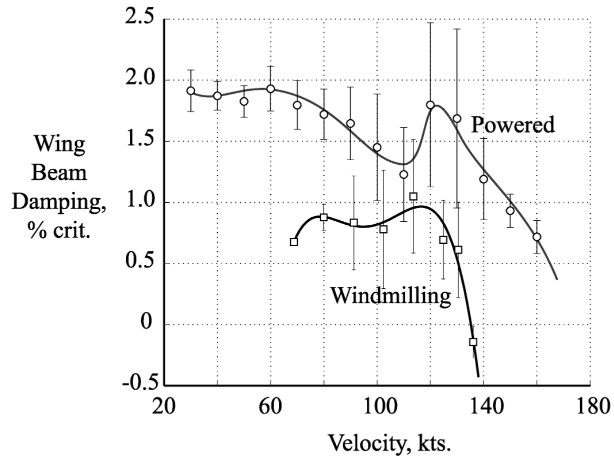


Figure 18. Comparison of wing beam mode damping between the windmilling and powered conditions for the soft-inplane rotor system. (0.63/rev dampers, 742 rpm, on-D/S).

the wing beam mode was generally less than 1.0% in windmilling flight for all the soft-inplane configurations considered. These configurations included on- and off-downstop (on- and off-D/S), 0.57/rev dampers, 0.63/rev dampers, and 550, 742, and 888 rpm. Unfortunately, these damping characteristics are inadequate for full-scale operation.

In powered-mode the system damping and the stability boundary both increased significantly as illustrated in figure 18. Although not a solution for the low-damping behavior associated with the windmilling condition, these results represent a substantial deviation from previous results associated with the baseline system, wherein the effect of power is only slightly stabilizing. Figure 19 shows that while the subcritical damping values increase significantly with power for the stiff-inplane rotor system, there is not a significant jump in the neutral stability point as there is for the soft-inplane system shown in figure 18.

A GPC active stability augmentation system was highly successful in application to both the new soft-inplane and the baseline stiff-inplane rotor systems. The plot of figure 20 shows very significant increases in damping of the baseline system that are extended well beyond the open-loop stability boundary (45 knots in wind-tunnel speed which equates to 100 knots full-scale). In fact, the damping of the wing beam mode is shown to be increasing as a function of the airspeed, rather than decreasing, as is the custom for the open-loop system. Similar results were also obtained for the new soft-inplane rotor system, although the system was not tested as far beyond the stability boundary due to the risk involved.

While not shown on a plot, damping of the chord and torsion wing modes also increased substantially

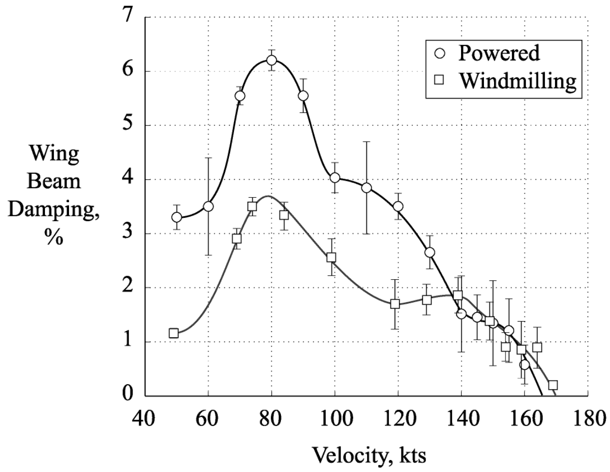


Figure 19. Comparison of wing beam mode damping between the windmilling and powered conditions for the stiff-inplane rotor system. (742 RPM, off-D/S).

under GPC, otherwise the system would become unstable under these modes. Data were also acquired within the same run at several rotor speeds between 550 and 888 rpm. The GPC control system was not affected by the rotor speed shifts. Data from this test shows that it is possible to attain the damping levels required for acceptable operation of a soft-inplane rotor system using GPC, and the control system shows robustness with respect to both rotor speed and airspeed deviations.

The last objective of this test was to demonstrate the reduction in hub and blade dynamic loads, which is the key benefit of using soft-inplane rotor systems. Blade and hub loads were measured for a defined set of pylon conversion angles (0, 15, 30, 45, 60, 75, and 90 degrees) and cyclic pitch settings (flapping up to 3

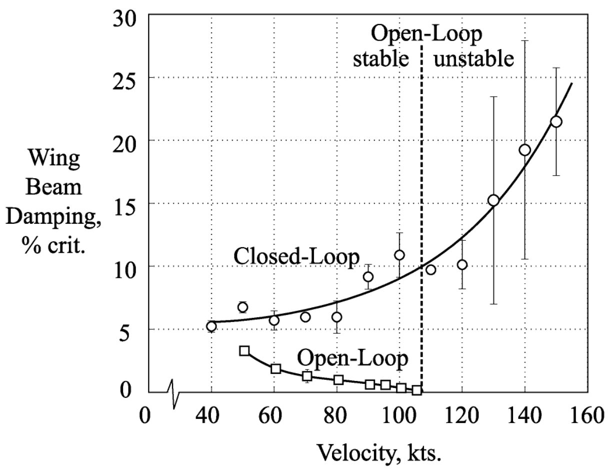


Figure 20. Effect of GPC active stability augmentation on wing beam mode damping for the stiff-inplane rotor system (742 rpm, off-D/S, windmilling).

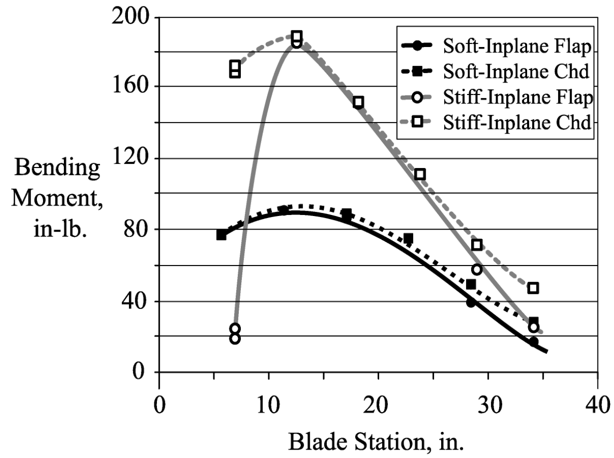


Figure 21. Effect of hub type on rotor blade and hub dynamic loads (half-peak).

degrees) in combination, which are designed to simulate tiltrotor free-flight maneuvers. The dynamic loads at each blade station were assembled between the various flight conditions, and the maximum sustained dynamic loads (half-peak-to-peak) are plotted in figure 21 as a function of blade span. As expected, the soft-inplane rotor system produces significantly lower dynamic loads. A reduction of approximately 50% in the highest (midspan) loads is indicated on the plot.

Key conclusions of this experimental activity are listed as follows:

1. The model-scale four-bladed soft-inplane rotor has key design parameters that are representative of full-scale.
2. In hover, the new soft-inplane rotor system produced adequate levels of damping throughout the rotor speed envelope. Ground resonance does not appear be a problem for the current soft-inplane design.
3. In airplane mode, damping levels for the new soft-inplane rotor system were extremely low and insufficient for full-scale application.
4. For the soft-inplane rotor, there is a large increase in system damping associated with moving from the windmilling to the powered-mode operating condition. For the baseline stiff-inplane design subcritical damping increases, but there is not a significant change in the stability boundary.
5. A GPC active stability augmentation system was very effective at increasing damping in all the fundamental wing modes simultaneously, for both the soft-inplane and stiff-inplane rotor systems.
6. The GPC controller was very robust with respect to rotor speed and airspeed changes, with the system damping still increasing at 45 knots beyond the corresponding open-loop stability boundary for the stiff-inplane rotor configuration.
7. A substantial reduction of blade and hub loads was obtained for the new soft-inplane design as

compared to the baseline stiff-inplane design during conversion mode operations.

Concluding Remarks

This paper has presented a review of recent rotorcraft tests conducted in the Langley Transonic Dynamics Tunnel (TDT). The research described covers a range of experimental investigations that utilizes the helicopter and tiltrotor testbeds available at the TDT. Results of these efforts will be used to support future rotorcraft research and development programs to produce more efficient, quieter, and smoother rotorcraft for use in the 21st century.

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