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AEROELASTIC MODEL HELICOPTER ROTOR TESTING IN THE LANGLEY TDT

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ABSTRACT

Wind-tunnel testing of a properly scaled aeroelastic model helicopter rotor is considered a necessary phase in the design development of new or existing rotor systems. For this reason, extensive testing of aeroelastically scaled model rotors is done in the Transonic Dynamics Tunnel (TDT) located at the NASA Langley Research Center. A unique capability of this facility, which enables proper dynamic scaling, is the use of Freon as a test medium. The paper presents a description of the TDT and a discussion of the benefits of using Freon as a test medium. A description of the model test bed used, the Aeroelastic Rotor Experimental System (ARES), is also provided and examples of recent rotor tests are cited to illustrate the advantages and capabilities of aeroelastic model rotor testing in the TDT. This paper demonstrates the importance of proper dynamic scaling in identifying and solving rotorcraft aeroelastic problems, and affirms the importance of aeroelastic testing of model rotor systems in the design of advanced rotor systems.

INTRODUCTION

Historically, the helicopter industry has not relied on wind-tunnel testing of aeroelastic models as much as has the fixed-wing industry (ref. 1). The reason for this lack of testing has been that new rotor designs have usually evolved from existing designs. The new rotor designs usually had aeroelastic characteristics that were reasonably predicted by extrapolations of existing data, and thus the need for wind-tunnel testing was reduced. Wind-tunnel testing that was conducted was usually done in air. Tests done at full-scale have been subject to tunnel speed restrictions, while testing reduced size models in air has not resulted in a simultaneous matching of advancing blade tip Mach number, advance ratio, and Reynolds number.

Rapid changes in rotorcraft technology have led to the development of new rotor systems such as hingeless and bearingless hub designs, and blades tailored to produce specific dynamic characteristics. These unique designs have provided the impetus to address the problems of rotor system loads, stability, and vibrations during the design phase rather than provide "fixes" to problems as they occur during development. These design considerations can best be addressed by wind-tunnel testing, at representative flight conditions, of a properly scaled aeroelastic model. Additionally, there are opportunities in model testing to thoroughly investigate potential improvements to rotor systems through aeroelastic design modifications (ref. 2-4).

Extensive testing of aeroelastically scaled model helicopter rotors is done in the variable density Transonic Dynamics Tunnel (TDT) located at the NASA Langley Research Center. A unique capability of this facility is the use of Freon-12[1] as a test medium, which greatly aids in the scaling of models for aeroelastic testing. Most model rotor tests conducted in the TDT utilize the Aeroelastic Rotor Experimental System (ARES). The main component of the ARES is a generic rotor test bed for measuring rotor loads and performance data, aeromechanical stability data, and vibration data. This paper will present some details on the TDT and discuss the benefits of using Freon-12 as a test medium. The model and associated instrumentation that comprise the ARES, as well as some software used in data acquisition and analysis, will also be described. Examples of some of the model aeroelastic rotor tests conducted recently in the TDT is included to illustrate the techniques used to address unique problems and research opportunities.

Aeroelastic Testing

General

The response of either a full-scale or model rotor blade is influenced by aerodynamic, elastic, inertial, and gravitational loads acting on the blades (ref. 5-6). For a model rotor blade to be a dynamically scaled version of a full-scale rotor blade, the relative magnitudes of these four forces should be the same between the model and full-scale blade. This is usually accomplished through the use of appropriate non-dimensional similarity parameters.

The success of the dynamic simulation effort depends on the ratio of the model non-dimensional similarity parameters to the same full-scale parameters being 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 rotor tip speeds are generally in the near-sonic range, duplicating Mach number can be important. 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 Reynolds number matching important. In addition, elastic and mass simulation requires duplicating rotating natural frequencies on a per-rev basis. This would be necessary for blade loads and vibration studies.

[1]Freon-12: Registered trademark of E. I. du Pont de Nemours and Co., Inc.

Scale Model Testing

The use of scale rotor models to model aeroelastic events can be justified through considerations of cost, safety, and ease of making design changes. When compared to full-scale flight studies, model tests also have the advantage of control of the basic aeroelastic parameters and test conditions (ref. 6).

The design of a scale model rotor which simultaneously matches all the full-scale similarity parameters is beyond the current state of the art, but for certain combinations of model design and test environment the job becomes much less difficult. The simulation task is made even more tractable if the aerodynamic test medium can be tailored.

Test Medium Considerations for Aeroelastic Testing

The capability to adjust the test medium for aeroelastic model studies is greatly enhanced by use of a heavy gas such as Freon-12. The properties of this gas, listed in Table I, enables a model scale rotor to achieve large Reynolds numbers, and a better match of Froude number and Mach number, all at a lower rotor rpm than the same size model in air. Specifically, for a 1/5-size rotor model, chosen to simultaneously match Froude and Mach number, Table II quantifies how closely the Freon-12 scaled rotor matches full-scale values.

The advantages for model construction, operation, and opportunities for direct research applications afforded by a Freon-12 test medium are perhaps more subtle, but equally attractive. Figure 1 illustrates the reduction in model power required to match tip Mach number and advance ratio, μ. A direct benefit of this to vibration and loads measurement is the possibility of using quiet belt-driven transmissions rather than conventional gearing. Model construction for rotor operation in Freon-12 is also eased (Figure 1) through lower loads and the allowance of heavier structural designs than those of an air-scaled model as shown in Table II. Research applications require lower time scales in Freon-12. This is a benefit to both data analysis and required control inputs, such as used in active control applications.

Research studies have been conducted to determine the suitability of Freon-12 as a test medium for a model rotor (ref. 7). These studies also utilized the Freon atmosphere to provide parametric variations in rotor aerodynamics. This was accomplished by subjecting a 1/5-size dynamically similar helicopter rotor in Freon-12, to the same tasks as a full-size helicopter rotor tested in air. Reynolds number variations were achieved through controlled Freon-12 density changes and the introduction of a wide chord model rotor which was not dynamically scaled.

In the area of integrated rotor performance, the dynamically scaled model rotor provided data trends and magnitudes which agreed well with full-scale rotor data (Figures 2-3) even at the lower values of model Reynolds numbers. The exact matching of full-scale rotor Reynolds number was accomplished by utilizing the wide chord model rotor, but with accompanying mis-matches in rotor solidity and dynamic scaling. The compiled performance results for the full-scale and model-scale rotors is shown in Figure 4. Region B of Figure 4 illustrates the expected performance trend with decreasing Reynolds number for the wide chord blade, i.e., more torque required at a given rotor task. The unexpected result of these tests is illustrated by Region A of Figure 4 which shows that better model performance correlation with full-scale values was achieved with a dynamically scaled rotor of the correct solidity than with a rotor which matched Reynolds number but which was not dynamically scaled.

The disadvantages of the use of Freon-12 as a test medium are chiefly cost and time because of pumping and safety considerations. Also, the ratio of specific heats is less for Freon-12 than for air and this would impact the energy and compressibility relationships of Freon; however, it has been documented (ref. 8) that below Mach 1.4 the accuracy of data obtained in a Freon atmosphere is very acceptable.

Thus, the benefits of Freon-12 for the testing of aeroelastic rotor models are considered significant. In addition, the capability to accurately simulate rotor dynamics appears to be as important a characteristic in model testing as the extended Reynolds number capability provided by Freon. Sections of this paper will illustrate the diverse range of test applications which have used these characteristics of Freon-12 to advantage.

Test Facilities

General

The facility chosen for scale model rotor testing can play an important role in matching aeroelastic parameters. Tunnel characteristics such as free-stream velocity range, wall effects, maximum model rotor size allowable, and test medium capabilities will determine the potential for aeroelastic testing. Many facilities are compatible with existing and planned rotor test beds, but very few offer the range of capabilities of the Langley Transonic Dynamics Tunnel (TDT). Since the majority of this paper describes testing experiences in the TDT to illustrate techniques and aeroelastic phenomena, a description of that facility is in order.

Characteristics of the TDT

The Langley Transonic Dynamics Tunnel was designed 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. A schematic of the TDT is shown in Figure 5. The TDT is a continuous-flow tunnel with a slotted test section and is capable of operation up to

Mach 1.2 at stagnation pressures up to 1 atm. These tunnel limits on Mach number and stagnation pressure have allowed rotor testing to be done at combinations of advancing tip Mach numbers and Reynolds numbers as shown in Figure 6. The tunnel test section is 16 feet square with cropped corners and has a cross-sectional area of 248 square feet. The size of the test section easily accommodates rotor models up to 10 feet in diameter. A simulated gust field may be applied to the test section flow in the form of a sinusoidal oscillation of the flow direction. This oscillation gust signature is generated by an arrangement of vanes on either side of the entrance section (Figure 7). Vane amplitude and frequency is variable and the two pairs may be operated in or out of phase to provide a symmetric or antisymmetric gust field. Tunnel wall corrections based on reference 9 are available for data correction. At low and moderate advance ratios, corrections to the tip path plane angle of attack are small as shown in Table III. A more detailed description of the TDT may be found in reference 10.

In addition to the TDT test section, an area is also available for hover testing and model buildup and checkout. This area is known as the Helicopter Hover Facility (HHF) and is located in a building adjacent to the TDT. The HHF is a high-bay room with the model test-stand enclosed by coarse-mesh screen 30 ft. x 30 ft. x 20 ft. high. The model is mounted on the test stand such that the rotor is approximately 15 feet above the floor. The HHF has its own hydraulic pump to supply pressure for operating the model control system. The motor-generator set used to run the model drive system in the TDT is also used to operate the model in the HHF. Instrumentation, other than that mounted on the model is also common between the TDT and HHF. At the present time, the data recording system in the HHF consists of a 14-channel analog tape recorder. Data reduction is done on the TDT computer system.

The TDT is equipped with a data acquisition system that can acquire large amounts of dynamic data over a wide frequency range. This system has the capability of providing real-time, interactive data reduction, analysis, and display as well as providing the capability for on-line monitoring and control of a wide variety of analog instrumentation. The data acquisition system consists of an analog front end that can typically process up to 50 channels of data, a multi-channel analog-to-digital subsystem that can process up to 50,000 samples of data per second, and a digital computer with graphics capability. A more detailed description of the TDT data acquisition system is given in reference 11.

Aeroelastic Rotor Experimental System

Rotary-wing tests conducted in the Langley TDT usually utilize the Aeroelastic Rotor Experimental System (ARES). The model part of the ARES is shown in Figure 8. Tests may be conducted using one of the three available rotor hubs: teetering, articulated, or hingeless. The ARES model has a streamlined helicopter fuselage shape enclosing the rotor controls and drive system. The ARES model rotor system is powered by a water cooled variable frequency synchronous motor rated at 47 HP output at 12,000 rpm. The motor drives the rotor shaft through a belt-driven two-stage speed reduction system. The ARES model rotor control system and rotor shaft angle of attack are remotely controlled. The model rotor shaft angle of attack is varied by an electrically controlled hydraulic actuator. Blade collective pitch and lateral and longitudinal cyclic pitch are input to the rotor through the swashplate. The swashplate is moved by three hydraulic actuators. This arrangement is particularly useful for exciting the rotor system during investigations involving rotor aeromechanical stability characteristics.

ARES Instrumentation

Instrumentation on the ARES model allows continuous measurements and displays of model control settings, rotor forces and moments, blade loads, and pitch link loads. The ARES model rotor shaft pitch attitude is measured by an accelerometer, and rotor control positions are measured by linear potentiometers connected to the swashplate. For the teetering hub, rotor flapping is measured by a rotary potentiometer. For the articulated and hingeless hubs, blade flap and lag position is measured as follows: the articulated hub uses rotary potentiometers mounted on the hub and geared to the blade cuff; the hingeless hub uses strain gages mounted on the appropriate flexures. The accuracy for these angular measurements is estimated to be within ± 0.25 degrees. Rotor shaft speed is determined by a magnetic sensor. The rotating blade data are transferred through a 30-channel slip-ring assembly. Rotor forces and moments are sensed by a six-component strain-gage balance mounted below the pylon and drive system. The balance is fixed with respect to the rotor shaft and pitches with the fuselage. The balance utilized by the ARES model was designed to provide measurement errors of one percent or less. The entire force measurement system, of course, contains other error sources. Based on replicated data points, the repeatibility of ARES balance data for constant shaft angle of attack, control angles and advance ratio has been estimated to be typically within the following limits:

$$C_L/\sigma \pm .0010$$
$$C_D/\sigma \mp .00025$$
$$C_Q/\sigma \mp .00015$$

Fuselage forces and moments are not sensed by the balance.

Additional instrumentation, other than that mounted on the ARES model, is used in the data acquisition process. This instrumentation is mounted in four cabinets (Figure 9) that are portable and are used with the ARES model in both the TDT and the HHF. Only the primary features of each of these instrumentation cabinets will be discussed in this paper. Cabinet No. 1 contains signal conditioning equipment consisting of the following: 30 Neff

Model 122 differential DC amplifiers; a remote shunt calibration box that allows remote insertion and removal of a calibration resistor for any data channel; monitor boxes that allow the output of any of the Neff amplifiers to be monitored; a control unit that supplies power to, and receives signals from the six component strain-gage balance mounted in the ARES model. Three outputs (DC, AC, and combined DC and AC) are available from each balance channel. This control unit also allows the output of each balance channel to be electrically "zeroed". Cabinet No. 2 contains control units as follows: a 3-channel Fourth Harmonic Generator that can produce a fourth harmonic signal for each of the swashplate actuators; a resolver that uses output from potentiometers or strain gages on the model hub to determine rotor longitudinal and lateral flapping, and blade coning; a decoder that monitors swashplate position in order to determine rotor collective pitch and longitudinal and lateral cyclic pitch; a Transient Command Generator that produces signals used as input to the model swashplate, and allows oscillation of the model swashplate with the following waveforms: a sine wave, doublet, stick-stir, and constant spectral input; and a 7-channel piezoelectric accelerometer signal conditioning unit. Cabinet No. 3 provides the electrical power for the various instrumentation as well as the digital displays on the model control panel. Cabinet No. 4 contains a time code generator that can generate or read an IRIG A or B coded signal, and a 14-channel Ampex PR2200 analog tape recorder.

ARES Software

Several data reduction computer programs are utilized both during and after testing with the ARES model. The primary data reduction codes used will be briefly discussed. A real-time program is employed during testing to monitor tunnel conditions and output from the model's strain-gage balance. The parameters that can be displayed while the tunnel and model are operating are shown in Table IV. These values aid in simulating a given rotor task during performance testing. For aeromechanical stability testing the moving-block method described in reference 12 is used on-line to determine the system damping. The moving-block computer program is used interactively, and an example of its output is shown in Figure 10. For processing data after testing is complete, two data reduction programs are routinely used. One of these programs is used to reduce data from the strain-gage balance and present it in both engineering units and coefficient form. Examples of output from this program are shown in Figure 11. Another post-test program is available to perform a harmonic analysis of selected data channels. Examples of output from this program are shown in Figure 12.

Research Studies in the TDT

In recent years both the TDT and the ARES have been utilized for rotary-wing testing that has involved rotor performance, blade loads, aeromechanical stability, and efforts to reduce helicopter vibration levels. A brief description of some representative studies will be presented to give the reader some insight into the research done at the TDT. Also, some future plans will be briefly discussed.

Conformable Rotor Studies

One area of research that has been conducted in the TDT has been conformable rotor studies, specifically the Aeroelastically Conformable Rotor (ACR) concept (ref. 13). The potential of a conformable rotor to alter unfavorable blade spanwise and azimuthal load distributions has been analytically and experimentally investigated by several research groups (refs. 14-15). During the tests in the TDT, the aeroelastic mechanism linking rotor configuration performance and loads to blade deflection was difficult to determine. In an effort to understand the coupling between configuration response and the resulting rotor aeroelastic environment, a series of parametric tests was initiated. Since the rotor blade tip operates in a very influential portion of the rotor disk, emphasis was given to parameter changes in this area.

Seven blade tip shapes were tested on a four-bladed articulated hub using two sets of instrumented model rotor blades of current planform design. One blade set was of conventional stiffness, while the other had reduced torsional stiffness. These tip shapes (Figure 13) were well controlled with regard to inertial characteristics (ref. 16). The use of a Freon test atmosphere aided blade and tip construction, and enabled a representative aerodynamic environment to be maintained during the tests. The test matrix for this investigation is shown in Table V.

Significant performance and loads differences were produced by the different tip shapes and stiffnesses. Configurations which exhibited low oscillatory loads also had the best performance, while the configurations with poor performance generated the highest loads (Figure 14). Another interesting result of these tests was the strong correlation between azimuthal variation of elastic twist and rotor behavior. As noted in reference 16, the configurations which exhibited small azimuthal activity in elastic twist were the best performers.

The utilization of a conformable rotor concept should be evaluated not only for how successfully it achieves its performance and loads goals, but also how well it can be "fielded". That is, how much change (if any) in current installation, maintenance, and rotor tuning is necessary for the new rotor concept to be employed. One aspect of this "fielding" process is rotor tracking sensitivity and its implications to rotor and fuselage loads.

As part of the conformable rotor studies in the TDT, a rotor track sensitivity investigation was conducted in which blades of conventional and reduced torsional stiffness with representative swept tips were subjected to a test matrix (Table VI) designed to perturb the track of one blade. This perturbation was accomplished by use of trailing-edge tab deflection. Initially, the tabs were undeflected and the rotor was tracked in hover. One-per-rev longitudinal and lateral fixed-system loads were minimized, and forward flight testing was begun. Forward flight testing was then repeated with the trailing-edge tabs deflected on one blade. In both cases data was acquired until either the test matrix was completed or until rotor loads became prohibitive.

The elastic response of the baseline and torsionally soft blades to tab deflection was correlated with fixed-system loads (ref. 17). This was done to assess the effect of potential tracking procedures on blade response and the accompanying "fuselage" vibration environment. The torsionally soft blades were found to respond very differently than the baseline blades to the same tab deflection. As shown in Figure 15, the torsional moments for both stiff and soft blades, due to tab deflection, resulted in different blade flapping magnitudes, flapwise loads, and fixed-system vibration.

Therefore, the evaluation of performance and loads for an advanced rotor design was accomplished using ARES in a representative aeroelastic simulation. In addition, causes for the rotor behavior were found while identifying further areas of practical concern for this passive rotor concept.

Active Control Testing

Testing of active control concepts to reduce fixed-system vibration levels has also been conducted in the TDT using the ARES. Specifically, this testing involved the Higher Harmonic Control (HHC) concept (ref. 18). The approach combined HHC experimental studies with the development of control algorithms suitable for real-time implementation of the required control inputs.

The HHC concept involves superimposing fixed-system swashplate motions at the blade passage frequency on the basic collective and cyclic requirements. The phase and amplitude of the HHC inputs are chosen to minimize the blade passage responses transmitted to the fixed system. Several controllers were developed for the HHC system. For application to ARES model testing in the TDT, the controllers were programmed on the TDT data acquisition system. Details of the choice of electronic control designs and software can be found in references 18 and 19.

Experimental verification of the HHC concept involved several tests where vibratory loads to be suppressed were obtained either from the ARES strain-gage balance, or model fuselage accelerometers, and these signals were used as inputs to the HHC system. During these studies, a four-bladed articulated model rotor was tested over a range of advance ratios simulating 1g flight with the rotor trimmed to the shaft. Data were recorded to quantify the vibratory load levels without the HHC operating. The HHC system was then activated and allowed to converge. Fixed-system vibration levels and blade loads were then recorded.

The success of the HHC in reducing fixed-system vibratory responses is shown in Figure 16. Variations of the ARES strain-gage balance and fuselage accelerometer outputs with and without the HHC operating indicate substantial control of the fixed-system vibration levels. It should be noted that although the required control inputs are small (less than one degree) the blade and control system loads usually increase with the HHC system operating. An example of this is shown in Figure 17.

These wind-tunnel tests were the first opportunity to evaluate an adaptive control system using optimal control theory for model helicopter vibration reduction. These experimental studies helped accelerate the successful application of the HHC concept to a full-scale helicopter (ref. 20).

Aermoechanical Stability Investigations

Experimental and analytical studies have also been recently conducted to investigate the ground resonance of soft in-plane hingeless rotors (ref. 21). These efforts were intended to aid in the identification of an analysis that can be used in both the design and testing phases of hingeless and bearingless rotor development. Another objective of the research was to develop an experimental technique for blade excitation and damping measurements in the rotating system.

The rotor model used for this investigation is a soft in-plane hingeless rotor that is not a dynamically scaled representation of a specific aircraft hub, but rather is representative of a typical full-scale design based on Mach number, mass ratio, and frequency simulation. The model blades were fabricated with fiberglass spars specifically for testing in Freon. The rotor hub (Figure 18) consists of metal flexures to accommodate flap and lead-lag motions and a mechanical feathering hinge to allow blade pitch motion. The flap and lead-lag flexures are each strain-gaged and calibrated to measure motion in those directions. The hingeless hub has the capability to parametrically vary blade sweep, droop, and precone of the blade feathering axis.

The Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics (CAMRAD) computer program was used as the theoretical tool for this investigation (refs. 22-23). The structural dynamic model of the rotor includes elastic degrees of freedom in flap bending, lead-lag bending, torsion and a rigid pitch degree of freedom. The blade is represented by a spanwise distribution of mass, flapwise and chordwise bending and torsion stiffness and moment of inertia. An estimated structural damping has also been included in the rotor data. The "aircraft" model consists of elastic motion of the ARES strain-gage balance and support system in the wind tunnel. The CAMRAD input data includes generalized mass, structural damping, frequency and mode shape of the "aircraft" elastic modes. These characteristics are set to the measured values. The rotor blade aerodynamic forces are calculated using lifting line theory and steady two-dimensional airfoil characteristics with corrections for unsteady and three-dimensional flow effects. The degrees of freedom used in the stability analysis are the flap and lag motion of the blades, the body pitch and roll motions and rotor dynamic inflow.

The test technique consisted of two steps. First, the model was excited in the fixed system by applying a longitudinal cyclic oscillation to the rotor through the swashplate. The amplitude of the swashplate oscillation was nominally 0.75 degrees. The frequency of the swashplate oscillation was initially set equal to the fixed-system value of the rotor in-plane frequency (lead-lag regressing mode) predicted by CAMRAD. The swashplate oscillation was then adjusted slightly to obtain the maximum rotor in-plane response. Once the rotor in-plane response was established, the swashplate oscillation was removed and the moving-block procedure was initiated to determine the system damping.

Testing was conducted in both hover and forward flight. A sample of the predicted and measured hover results is shown in Figure 19 for a collective pitch of eight degrees. The predicted and experimental lead-lag frequency are seen to be in good agreement. The regressing lag mode damping in the fixed system is also well predicted. An unstable region is indicated near the regressing lag-roll coalesence rotor speed. Due to rotor stress level limitations, the test could not be carried out for rotor speeds higher than 650 rpm. Presented in Figures 20 and 21 are analytical and experimental lead-lag damping results which show the effect of blade droop and pre-cone angles on the damping levels in forward flight.

These wind-tunnel tests aided in developing a satisfactory technique for aeromechanical stability testing, as well as identifying an analysis that produced good correlation with the experimental results.

Tilt-Rotor Research

The most recent rotary-wing tests conducted in the TDT did not involve the ARES. These tests were conducted in support of the design development phase of the Joint Advanced Vertical Lift (JVX) tilt-rotor aircraft. Tests in the TDT of aeroelastic models of tilt-rotor concepts such as the JVX is not a recent development. During the late 1960's and early 1970's, several tilt-rotor concepts were tested in the TDT (refs. 24-26). These tests contributed significantly to the successful development of the XV-15 tilt-rotor aircraft.

The model used in the TDT tests was designed and built by Bell Helicopter-Textron and the Boeing-Vertol Company and was a 0.2-size aeroelastically scaled, semi-span model of a preliminary JVX design (Figure 22). The model consisted of a cantilevered wing and pylon/rotor system that could be operated with the rotor either powered or windmilling.

In general, the purpose of the test was to provide an experimental data base to be used for correlation with analyses in the design development phase of the JVX program. Specific test objectives were to determine wing/rotor stability in the airplane mode, and to measure rotor and control system loads and vibration data primarily in the helicopter-to-airplane conversion corridor. An initial test series was conducted to determine design parameter effects on an early baseline design. A second test series was conducted to determine the effects of design updates.

The model was tested in both air (low Mach number operation) and Freon (high Mach number operation) at densities corresponding to altitudes from sea level to 15,000 feet. A variety of model parameters were tested. These included: 1) pylon to wing locking (on and off downstop), 2) rotor rpm, 3) wing aerodynamics, 4) wing spar stiffness, 5) rotor pitch-flap coupling, 6) rotor control system stiffness, 7) a coning hinge hub, and 8) rotor blade stiffness. Sub-critical damping data were obtained by exciting the model in the wing beam, chord, and torsion modes using a unique Freon jet system mounted on the wing. The system damping was then extracted from the model response to this excitation using the moving-block method and from decay traces on a strip chart recorder.

For almost all configurations tested, the wing beam mode had the lowest flutter speeds. The single exception occurred during the first series of tests when a chord mode instability was induced using a spar designed for that sole objective. In addition, there were several instances in the second series of tests where the chord mode approached an instability at the same condition that the beam mode became critical. Figure 23 shows that the various design updates increased flutter speeds. The data shown in the figure are for the model in air with the pylon locked to the wing (on downstop) and unlocked (off downstop). Various percentages of nominal rotor speed (874 RPM) were selected for testing. The actual speed at which the instabilities occurred have been normalized to a reference flutter speed. Initial predictions of flutter speed proved unreliable. Consequently, an immediate outcome of the first series of tests was a critical re-examination of analyses and the model used therein. As a result, the design updates were successful not only in raising flutter speeds, but were also valuable in verifying the improved analytical methods.

As in previous stability tests, the capabilities of the TDT were utilized to provide a high quality data base for verification and improvement of analyses during the design development phase of an advanced rotorcraft concept.

Research Opportunities

Future plans for the TDT and ARES involve gust sensitivity studies of advanced rotor systems such as hingeless and bearingless concepts. Reference 27 indicates that advanced rotor systems may be susceptible to gust-induced limitations due to rotor loads and response characteristics. For example, blade loadings may become excessively high when gusts are encountered during nap-of-the-earth maneuvers. Increased load transfer through advanced hub designs may also result from rotor gust penetrations.

The planned research approach for rotor gust response studies in the TDT is as follows: measure the flow characteristics of the TDT gust system at specific model rotor locations in the tunnel test section for operating conditions where important aeroelastic phenomena are predicted by analyses. This is to be followed by a series of model rotor tests where parametric variations of hub geometry and stiffness, rotor operating environment, and gust signatures are made and the rotor and fixed-system loads are observed and correlated with analyses.

Modifications are also planned for the ARES model. These modifications consist of structural and instrumentation improvements to the model system. The major modification planned is to add body degrees-of-freedom in pitch, roll, yaw, and longitudinal and lateral translation. These motions will be accomplished by mounting the entire model on six hydraulic servo-actuators. The servo-actuators will be electronically controlled to continuously position the model to simulate aircraft with various inertial characteristics. It is planned to use this system mainly for aeromechanical stability investigations.

Concluding Remarks

This paper has shown the importance of proper dynamic scaling in identifying and solving rotorcraft aeroelastic problems. The unique qualities of the Langley Transonic Dynamics Tunnel (TDT) and its associated facilities for model rotor aeroelastic testing have been described. Aeroelastic testing of model rotor systems has been shown to be a necessary step in the design of advanced rotorcraft. The utilization of these facilities for rotor testing which has general applicability is emphasized. Additionally, several research experiences have been cited to define the scope of model rotor testing in the TDT as well as the details of the methodology used to obtain some unique results.

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TABLE I.- Properties of Freon-12 and Air
Standard Day, Full Atmospheric Pressure

	Freon-12	Air
Speed of Sound, ft/sec	500.4	1117.
Density, slugs/ft^3	.009916	.002378
Ratio of Specific Heats	1.13	1.4
Absolute Viscosity, lb sec/ft^2	2.622×10^{-7}	3.719×10^{-7}

TABLE II.- Scaling Parameters for a 1/5-Scale Model in Air and Freon-12 Test Mediums

		Scale Factor[a] (Model Value / Full Scale Value) Air	Freon-12
Mach number	Fluid inertia force / Fluid elastic force	1.0	1.0
Lock number	Fluid inertia force / Rotor inertia force	1.0	1.0
Advance ratio		1.0	1.0
Froude number	Rotor inertia force / Rotor weight force	5.0	1.0
Reynolds number	Fluid inertia force / Fluid viscous force	0.2	0.53
Time		0.2	0.446
Angular velocity		5.0	2.24
Linear velocity		1.0	0.448
Force		0.04	0.0334
Moment		0.008	0.00667
Power		0.04	0.0149
Structural frequencies (per rev)		1.0	1.0
Mass		0.008	0.0334
Stiffness		0.0016	0.00135

[a] Based on standard day condition, full atmospheric pressure

TABLE III.- TDT Tunnel Wall Corrections To Rotor Tip Path Plane
(C_L = .0076, α_{TPP} = -8°)

Rotor Radius ft.	$\Delta\ \alpha_{TPP}$, deg.			
	μ = .15	μ = .20	μ = .25	μ = .30
3	.45	.25	.17	.12
4	.80	.46	.30	.21
5	>1	.71	.47	.32
6	>1	>1	.67	.47

Note: μ = Advance Ratio.

TABLE IV.- Parameters for Display During Model and Tunnel Operations

Quantity	Definition	Units
α_s	Shaft Angle of Attack	deg.
C_D/σ	Rotor Drag Coefficient/Solidity Ratio	---
C_H/σ	Rotor Drag Component Perpendicular to Rotor Shaft/Solidity Ratio	---
C_L/σ	Rotor Lift Coefficient/Solidity Ratio	---
C_Q/σ	Rotor Torque Coefficient/Solidity Ratio	---
C_T/σ	Rotor Lift Component Parallel to Rotor Shaft/Solidity Ratio	---
C_Y/σ	Rotor Side Force Coefficient/Solidity Ratio Perpendicular to Rotor Shaft	---
D	Rotor Drag Force	lbs.
H	Rotor Drag Force Component Perpendicular to Rotor Shaft	lbs.
HP	Rotor Horsepower Required	---
L	Rotor Lift	lbs.
M_T	Rotor Rotational Tip Mach Number	---
$M_{1,90}$	Rotor Advancing Tip Mach Number	---
M_∞	Tunnel Freestream Mach Number	---
Q	Rotor Torque	in-lbs.
q	Tunnel Freestream Dynamic Pressure	lbs/ft^2
T	Rotor Lift Force Component Parallel to Rotor Shaft	lbs.
T_∞	Tunnel Static Temperature	°F
Y	Rotor Side Force	lbs.
μ	Rotor Advance Ratio	---

Table V. Target Test Conditions

μ	M_T	α_s	$\frac{C_L}{\sigma}$	α_s	$\frac{C_L}{\sigma}$	α_s	$\frac{C_L}{\sigma}$
.30	.65 .68 .70	-6.0°, -7.8° ↓	.06	-4.5°, -5.9° ↓	.08	-3.6°, -4.7° ↓	.10
.35	.65 .67	-8.2°, -10.5° ↓	.06	-6.1°, -7.9° ↓	.08	-4.9°, -6.3° ↓	.10
.40	.63 .65	-10.6°, -13.6° ↓	.06	-8.0°, -10.3° ↓	.08	-6.4°, -8.3° ↓	.10

Symbols defined in TABLE IV

Table VI. Track Sensitivity Test Conditions

μ	α_s	$\frac{C_L}{\sigma}$	Tab Deflection	M_T
.05 .20 .30 .40	0° 0° -5° -10°	.075 ↓	0°, 4° down ↓	.65 ↓

Symbols defined in Table IV

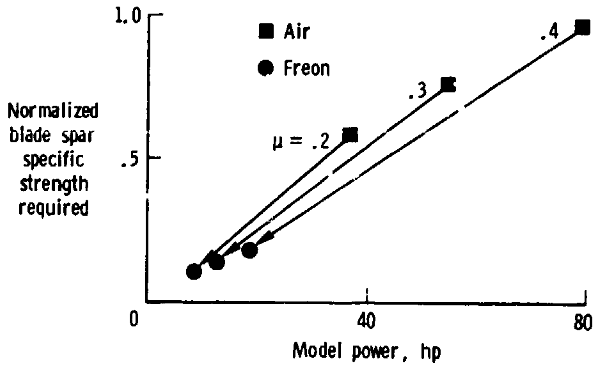

Figure 1.- Typical Rotor Model Power and Required Strength for Air and Freon-12.

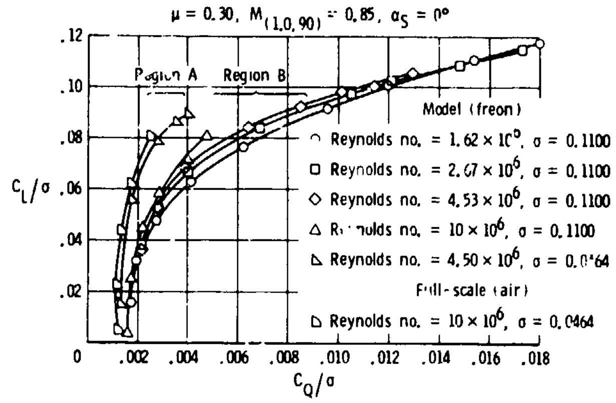

Figure 4.- Effect of Scaling Parameters on Freon Model and Full-Scale Rotor Performance.

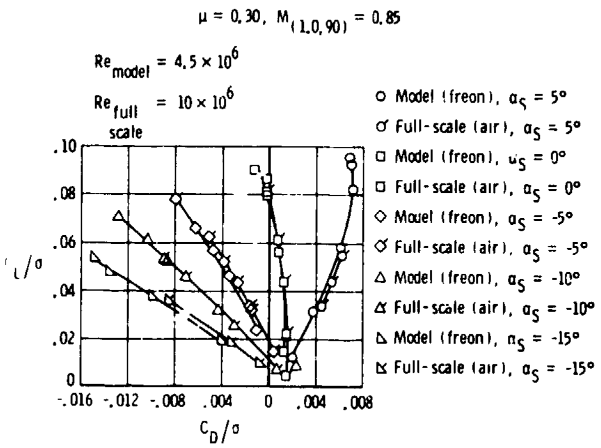

Figure 2.- Full Scale and Model Rotor Performance.

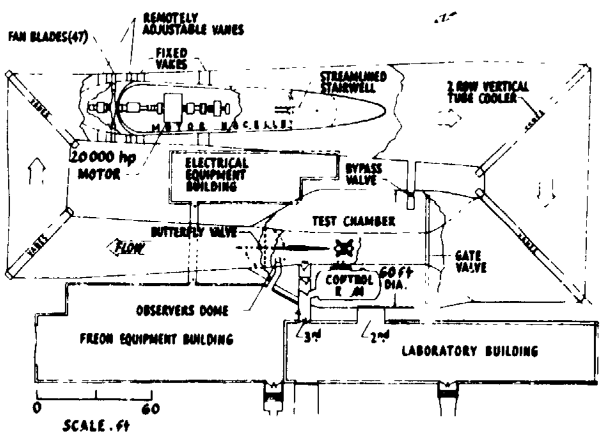

Figure 5.- Langley Transonic Dynamics Tunnel.

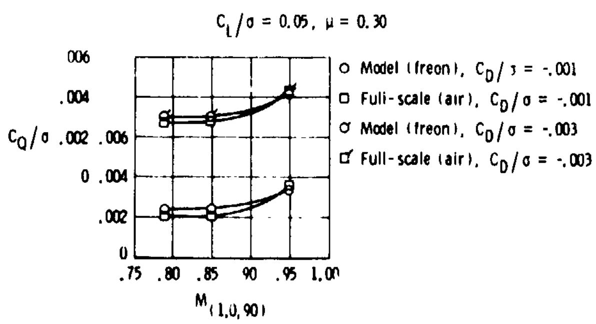

Figure 3.- Full Scale and Model Rotor Performance.

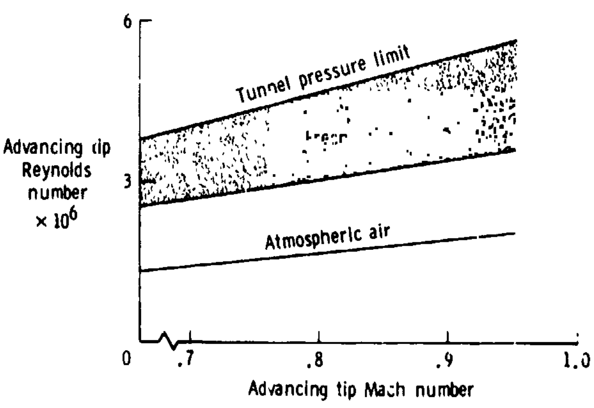

Figure 6.- Typical Model Reynolds Number Versus Advancing Tip Mach Number in Air and Freon-12.

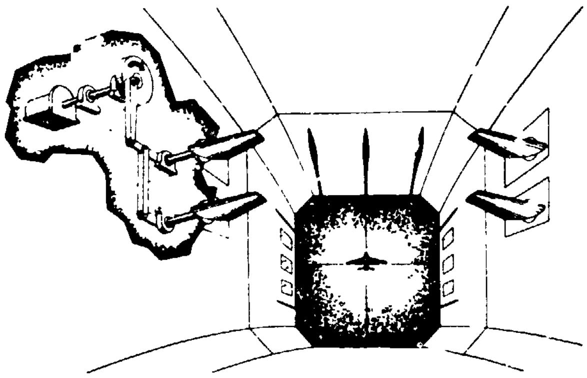

Figure 7.- Sketch of Gust Vanes and Model, With Cutaway Showing Schematic of Mechanism.

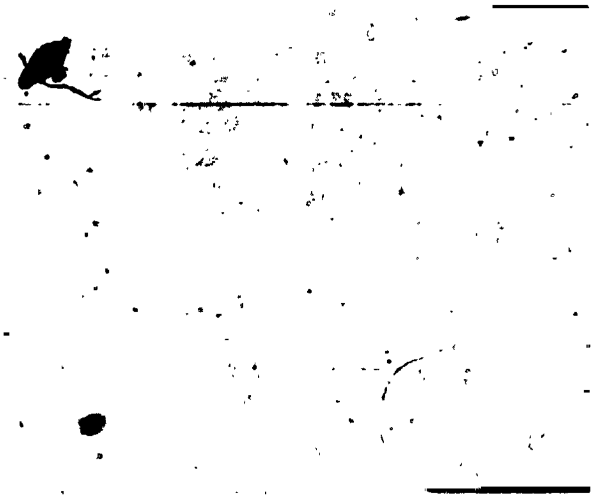

Figure 9.- A.R.E.S. Instrumentation.

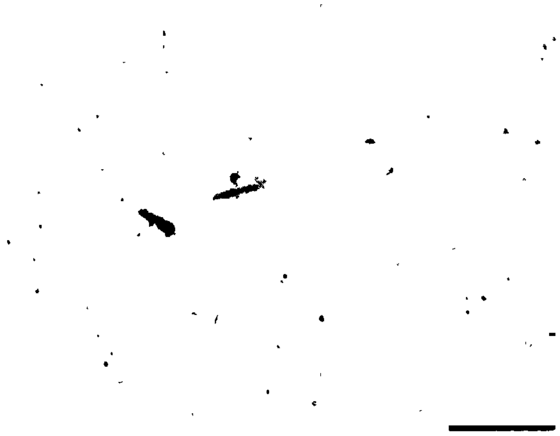

Figure 8.- Aeroelastic Rotor Experimental System Model in TDT.

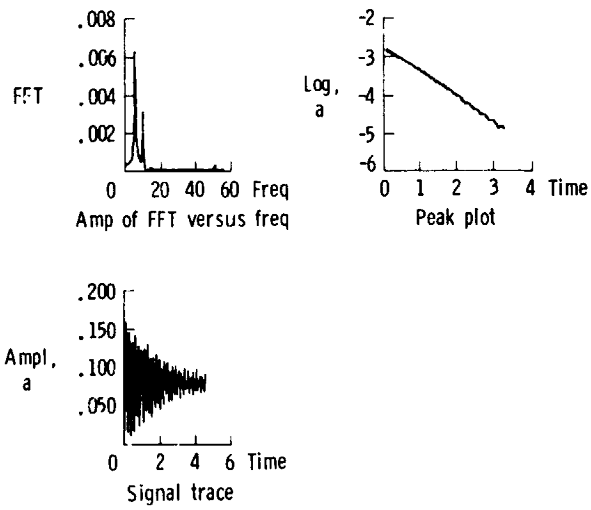

Figure 10.- Sample Real-Time Display of Moving-Block Results.

AEROELASTIC ROTOR EXPERIMENTAL SYSTEM BALANCE PROGRAM

PT. (Test point)	P (Static pressure)	H (Stagnation pressure)	X (Freon purity)	GAMMA (Ratio of specific heats)	TSTAT (Static temperature)	MACH (Free stream Mach number)	Q (Dynamic pressure)	VEL (Free stream velocity)	RHO (Freon density)	RN (Reynolds number/ft free stream)
554	1021.6	1026.9	.980	1.137	64.7	.095	5.3	47.1	.004701	849685
555	1021.8	1027.2	.980	1.137	64.7	.097	5.5	48.0	.004702	865954
556	1022.0	1027.5	.980	1.137	64.7	.097	5.5	48.0	.004703	866120
557	1020.1	1029.2	.980	1.137	65.4	.125	9.1	61.8	.004687	1109954
558	1020.4	1029.5	.980	1.137	65.4	.125	9.1	61.8	.004688	1110273
559	1021.7	1029.7	.980	1.137	65.4	.124	9.0	61.4	.004689	1104628
560	1016.2	1034.1	.980	1.137	65.6	.181	18.9	89.6	.004661	1599843

Figure 11.- Sample Output From A.R.E.S. Data Reduction Program.

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HELICOPTER FORWARD FLIGHT PERFORMANCE DATA

PT.	ALPHA	OMEGA	THETA	N	A	PM	RM	Y	S
554	-1.2	618.0	3.9	99.0	2.5	31.4	-18.1	266.6	-2.1
555	-1.2	618.0	3.9	99.7	2.8	27.1	-24.4	271.7	-2.2
556	-1.2	618.0	4.0	100.3	3.5	13.2	-34.5	280.9	-2.2
557	-2.3	617.0	4.0	90.6	5.2	15.4	-59.1	301.2	-2.6
558	-2.3	618.0	4.0	90.6	5.4	6.3	-67.5	310.4	-2.6
559	-2.3	618.0	4.0	90.6	5.9	-.8	-73.8	316.6	-2.6
560	-5.2	618.0	4.0	37.1	10.4	11.2	-132.6	315.7	-3.7
Test point	Shaft angle of attack	Rotor rotational speed, rpm	Collective pitch	Normal force	Axial force	Pitching moment (hub)	Rolling moment (hub)	Yawing moment	Side force

Figure 11.- Continued.

HELICOPTER FORWARD FLIGHT PERFORMANCE DATA

SHAFT SYSTEM

PT.	ALPHA	OMEGA	A1	B1	THETA	V/OMEGA R	MTIP	CL/SIGMA	CD/SIGMA	CT/SIGMA	CH/SIGMA	CY/SIGMA	CQ/SIGMA	HP
554	-1.2	618.0	-2.6	1.3	3.9	.142	.688	.03905	.00012	.03903	.00058	-.00085	.00196	2.6
555	-1.2	618.0	-2.6	1.3	3.9	.165	.687	.03933	.00026	.03929	.00111	-.00085	.00198	2.7
556	-1.2	618.0	-2.6	1.3	4.0	.165	.687	.03956	.00053	.03954	.00140	-.00085	.00205	2.8
557	-2.3	617.0	-2.4	1.7	4.0	.212	.713	.03600	.00063	.03595	.00206	-.00101	.00221	2.9
558	-2.3	618.0	-2.4	1.7	4.0	.212	.714	.03588	.00073	.03562	.00215	-.00102	.00227	3.0
559	-2.3	618.0	-2.4	1.7	4.0	.211	.714	.03587	.00092	.03561	.00234	-.00102	.00232	3.1
560	-5.2	618.0	-1.9	1.8	4.0	.338	.770	.01565	.00278	.01479	.00412	-.00147	.00232	3.1
Test point	Shaft angle of attack	Rotor rotational speed, rpm	Lateral cyclic	Longitudinal cyclic	Collective pitch	Advance ratio	Tip Mach number	Lift force coefficient/ solidity ratio	Drag force coefficient/ solidity ratio	Normal force coefficient/ solidity ratio	Axial force coefficient/ solidity ratio	Side force coefficient/ solidity ratio	Torque coefficient/ solidity ratio	Rotor horsepower

Figure 11.- Concluded.

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RUN NO 28 CHANNEL NO 4

PT NO		MEAN	1/2 P-P	RPM	1P	2P	3P	4P	5P	6P	7P	8P	
681		38.13	16.25	638	11.Ø7	5.28	4.93	1.59	.69	.67	.1Ø	.71	AMP
	RMS	1/2 P-P=	13.46		144.27	31Ø.Ø3	354.94	284.98	1.35	3Ø5.77	232.88	73.93	PHASE
682		35.98	16.79	64Ø	11.74	5.77	4.54	1.37	.69	.52	.12	.44	AMP
	RMS	1/2 P-P=	13.51		144.29	3Ø9.73	17.Ø3	297.62	75.68	32Ø.26	344.79	93.18	PHASE
683		38.61	16.41	638	1Ø.98	5.16	4.89	1.61	.46	.64	.14	.92	AMP
	RMS	1/2 P-P=	13.34		144.38	312.94	356.49	285.74	354.26	3Ø7.24	213.67	72.Ø8	PHASE
684		36.33	16.70	64Ø	11.17	5.76	4.55	1.48	.55	.54	.13	.49	AMP
	RMS	1/2 P-P=	13.52		142.35	3Ø7.16	1Ø.24	288.87	83.82	31Ø.56	337.32	74.93	PHASE
685		33.72	18.21	641	11.21	6.43	4.77	1.52	1.41	.18	.15	.22	AMP
	RMS	1/2 P-P=	14.Ø4		145.72	338.59	36.17	3Ø7.91	69.77	313.13	337.42	1Ø4.24	PHASE
686		34.1Ø	17.72	64Ø	1Ø.92	6.Ø9	4.7Ø	1.52	1.4Ø	.43	.11	.17	AMP
	RMS	1/2 P-P=	13.57		14Ø.12	337.21	31.42	3Ø5.5Ø	66.95	317.13	344.39	127.57	PHASE
687		34.19	17.51	690	1Ø.74	6.13	5.63	2.2Ø	1.76	.54	.18	.17	AMP
	RMS	1/2 P-P=	14.Ø3		141.Ø3	307.14	28.23	292.49	56.10	3Ø8.57	357.12	85.57	PHASE
688		33.97	17.93	693	1Ø.75	6.54	5.64	2.Ø3	1.74	.52	.17	.27	AMP

Figure 12.- Sample Output From A.R.E.S. Harmonic Analysis Program.

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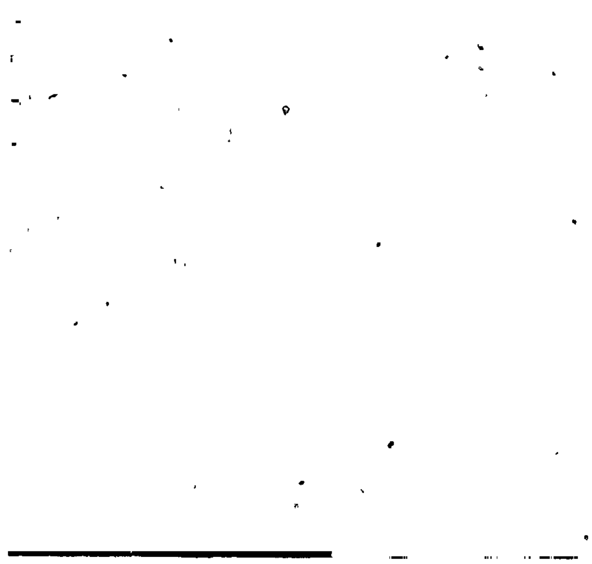

Figure 13.- Parametric Tip Shapes for Conformable Rotor Tests.

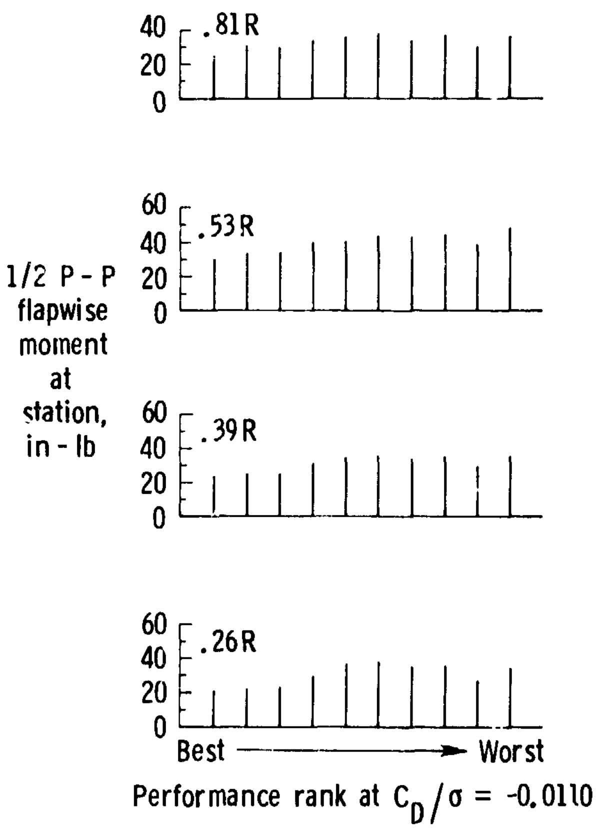

Figure 14.- Conformable Rotor Loads and Performance.

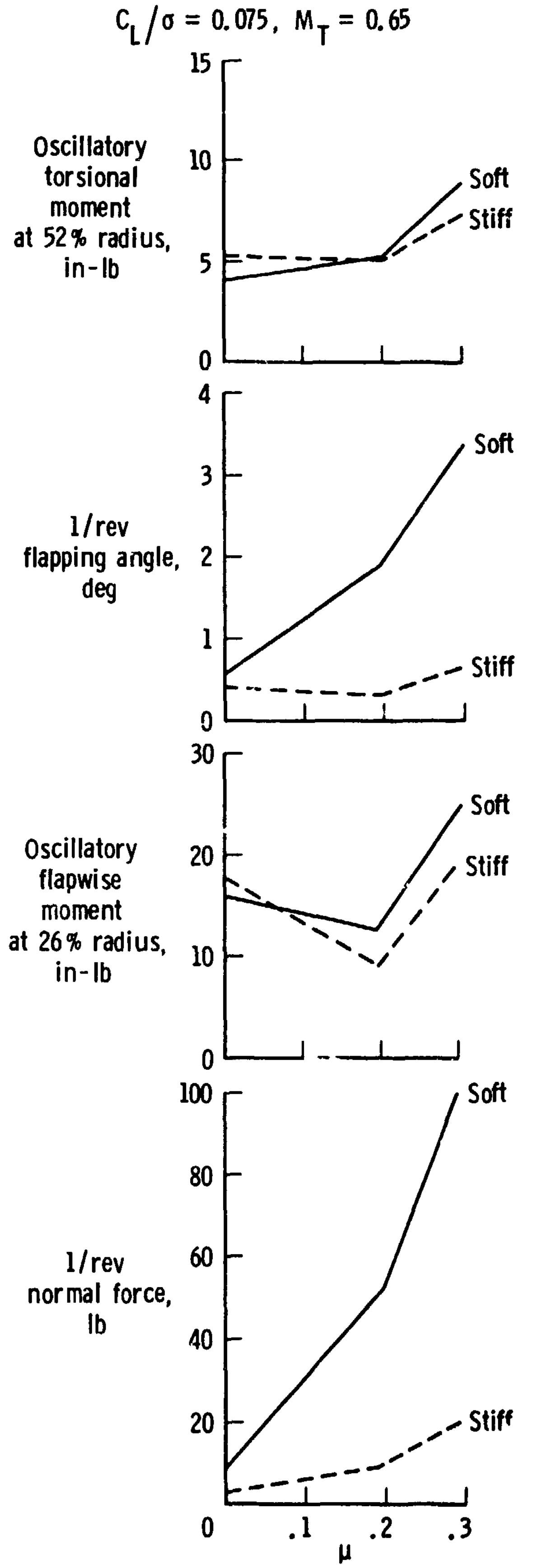

Figure 15.- Effect of 4° Tab Deflection on Torsionally Soft and Stiff Blade Response.

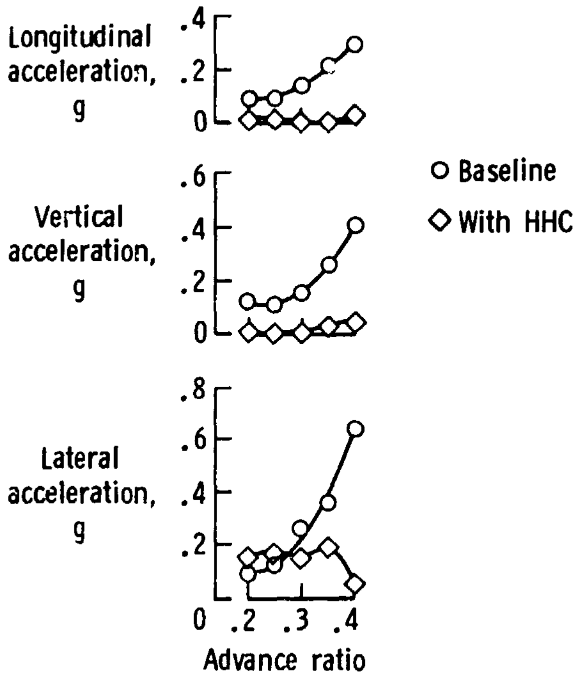

Figure 16.- Effect of Higher Harmonic Control on Fixed System 4p Vibration Levels.

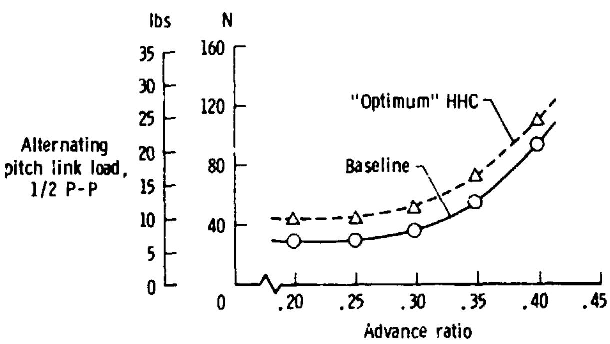

Figure 17.- Variation of Alternating Pitch Link Load (1/2 Peak-to-Peak Values) With Advance ratio.

Figure 18.- Model Hingeless Rotor Hub.

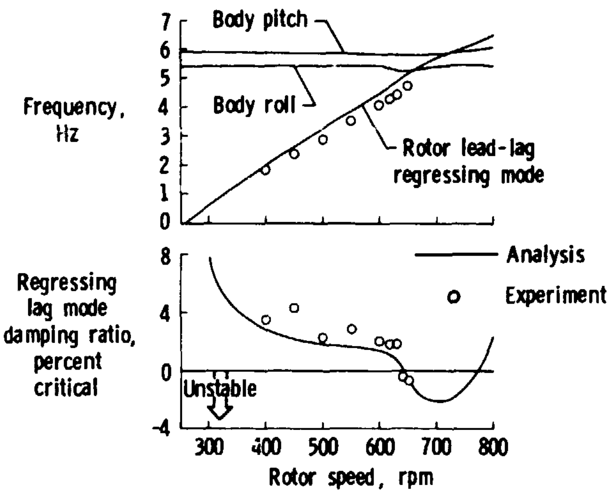

Figure 19.- Comparison of Predicted and Measured Stability as a Function of Rotor Speed in Hover.

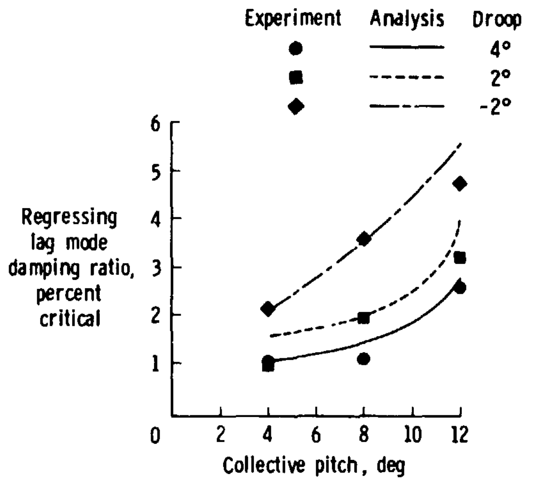

Figure 20.- Effect of Blade Droop Angle on Lead-Lag Damping at Advance Ratio = 0.30.

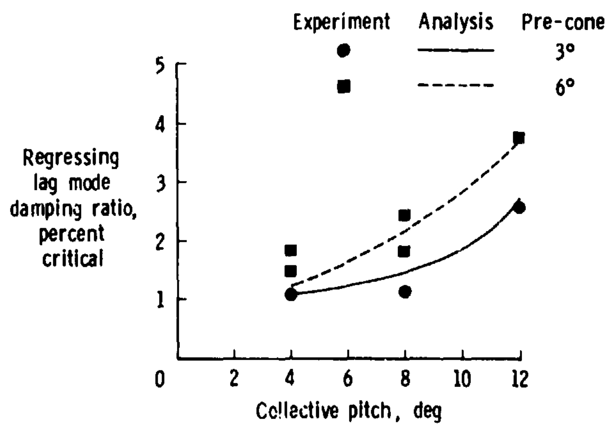

Figure 21.- Effect of Blade Pre-Cone Angle on Lead-Lag Damping at Advance Ratio = 0.30.

Figure 22.- 0.2 Scale JVX Aeroelastic Model.

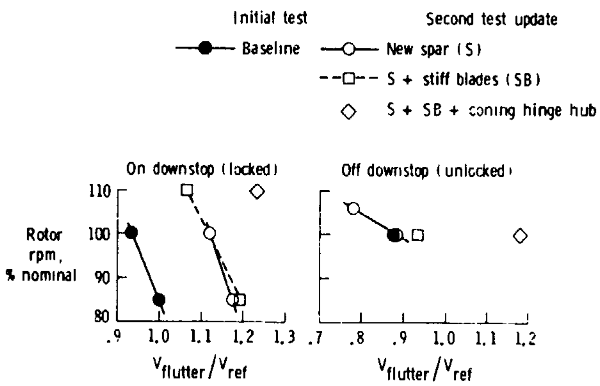

Figure 23.- Experimental Results of JVX
Model Wind Tunnel Tests.

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15. Supplementary Notes

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16 Abstract

Wind-tunnel testing of a properly scaled aeroelastic model helicopter rotor is considered a necessary phase in the design development of new or existing rotor systems. For this reason, extensive testing of aeroelastically scaled model rotors is done in the Transonic Dynamics Tunnel (TDT) located at the NASA Langley Research Center. A unique capability of this facility, which enables proper dynamic scaling, is the use of Freon as a test medium. The paper presents a description of the TDT and a discussion of the benefits of using Freon as a test medium. A description of the model test bed used, the Aeroelastic Rotor Experimental System (ARES), is also provided and examples of recent rotor tests are cited to illustrate the advantages and capabilities of aeroelastic model rotor testing in the TDT. This paper demonstrates the importance of proper dynamic scaling in identifying and solving rotorcraft aeroelastic problems, and affirms the importance of aeroelastic testing of model rotor systems in the design of advanced rotor systems.

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