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FULL-SCALE WIND TUNNEL EVALUATION OF THE SIKORSKY FIVE-BLADED BEARINGLESS MAIN ROTOR

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Abstract

A Sikorsky Bearingless Main Rotor (SBMR) was successfully tested in the 40- by 80-foot test section of the NASA Ames National Full-Scale Aerodynamics Complex (NFAC). The SBMR is a five-bladed 44-foot diameter demonstrator rotor system designed around existing S-76 hardware, and had been previously tested on the Sikorsky Main Rotor Whirl Stand. The wind tunnel test was conducted to obtain information about the SBMR in the areas of dynamics and stability, rotor structures and loads, handling qualities, aeroperformance and acoustics. Effects of open-loop higher harmonic control on rotor loads, performance and acoustics were also evaluated. A high-level summary of the results from each of these areas is presented in this paper. As part of this test program, improved wind tunnel test methodologies were developed in the areas of rotor balance dynamic calibrations, on-line fatigue monitoring, and frequency-response testing. These new methodologies, along with descriptions of new test hardware in the NFAC, are also presented.

Introduction

The Sikorsky Bearingless Main Rotor (SBMR) Demonstrator was designed using existing S-76 composite main rotor blades and a new five-bladed hub, employing design features similar to the rotor proposed for the RAH-66 Comanche. The SBMR was tested on the Sikorsky Main Rotor Whirl Stand, concluding in August 1991. Earlier that year, NASA had proposed a joint venture with Sikorsky, to test the SBMR in the NASA Ames 40- by 80-Foot Wind Tunnel. An initial planning meeting was held in late May 1991, and test planning began in June. A test justification meeting was held in July, and a joint test planning meeting was held in January 1992. Component laboratory testing, hardware fabrication and final documentation submittal to NASA were all completed in April 1992. Sikorsky/NASA hardware build-up and preliminary instrumentation work began in late April, and tunnel entry was accomplished in June. Testing was successfully completed in October 1992.

The extensive efforts to prepare for the wind tunnel test included laboratory component tests, full rotor system tests and analysis. Static and fatigue tests, including damage tolerance evaluations, were conducted on critical rotor components to establish structural limits and identify inspection intervals. Dynamic and hover whirl tests were conducted to identify dynamic and operational characteristics of the rotor system. Analytical predictions were generated through comprehensive modeling studies in each discipline, providing pretest estimates of operational trends and establishing an envelope to be used as a guide during wind tunnel operations.

The primary objective of the wind tunnel test was to evaluate the SBMR in the following five areas: dynamics and stability, rotor structures and loads, handling qualities, aeroperformance and acoustics. Data from each of these areas could then be correlated against analysis to gain confidence in the analytical techniques used in the Comanche design, to improve modeling if needed and to validate design concepts already selected. A secondary objective of this test was to evaluate the effects of active controls on rotor loads, performance and acoustics.

In this paper, the SBMR wind tunnel test program is described in detail. A description of the experiment is

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provided, with particular emphasis on test hardware used for the first time in the NFAC. Specific test objectives and approaches are then described, followed by a discussion of three new test methods developed to help accomplish these objectives. Finally, a high-level summary of the research results are presented.

Description of the Experiment

The test program was conducted in the National Full-Scale Aerodynamic Complex (NFAC) 40- by 80-Foot test section using a full-scale five-bladed bearingless rotor system mounted on NASA's Rotor Test Apparatus (RTA). Figure 1 shows the model installed in the wind tunnel. The hardware and instrumentation used during this test program are described below. Special emphasis is placed on those items which were used for the first time.

Rotor System Hardware

The SBMR is a five-bladed version of the basic production S-76 rotor with a bearingless rotor head. A schematic of the rotor head is shown in Fig. 2. The bearingless head utilizes a composite flexbeam in place of bearings to accommodate the flap, lead-lag, and pitching motions as well as the full centrifugal load of the blades. The rectangular-shaped flexbeams are attached to a steel clevis-type rotor hub with a two-bolt attachment. A composite torque tube, whose main function is to transmit pitch displacements from the pushrods to the outboard end of the flexbeam, surrounds each flexbeam and is attached to the outboard ends of the beams with a four-bolt joint. The torque tube extends past the flexbeam and is attached

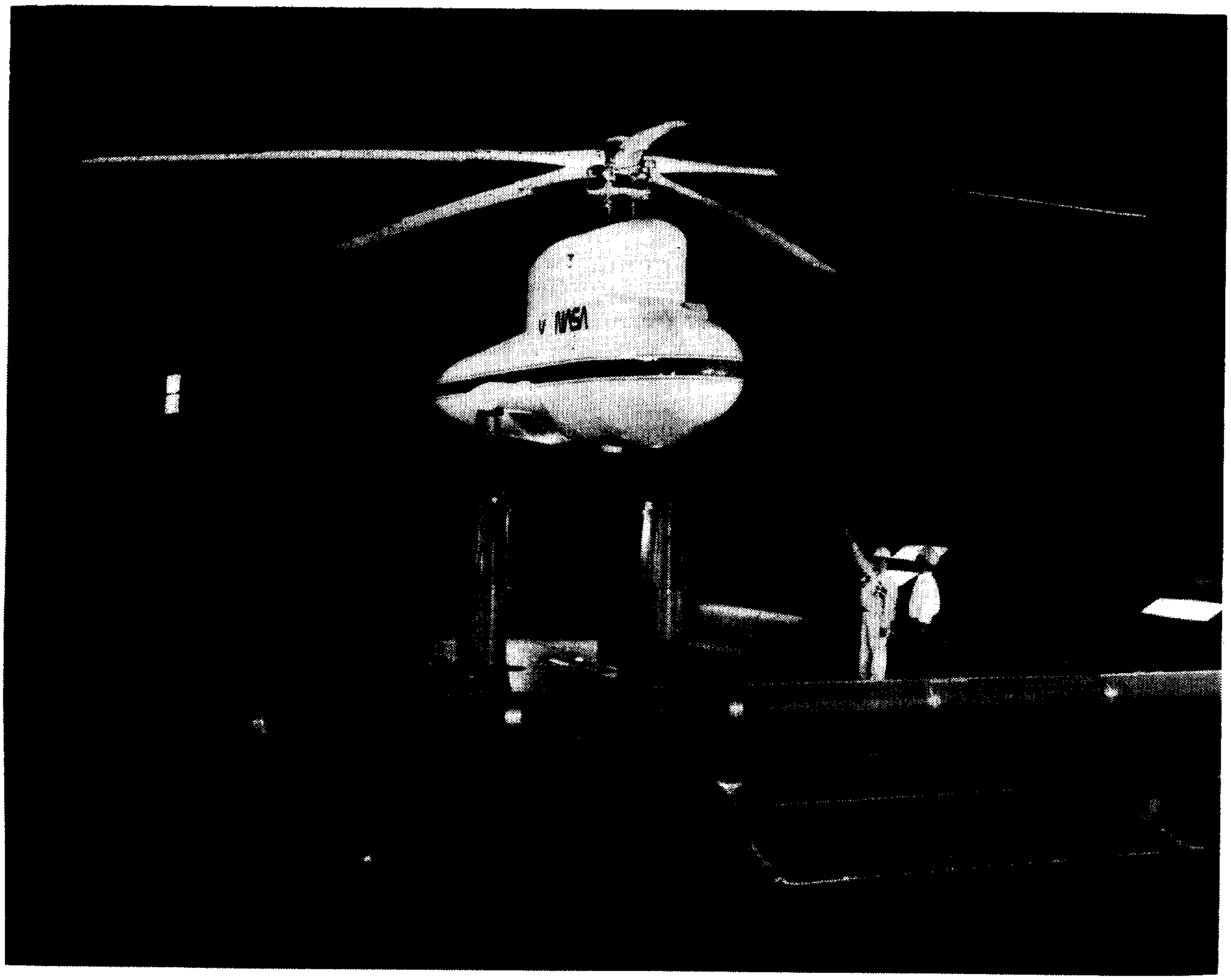

Figure 1. Sikorsky Bearingless Main Rotor on Rotor Test Apparatus in 40- by 80-foot test section

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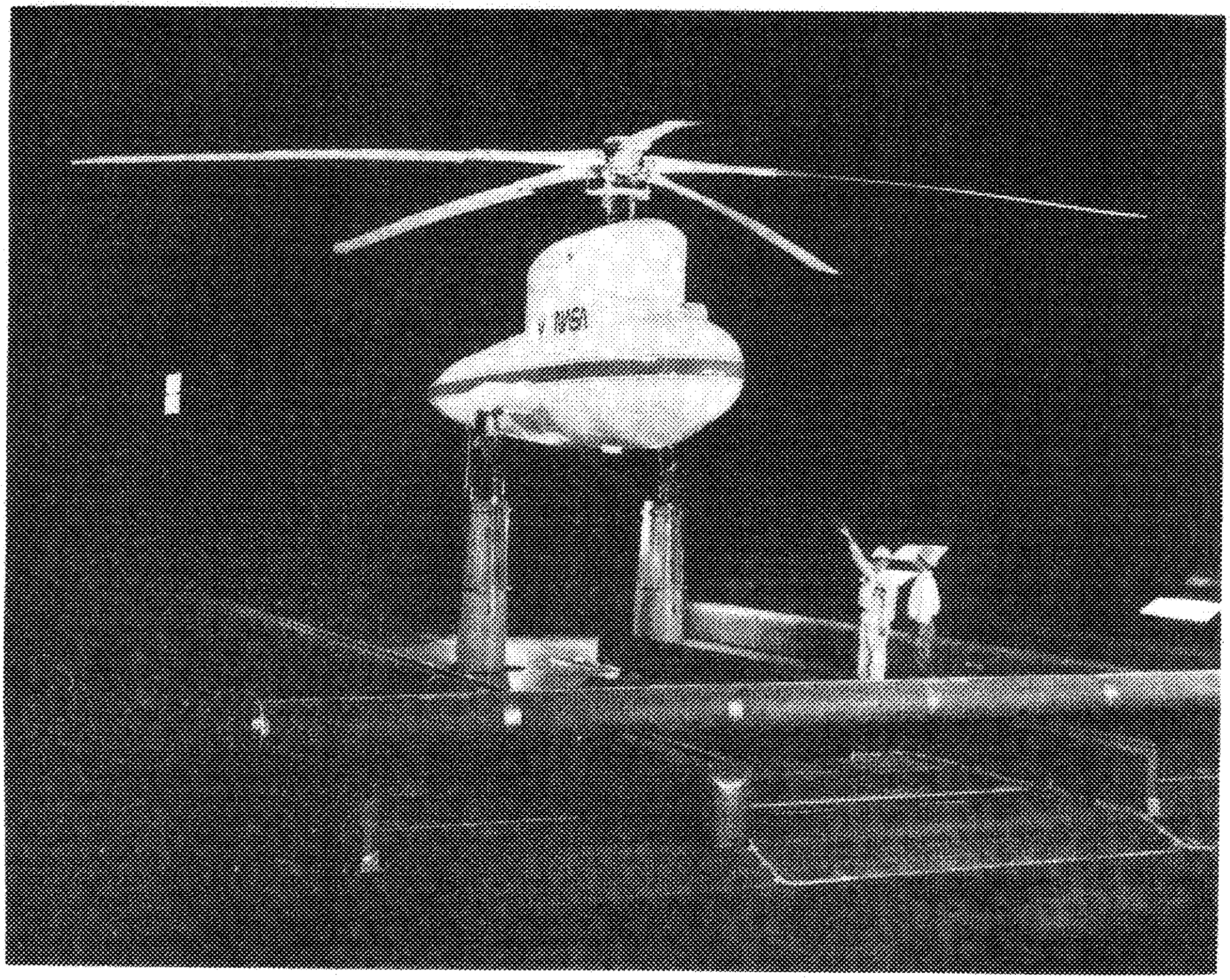

Figure 1. Sikorsky Bearingless Main Rotor on Rotor Test Apparatus in 40- by 80-foot test section

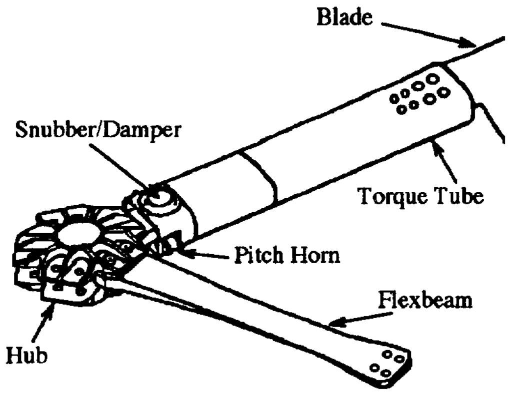

Figure 2. Schematic of SBMR rotor system

to the rotor blades with another four-bolt attachment. The SBMR utilizes trailing-edge pushrods. It should be noted that the SBMR is a demonstrator system; no attempt was made to optimize the design for peak aerodynamic performance.

An elastomeric snubber/damper assembly is attached between the inboard ends of the torque tube and flexbeam. The snubber/damper provides a centering point for the torque tube pitch motion while also providing damping for the blade's lead-lag motion.

The rotor blades were fabricated from prototype composite S-76 blades by cutting off a portion of the existing inboard blade and bonding on new laminates to complete the new inboard joint. The composite blades are a set of S-76 experimental blades that are identical in size and cross-section to the production blades, except that the spar is composite instead of titanium. The final rotor radius and chord are the same as the production S-76, 22 ft and 15.6 in respectively. The SBMR is designed to a nominal 1 G thrust of 10,500 lb.

Rotor/Hub Instrumentation

Rotor system strain gage instrumentation was included on two S-76 main rotor blades, five flexbeams (two with complete sets of gages), two torque tubes, five rotating pushrods, two rotating scissors and the hub. The RTA rotor shaft was gaged to measure shaft bending at four locations, from which to derive hub vibratory shears and moments. Snubber/damper motion and temperature were also recorded. Rotating system measurements were limited to a total of 48 at any given time, due to slipring limitations. Non-rotating measurements included three strain-gaged stationary pushrods and one stationary scissor.

RTA Test Stand

The RTA is a special-purpose drive and support system for operating helicopter rotors in the NFAC. Originally built in the mid-1970's, it houses two electric drive motors, a right-angle transmission, the electro-hydraulic servo-actuators of the primary control system, and a dynamic control system capable of introducing time-varying perturbations to the non-rotating swashplate. Recently, the RTA was modified to include installation of a five-component rotor balance. In addition, the rotor control capabilities have been improved with the addition of two new control consoles. In the following sections, these added capabilities are discussed in detail.

Rotor Balance. A five-component rotor balance with steady and dynamic load measuring capability is integrated into the RTA. The Steady/Dynamic Rotor Balance (S/DRB) is located between the RTA transmission and upper housing, approximately 73 in below the rotor hub. It consists of two 32-in diameter rings, connected to each other by four rectangular, instrumented flexures. The balance peak load capacities are: 22,000 lb of thrust, 4400 lb of shear force, and 694,000 in-lb of moment at the balance. The maximum allowable hub moments are dependent on hub height above the balance; for this configuration, the limit is 371,000 in-lb. The balance shares a common centerline with the rotor shaft. The rotor shaft has an in-line flex-coupling, which is instrumented to measure rotor torque up to a maximum of 433,000 in-lb.

An extensive static calibration of the S/DRB was performed prior to the wind tunnel test. For this calibration, the balance was installed in the RTA model and this assembly was positioned in a special calibration test rig. Hydraulic actuators were used to apply the static calibration loadings. A total of 57 calibration loading sequences were performed for a total of ~1080 calibration points. These data were then analyzed to determine a calibration coefficient matrix which accounts for gage interactions. This coefficient matrix could then be used in an iterative scheme to convert the balance gage voltages to engineering unit data. This method was subsequently used to calculate the balance loading from the calibration voltage data. The error between the predicted balance loading and the known applied calibration loading was calculated. The standard deviation of these errors for all static calibration load points was less than 0.3% of the balance gage capacity for all primary balance gages as shown in Table 1.

The S/DRB was designed to measure dynamic as well as steady hub loads. Details of the calibration procedures necessary for determining accurate dynamic loads are presented later in this paper.

Table 1. S/DRB calibration accuracy

Parameter	Maximum Capacity	Std. Deviation of error	
		Value	% capacity
Normal Force	22000 lb	25 lb	0.12
Axial Force	4400 lb	7 lb	0.14
Side Force	4400 lb	12 lb	0.25
Pitch Moment	694,000 in-lb	324 in-lb	0.05
Roll Moment	694,000 in-lb	504 in-lb	0.07

This test program was the first to use the S/DRB to acquire high quality rotor loads above 100 knots.

Control consoles. The RTA control consoles consist of two separate, and somewhat independent, position control systems; the Primary Control Console (PCC) and the Dynamic Control Console (DCC). Both of these consoles are pictured in Fig. 3.

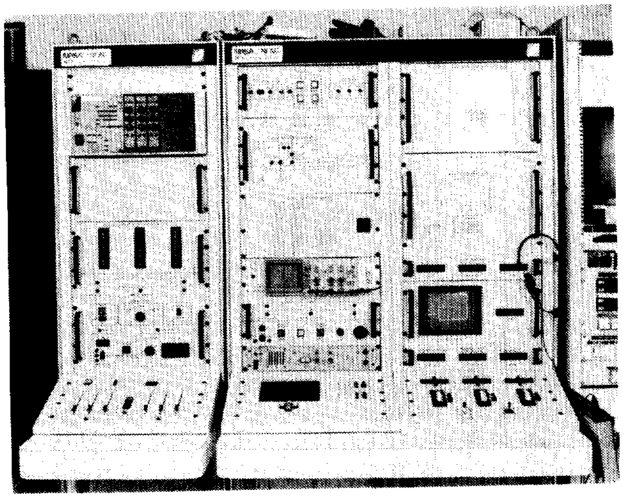

Figure 3. Dynamic Control Console (left) and Primary Control Console (right)

The Primary Control Console (PCC) provides the operator with static control of the three linear hydraulic (primary) actuators. This position control is achieved by driving three "walking beam" control rod linkages, whose positions define the orientation of the swashplate; and, hence, rotor blade collective and cyclic pitch. All actuator control is provided by specially-designed digital and analog circuitry. In addition to control functions, the control console also provides numerous displays to give the operator visual feedback of conditions on the test rig, particularly for blade flapping.

Calibration of the PCC was done to provide a measure of rotor blade pitch. This calibration was done indirectly by correlating the positions of the three non-rotating control actuators with actual blade pitch. Measurements were made statically (non-rotating) and calibrated throughout the entire range of anticipated pitch control positions.

The Dynamic Control Console (DCC) provides the operator with control of three rotary hydraulic (dynamic) actuators to provide oscillatory and ramp pitch angle perturbations about the nominal angle set by the PCC. Internal DCC capabilities allow inputs through a single actuator, in any of the helicopter's control axes (collective, lateral or longitudinal), or nutation (regressing or progressing). Frequencies up to 40 Hz may be input through the DCC for stability estimation or natural frequency investigations. Inputs are also possible at integer harmonics of the main rotor speed (1 per rev and 5 per rev inputs were used during this program in support of HHC testing). In addition to these internal capabilities, externally generated signals can be used to drive the dynamic actuators. For example, an external PC system was used in this test to input swept-sinusoidal frequency sweeps (or "chirps") through the DCC for handling qualities frequency response tests.

The SBMR test program was the first to use these newly designed consoles together.

Acoustic Survey Apparatus

Acoustic data were acquired using microphones mounted on the new Acoustic Survey Apparatus (ASA). The ASA consists of a vertical strut mounted on a 40-ft airfoil-shaped crossbeam which in turn rides on two 80-ft streamwise rails. Depending on specific test requirements, the vertical strut can be designed to place microphones at any desired heights. For this test, a 19-ft strut was chosen to place the microphones at several different heights. Five microphones were used, two near the top of the strut to measure rotor in-plane noise, and three near the bottom of the strut to measure blade-vortex interaction noise. In general, the vertical strut can be moved to any location along the crossbeam and the crossbeam can be moved as a single unit to any location along the streamwise rails. Movement of the ASA is controlled remotely by a stand-alone computer system. This system allows for continuous operation of the ASA during wind tunnel operations with the capability of automatically positioning the microphones at preprogrammed locations. Figure 4 shows the installation of the ASA with the vertical strut positioned on the advancing side of the SBMR model. As can be seen in this figure and Fig. 1, downstream motion of the ASA crossbeam was limited for this test by the two front model support struts. In addition to this geometrical limitation, structural concerns

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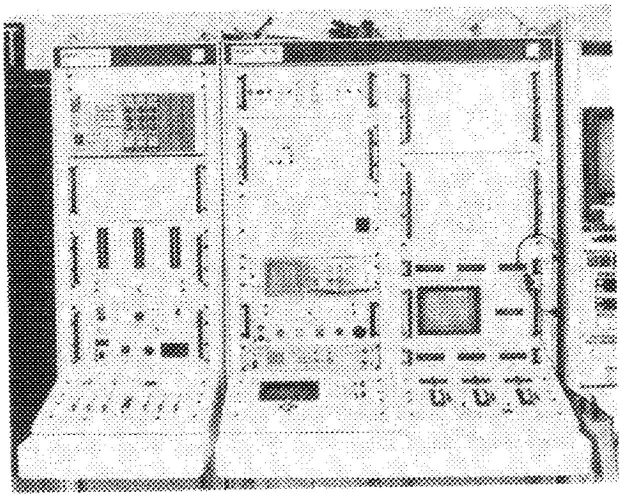

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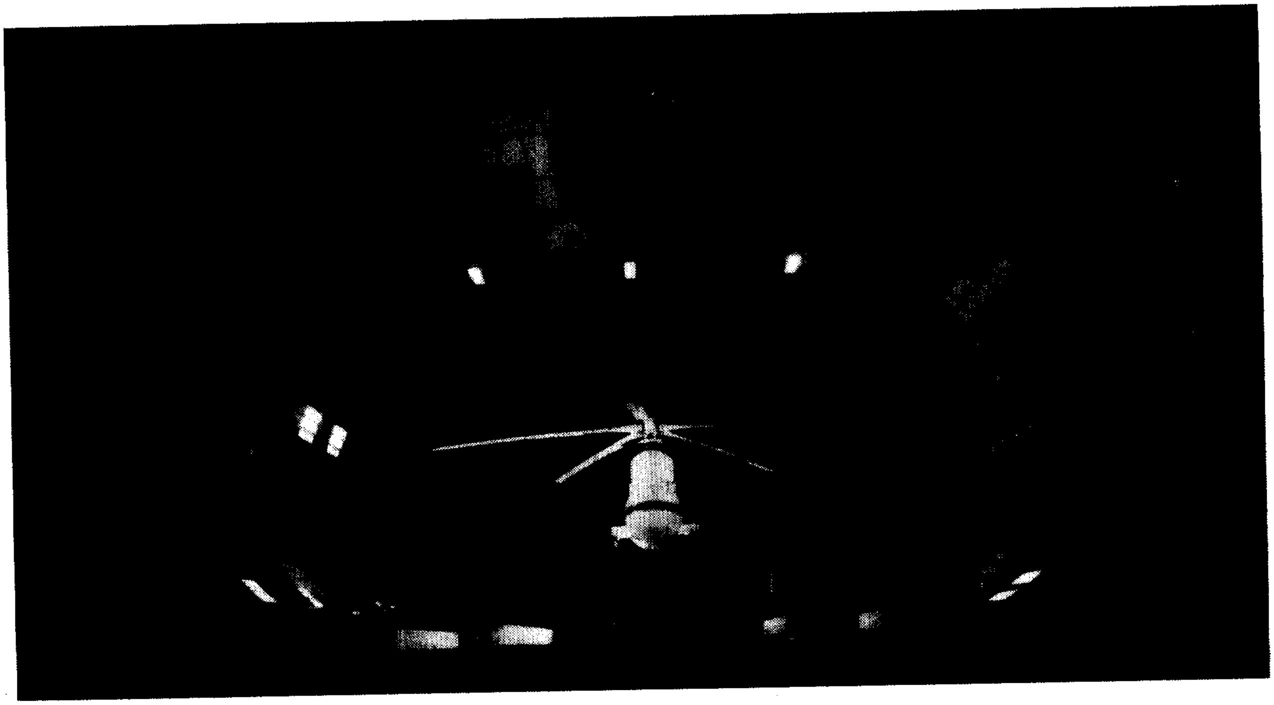


Figure 4. SBMR model installation showing vertical microphone strut on ASA

limited testing with the ASA to speeds below 200 knots (post-test modifications to the ASA will allow higher speeds for future tests).

The new ASA provides an enhanced acoustic testing capability for the NFAC. For rotorcraft testing, it allows for positioning of the microphones to determine the locations of peak noise. This test program was the first to use the ASA.

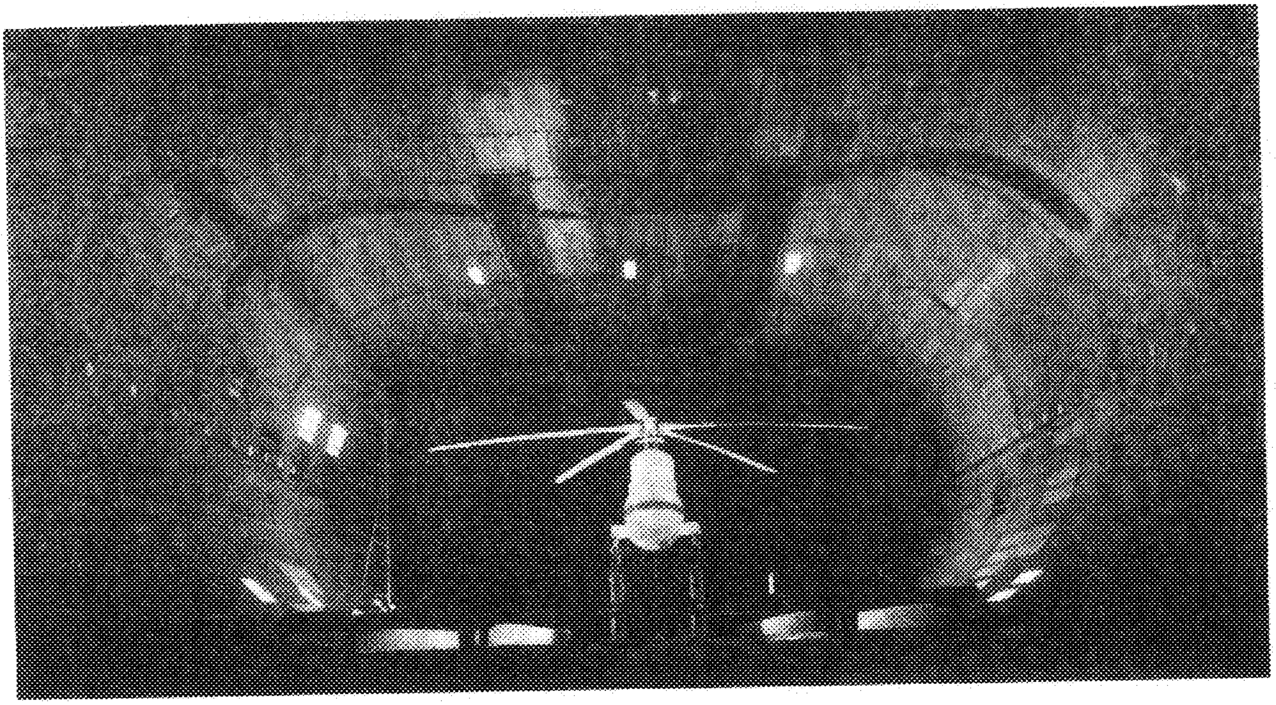
Test Objectives and Approach

The primary objective of the test was to evaluate the SBMR in the following five areas: dynamics and stability, rotor structures and loads, handling qualities, aeroperformance and acoustics. In addition, the effect of active controls on rotor loads, performance and acoustics was evaluated. In the following section, the specific objectives for each of these areas are discussed, as well as the test approach used.

In the dynamics area, the objectives were to provide a data base for correlation of rotor frequency, stability, and loads with analytical predictions, and to define the dynamic characteristics of the rotor throughout the steady-state operational envelope. Frequency and damping in the first lead-lag mode were determined by nutating the swashplate using the Dynamic Control Console (DCC), and analyzing the transient decay response of the flexbeam chordwise bending moment as pitch inputs were terminated. Blade modal responses were determined both by exciting the rotor in single actuator mode in hover, and by performing rotor speed sweeps at constant advance ratio, at a number of nominal tunnel velocities and thrust settings. General dynamic information was obtained by trimming the rotor to representative aircraft steady operating conditions, and measuring rotating and fixed system responses.

In the rotor structures area, the primary objective was to provide a data base for correlation of design loads predictions by measuring rotor loads throughout the operating envelope. This was accomplished by performing flapping (pitch moment) perturbations, up to the maximum shaft bending capability of the RTA shaft, at various combinations of shaft angle, tunnel speed and rotor thrust. The resulting vibratory hub loads, control loads, blade moment distributions, power required, and snubber/damper motion and temperature were then measured.

For handling qualities, the primary objectives were to provide a data base for correlation of stability and control derivatives, and rotor frequency response data, and to define the rotor control characteristics throughout the steady-state operating envelope. Stability and control derivatives were



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For handling qualities, the primary objectives were to provide a data base for correlation of stability and control derivatives, and rotor frequency response data, and to define the rotor control characteristics throughout the steady-state operating envelope. Stability and control derivatives were determined by varying rotor controls, tunnel speed, and shaft and yaw angle about a given trim condition. Rotor frequency response was determined using the new wind tunnel test methodology described in the next section.

In the aerodynamic performance area, the objectives were to provide rotor performance data at various tunnel speeds and shaft angles for correlation with analysis and to determine the effect of the rotor hub and torque tubes on performance. The effect of number of blades on performance could also be determined by comparing data from this test with data acquired during previous four-bladed S-76 wind tunnel tests. Tare data were acquired for the bare hub and for the torque tubes without blades installed. These tares were then removed from the blades-on data to provide isolated rotor performance information.

For acoustics, the primary objective was to assess the potential for reducing rotor noise using a five-bladed rotor design. In particular, the effect of number of blades on blade vortex interaction (BVI) noise and high-speed impulsive (HSI) noise was evaluated. To accomplish this, acoustic data were acquired at various microphone locations both in and below the rotor plane at various azimuthal and radial locations using the ASA in order to determine the peak noise locations. These data could then be compared with data acquired in past and future wind tunnel tests and flight tests of the four-bladed S-76 rotor to determine the effect of number of blades.

In the active controls area, the primary objective was to evaluate the effectiveness of open-loop higher harmonic control (HHC) inputs on rotor loads, performance and acoustics. This was accomplished by inputting 1P and 5P cyclic and collective pitch excitations at various blade azimuth ("phase") angles and comparing results from non-HHC test conditions.

New Test Methodologies

During this test program, three new wind tunnel test methodologies were developed which proved particularly useful in meeting the SBMR test objectives. The first, dynamic calibration of the rotor balance, allowed for determination of dynamic hub loads. The second, an automated fatigue monitoring system, allowed on-line tracking of component fatigue damage. The third involved the use of frequency-response methodology for conducting handling qualities and dynamics research. Discussion of these methodologies follows.

Rotor Balance Dynamic Calibration

For a complete evaluation of the SBMR in the areas of dynamics and handling qualities, it was necessary to determine the vibratory fixed-system loads at the rotor hub. In particular, the rotor-induced loads, independent of the RTA or wind tunnel dynamic characteristics, were desired. The recent addition of the S/DRB to the RTA made this determination possible. To make full use of the balance capabilities, however, a comprehensive dynamic calibration methodology was required. A summary of the methodology developed for this program is outlined below.

The general calibration approach was to measure the frequency responses of the balance to known vibratory inputs. These frequency responses could then be used to correct the balance data acquired during the test program, thereby negating the effects of the RTA and wind tunnel. It should be noted that because of its bearingless rotor design, the SBMR could transmit blade loads to the fixed frame balance either through the flexbeam and hub or through the torque tube and pushrods. In order to back out the true vibratory hub loads (i.e., loads through the rotor shaft), it was necessary to determine the balance frequency responses for each of these redundant load paths. This was accomplished through two separate dynamic balance calibrations.

A significant effort was expended in the calibration of loads through the flexbeam and hub, since this was the primary load path. It was known prior to testing that the RTA installation would have a large effect on the balance frequency response. To minimize uncertainties, the calibration was therefore performed with the RTA mounted in the wind tunnel. It was also known that the amount of mass attached to the top of the shaft was very important. Two different masses were used in this program. The first simulated the hub mass only, while the second included the mass of the blades. Both of these configurations were required in order to allow for different methods of post-test data correlation. A number of other parameters were identified prior to the test program as possibly having an effect on the balance frequency response. These included rotation rate, steady rotor thrust, input force and RTA shaft angle. One of the objectives of this calibration was to evaluate the importance of these parameters.

During calibration, variable frequency inputs were provided by a hydraulic actuator attached to a large (11600 lb) reaction mass. These oscillatory loads were input at the equivalent SBMR hub height through special adaptor hardware mounted on the RTA rotor shaft. This hardware consisted of a rotating bearing assembly which allowed for rotation of the shaft while the hydraulic actuator remained stationary. This assembly also allowed for the addition of weights to simulate the combined rotor blade/hub mass and center of gravity, and allowed for the application of a steady vertical force to simulate rotor thrust. The calibration consisted of shaking the RTA in five orientations: vertically, longitudinally, laterally, vertically with a one ft longitudinal offset from the rotor centerline

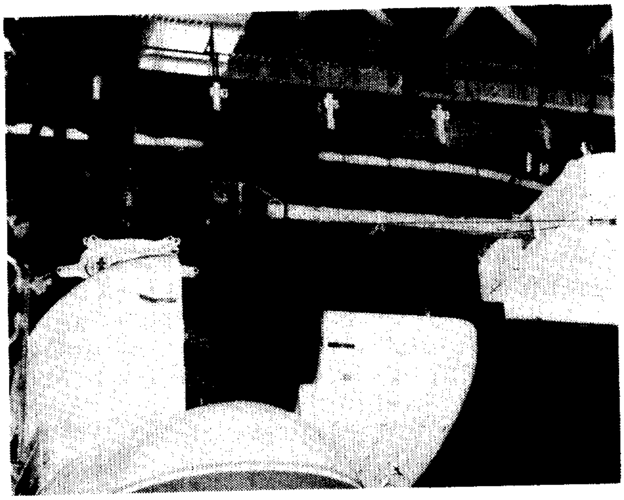

Figure 5. Installation setup for dynamic balance calibration in lateral direction

and vertically with a one ft lateral offset from the rotor centerline. These latter two orientations were used to produce pitching and rolling moments, respectively. Figure 5 shows the installation setup for calibration in the lateral direction. Parameter variations during calibration included rotation rate (0-378 RPM), steady vertical force (0-4000 lb), shaker force amplitude (100-600 lb), and force input type (random or discrete frequency excitation). Higher vertical forces and variations in shaft angle were not looked at due to hardware limitations.

The results of this calibration consisted of a large set of frequency response functions (balance signal/input load) for each orientation. These frequency response functions were compared with each other to evaluate the relative importance of each of the varied parameters. The general result was that some differences were seen, especially at balance/RTA resonances. However, at the SBMR rotor harmonics (multiples of 5.25 Hz), the effects were relatively small. Figure 6 is an example of the effect of rotation on the frequency response function for the lateral/side force direction.

In comparison to the primary load path calibration, the calibration of loads through the torque tubes and pushrods was quite simple. For this testing, the hub and swashplate were removed and each stationary pushrod was shaken individually in the vertical direction. Parameter variations for this calibration included only shaker force amplitude (25-100 lb), and force input type. This test yielded frequency response functions between the balance output and the stationary pushrod output.

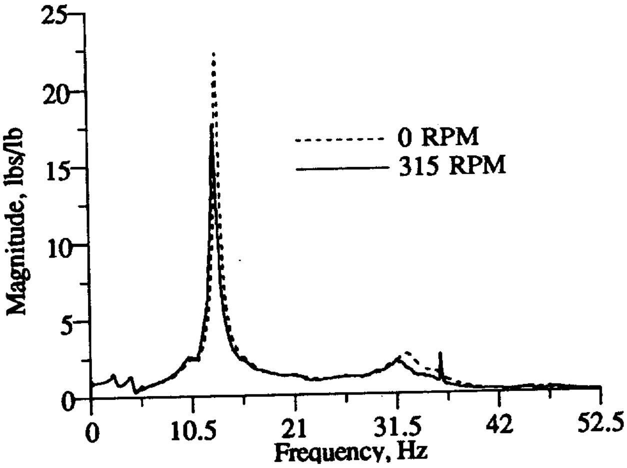

Figure 6. Effect of rotation on dynamic balance calibration (frequency response function) for the lateral/side force direction, random excitation, 500 lb amplitude, no vertical force

A data reduction routine was developed for use during the wind tunnel test to take the results of the calibration and provide dynamic rotor loads at the hub. This routine corrected the dynamic balance data using the frequency response functions generated from the primary load path dynamic calibration. The data were then sent through the standard balance matrix equations, and resolved into forces and moments at the hub. To simplify the data reduction process during the test, only one set of frequency response functions was implemented, and the control system loads were not subtracted. Software efforts are currently underway to account for the redundant load path and more fully utilize the calibration results, thus providing a more accurate determination of dynamic hub loads.

The dynamic calibration for this test has verified the ability of the S/DRB to measure dynamic hub loads on the RTA. This is a significant addition to the testing capabilities of the NFAC. Nonetheless, further refinement of the calibration procedures is possible. Specifically, the effect of shaft angle and higher thrust levels remain to be evaluated. In addition, improved data reduction techniques are possible which may incorporate all parameter variations, rather than using only one set of frequency response functions.

On-Line Fatigue Monitoring System

Since the rotor's design envelope was being pushed during this program, it was anticipated that some fatigue damage would accumulate on various rotor components. In order

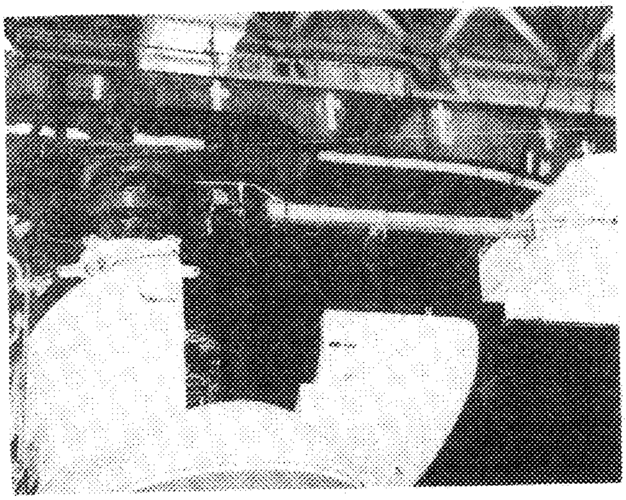

Figure 5. Installation setup for dynamic balance calibration in lateral direction

and vertically with a one ft lateral offset from the rotor centerline. These latter two orientations were used to produce pitching and rolling moments, respectively. Figure 5 shows the installation setup for calibration in the lateral direction. Parameter variations during calibration included rotation rate (0-378 RPM), steady vertical force (0-4000 lb), shaker force amplitude (100-600 lb), and force input type (random or discrete frequency excitation). Higher vertical forces and variations in shaft angle were not looked at due to hardware limitations.

The results of this calibration consisted of a large set of frequency response functions (balance signal/input load) for each orientation. These frequency response functions were compared with each other to evaluate the relative importance of each of the varied parameters. The general result was that some differences were seen, especially at balance/RTA resonances. However, at the SBMR rotor harmonics (multiples of 5.25 Hz), the effects were relatively small. Figure 6 is an example of the effect of rotation on the frequency response function for the lateral/side force direction.

In comparison to the primary load path calibration, the calibration of loads through the torque tubes and pushrods was quite simple. For this testing, the hub and swashplate were removed and each stationary pushrod was shaken individually in the vertical direction. Parameter variations for this calibration included only shaker force amplitude (25-100 lb), and force input type. This test yielded frequency response functions between the balance output and the stationary pushrod output.

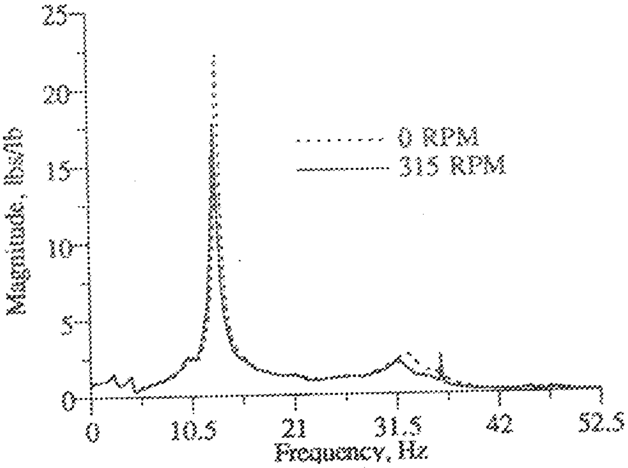

Figure 6. Effect of rotation on dynamic balance calibration (frequency response function) for the lateral/side force direction, random excitation, 500 lb amplitude, no vertical force

A data reduction routine was developed for use during the wind tunnel test to take the results of the calibration and provide dynamic rotor loads at the hub. This routine corrected the dynamic balance data using the frequency response functions generated from the primary load path dynamic calibration. The data were then sent through the standard balance matrix equations, and resolved into forces and moments at the hub. To simplify the data reduction process during the test, only one set of frequency response functions was implemented, and the control system loads were not subtracted. Software efforts are currently underway to account for the redundant load path and more fully utilize the calibration results, thus providing a more accurate determination of dynamic hub loads.

The dynamic calibration for this test has verified the ability of the S/DRB to measure dynamic hub loads on the RTA. This is a significant addition to the testing capabilities of the NFAC. Nonetheless, further refinement of the calibration procedures is possible. Specifically, the effect of shaft angle and higher thrust levels remain to be evaluated. In addition, improved data reduction techniques are possible which may incorporate all parameter variations, rather than using only one set of frequency response functions.

On-Line Fatigue Monitoring System

Since the rotor's design envelope was being pushed during this program, it was anticipated that some fatigue damage would accumulate on various rotor components. In order to meet the NFAC requirements to monitor this accumulation, an on-line fatigue monitoring system was developed. This system was designed to measure, calculate and display the magnitude of each fatigue critical parameter for each rotor revolution, in real time. This is in contrast to earlier manual systems, which could not perform these functions until after a test run was complete.

The new fatigue monitoring system was developed utilizing Macintosh-based LABVIEW software. The developed system is capable of recording up to 16 input measurements and derived parameters can be calculated from any of these inputs. A complete description of the data acquisition software developed for this program can be found in Ref. 1. During the SBMR test, the rotor 1P signal triggered acquisition of data samples equally spaced about the azimuth. The vibratory load was then calculated from the maximum and minimum values measured during the current rotor revolution, compared to the endurance limit for each parameter, and recorded if the endurance limit was exceeded. Endurance limits, established from fatigue tests, were adjusted as necessary to address the maximum predicted test steady level. The on-line screen display consisted of a series of bins representing increasing magnitude above the endurance limit. For each exceedance cycle, the appropriate bin was indexed. Two sets of bins were displayed, one showing the cycles from the most recent period, and one showing a summary of all cycles during the current run. The fatigue monitoring system was also configured to capture the maximum and minimum values of each parameter for an entire run to calculate the ground-air-ground cycle. After each run, the steady load levels of each parameter were reviewed, and Goodman corrections made if necessary. The summary of damaging cycles was then input to a spreadsheet, in order to compute the accumulated fatigue damage for the entire test.

The new fatigue monitoring system had three distinct advantages over earlier systems and worked exceptionally well. First, it allowed real-time judgements concerning fatigue damage accumulation to be performed during a particular test run. Second, it allowed multiple parameters to exceed their endurance limits simultaneously, while maintaining accurate fatigue damage accumulation records. Third, it reduced the workload of test personnel in preparation for the next test run. Overall, the system allowed the SBMR to be extensively tested in an efficient manner.

Frequency-Response Test Technique

One of the objectives of the handling qualities portion of the test was to obtain detailed rotor frequency response data. These data are needed to help correlate and develop the bearingless-main-rotor analytical models used in control systems design. During the SBMR program, a new method was used to generate the required data. Rather than using discrete frequency methods as in the past, frequency responses were obtained using system identification techniques and CIFER (Comprehensive Identification from FrEquency Responses) software. The method used is similar to that used in previous BO-105 flight tests (Ref. 2), but was applied for the first time in a full-scale wind tunnel test during this program.

The frequency response data were generated by inputting an increasing frequency sinusoidal waveform (or "chirp") through the rotor control system. Either a collective or a cyclic (lateral or longitudinal) channel was selected and the input signal applied through the RTA dynamic control console (DCC). A PC-based program was used to generate the signal, with random white noise summed into the sinusoidal signal to fill any gaps in the frequency domain caused by the digital implementation. The PC program provided the capability to specify the start and stop frequency, sample rate, and amplitude/frequency shaping. The chirp signal amplitude was shaped around known rotor and RTA response frequencies. This permitted maximizing input amplitudes across the frequency spectrum, resulting in the highest quality data possible. The frequencies of the input signal were chosen to obtain dynamic rotor information up to 2P in order to cover the operational range of both pilot and automatic flight control systems.

Data time histories were recorded during chirp testing using a modified version of NASA's existing dynamic data acquisition software. This modified version allowed data to be recorded over the long time periods necessary for frequency domain identification (up to 512 rotor revolutions at a rate of 16 points per revolution). Data recorded included the RTA balance normal, axial and side forces, main rotor shaft bending, and the root end flap and chordwise bending from all five flexbeams. These data were reduced post-run using a special version of NASA's Rotor Data Reduction System (RDRS) to generate the derived time histories necessary for frequency response determination using CIFER. These derived values included input time histories, such as collective and cyclic pitch, and output time histories, including shaft axis forces and moments at the hub. Using multi-blade coordinate transformations, time histories of the steady, cosine and sine components of flap and lag were also calculated. Figure 7 shows an example of both an input and output time history for one test condition.

Time histories such as these could then be used to generate rotor frequency response information using CIFER software. Figure 8 is an example of the type of frequency response information available from this code. The figure shows the yawing moment and steady flexbeam chordwise-bending responses to longitudinal cyclic pitch input in terms of magnitude, phase, and coherence. The coherence function, which is a measure of the accuracy of

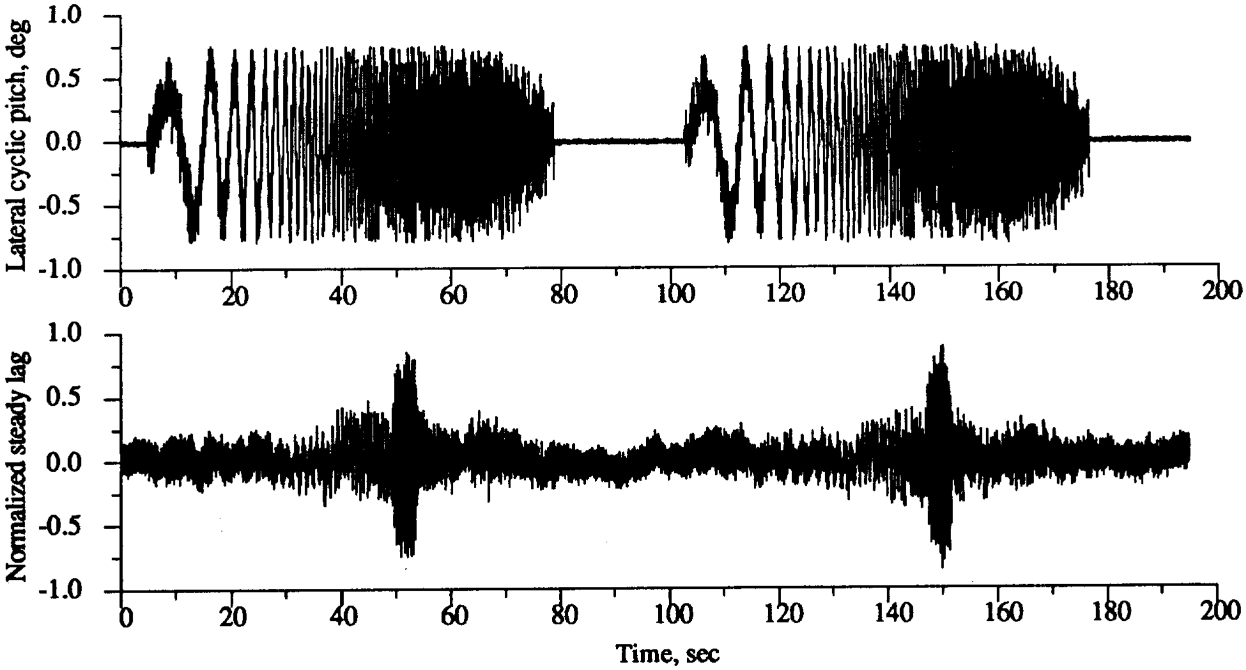

Figure 7. Sample time histories from frequency response testing, a) lateral cyclic pitch input, b) steady lag ouput

the identification, indicates excellent identification has been achieved up to a frequency of approximately 30 rad/s. In addition to providing frequency response information, CIFER may be further utilized to conduct state-space model identification and model-structure determination to complete the system identification process. Details of these processes can be found in Ref. 2.

This new technique provides an excellent way to evaluate rotor frequency response characteristics during wind tunnel testing. In particular, excitation of rotor dynamics using a chirp-type input offers a more comprehensive means of rotor excitation than discrete inputs and can be accomplished in a fraction of the time. Given typical wind tunnel scheduling constraints, this latter benefit is very important.

Test Envelope

During the course of the SBMR wind tunnel program, the rotor was tested up to thrust levels of 19,000 lb, rotor speeds to 346 RPM (110% N_R), tunnel velocities to 200 knots, pitching moments to RTA shaft bending limits, shaft angles to +/- 10 deg, and yaw angles to +/- 5 deg. Approximately 1800 data points, including 220 stability points and 460 acoustic points, were recorded during blades-on wind tunnel testing. The rotor thrust/tunnel velocity envelope achieved during the course of the program is presented in Fig. 9. Significantly, nearly all test conditions were limited by either ASA limits (tunnel velocity) or RTA limits (normal force, power and shaft bending), as opposed to structural and control limitations of the SBMR.

Results and Discussion

During this program, all significant SBMR wind tunnel test objectives were attained. Presented below is a summary of some of the research accomplishments, including representative results in each of the major disciplines.

In the dynamics area, rotor stability trends and rotor natural frequencies were generally close to predictions. The SBMR was found to be stable for all conditions tested in the wind tunnel. Figure 10 compares rotating-frame regressing lag damping measurements with UMARC predictions as a function of tunnel velocity for one thrust condition. Note that the method for trimming the rotor had only a slight effect on the stability data for this case. Because all five flexbeams were instrumented, it was possible to determine lag damping in both the rotating and fixed reference frames. Comparison of these damping

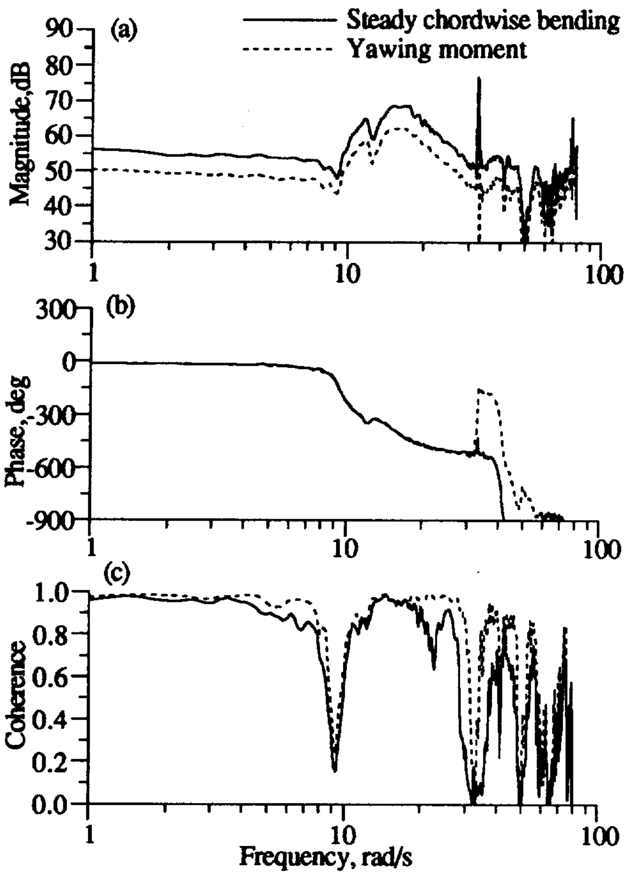

Figure 8. Sample frequency response results from CIFER showing yawing moment and steady flexbeam chordwise-bending responses to longitudinal pitch inputs. a) magnitude, b) phase, c) coherence

determinations, along with detailed discussions of other stability results, are presented in Ref. 3. Both discrete frequency dynamic inputs in hover and constant advance ratio rotor-speed sweeps were utilized to determine blade rotating natural frequencies. The resultant Southwell plot for the rotor, including predictions from UMARC, is presented in Fig. 11. An important aspect of the rotor test was to measure the rotor vibratory loads contributing to fixed-system 5P vibration. Typical flapwise and chordwise 4P, 5P and 6P normalized moments as a function of tunnel velocity (with the rotor trimmed to representative steady operating conditions) are presented in Fig. 12. As expected, the five-bladed SBMR produced low flap moments (Fig. 12a) for these frequencies at high velocities, which should lead to low vertical 5P vibration in an aircraft application.

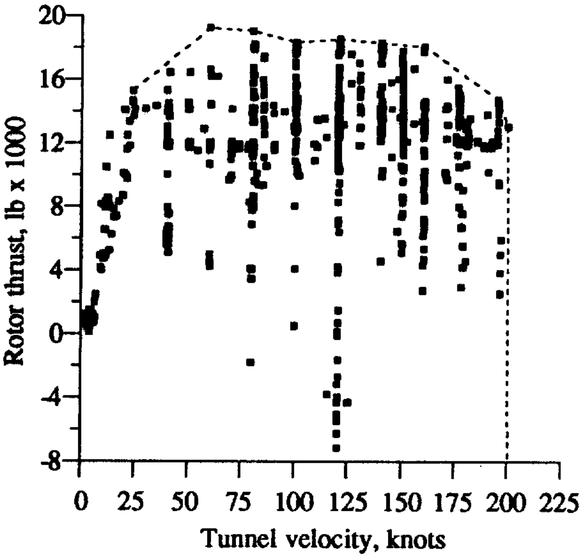

Figure 9. Thrust/velocity envelope for wind tunnel test

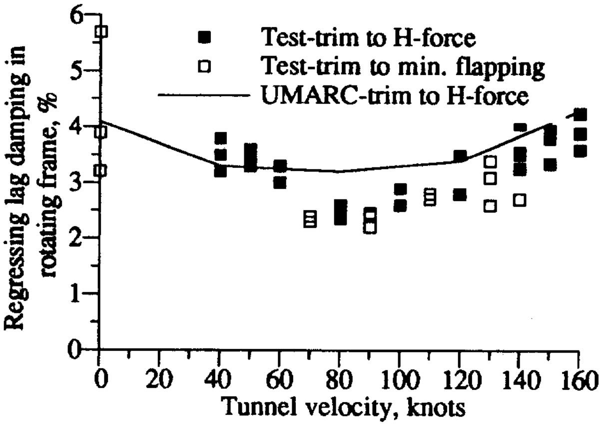

Figure 10. Comparison of measured lag damping with predictions, 315 RPM, 14000 lb thrust

The majority of rotor structure testing consisted of variations in pitch moment at three constant thrust levels and at three shaft angles (-5, 0 and +5 deg) for a number of tunnel speeds. One of the objectives of this testing was to correlate measured rotor loads with predictions. As an example of this, Fig. 13 shows the vibratory flexbeam root chordwise-bending moment versus steady hub pitching moment at 120 knots. Also shown for comparison are the pre-test predictions and the design chordwise bending/pitching moment relationship used for the Comanche rotor design. During testing, the SBMR was found to be quite robust resulting in low accumulated

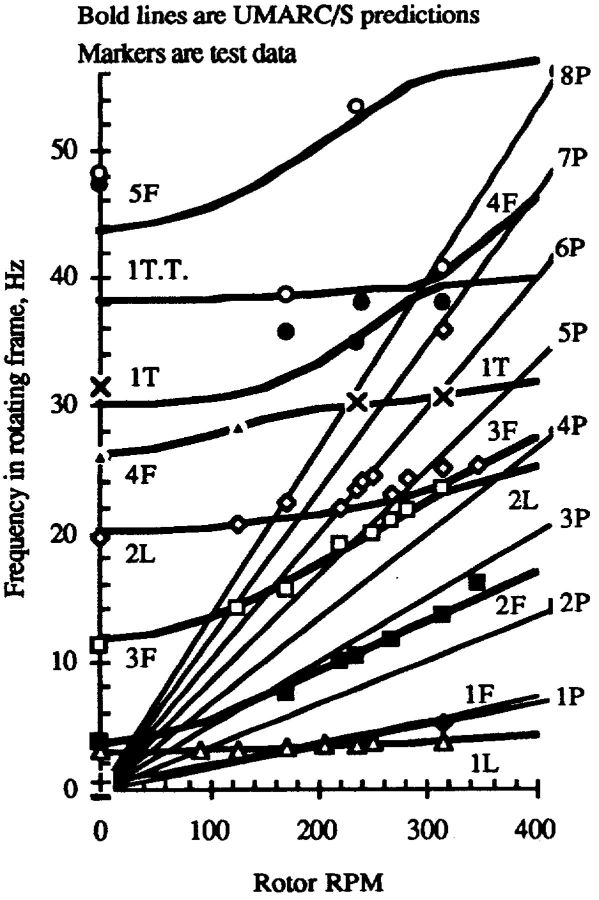

Figure 11. SBMR Southwell diagram, including predictions and measurements

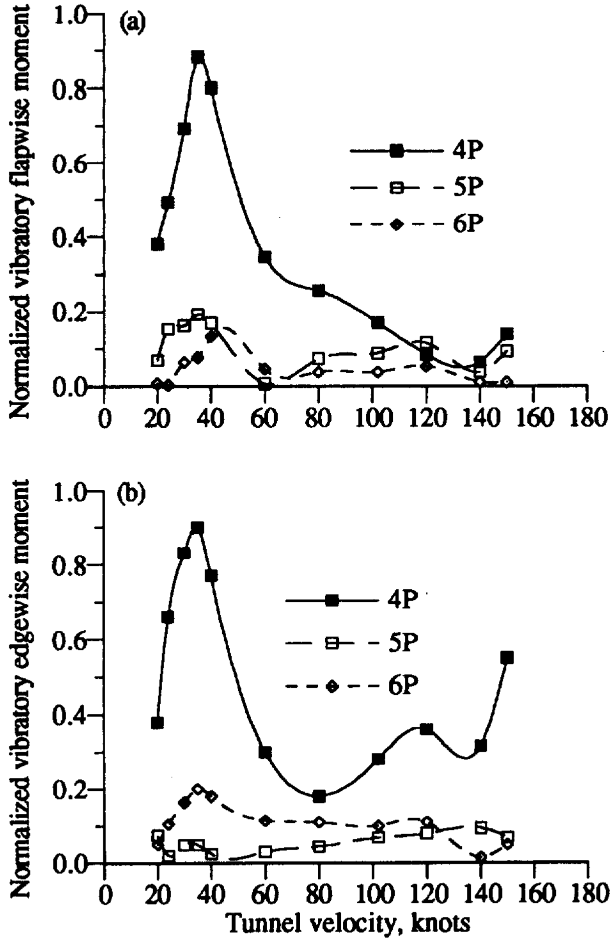

Figure 12. Typical flexbeam root vibratory moments contributing to 5P vibration, 315 RPM, a) flapwise moment and b) chordwise moment

fatigue damage. In general, the testing was not limited by the rotor system, but rather by either RTA power limits at high thrust/negative shaft angle/negative pitch moment conditions, or by RTA shaft bending moment limits at all high pitch moment conditions, whether forward or aft. Another important objective of these tests was to correlate the measured vibratory flap and chord spanwise bending moment distributions with analytical predictions. Figures 14 and 15 show comparisons of these distributions with finite element predictions for a typical high thrust/high pitch moment condition. Correlation is seen to be good for both directions. Another objective of these tests was to establish relationships between measured rotor motions and structural loads, and such operating conditions as thrust and velocity. Several tunnel speed sweeps at constant thrust enabled plots such as that presented in Fig. 16 to be generated for later correlation with analysis.

In the area of handling qualities, control response data were acquired for a large number of different flight conditions. An example of these data for one flight condition, level flight at 85 knots, is presented in Fig. 17. This figure shows both the measured and predicted effects of longitudinal cyclic pitch on hub pitching moment, and is typical of the generally good correlation of the data with GenHel predictions. As discussed earlier, rotor frequency response data were acquired during this test using a combination of chirp-type dynamic excitation and CIFER software. An example of the type of information generated is provided in Fig. 18 for a 100 knot level-flight condition. The figure shows the roll moment response to lateral cyclic pitch input in terms of magnitude, phase, coherence, and input and output power spectra. Also included in this figure are the GenHel predictions for this condition. It should be noted that for this particular test

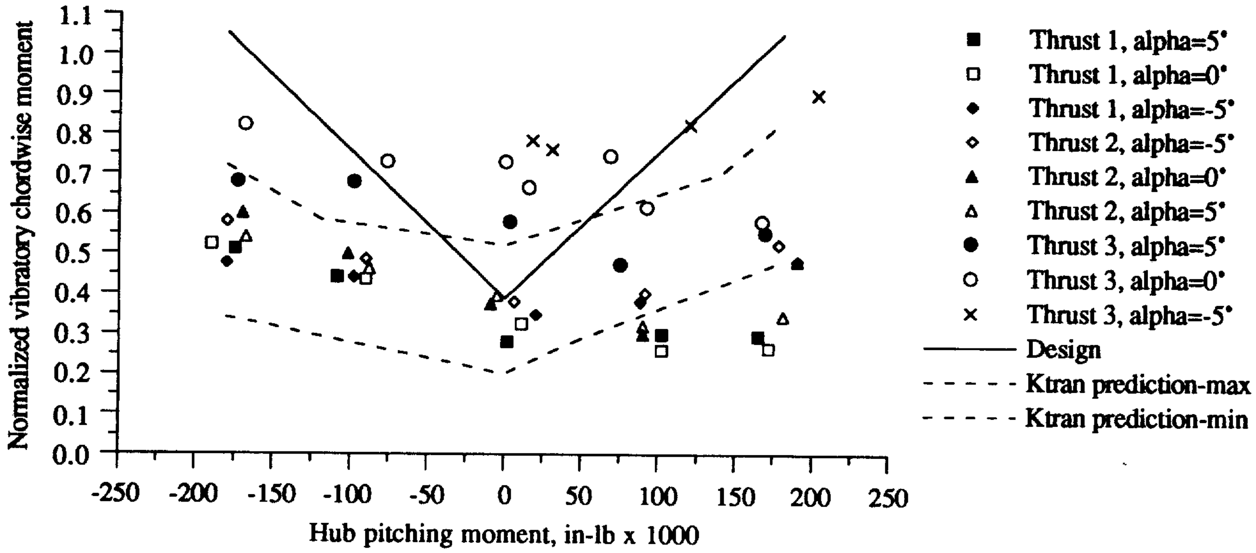

Figure 13. Flexbeam root vibratory chordwise-bending moment versus hub pitching moment, 315 RPM, 120 knots

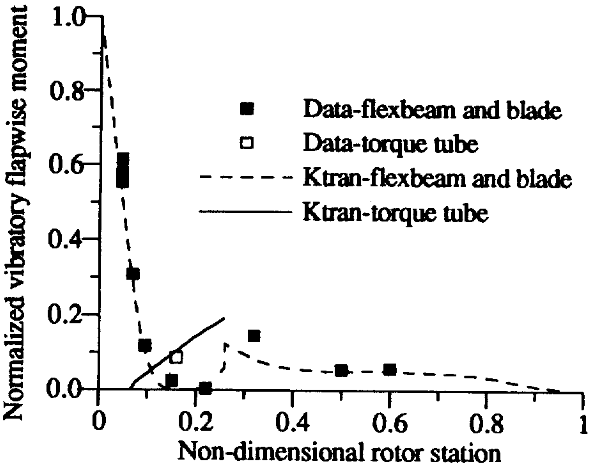

Figure 14. Comparison of spanwise vibratory flap moment with predictions, typical thrust/pitch moment, 315 RPM, 160 knots

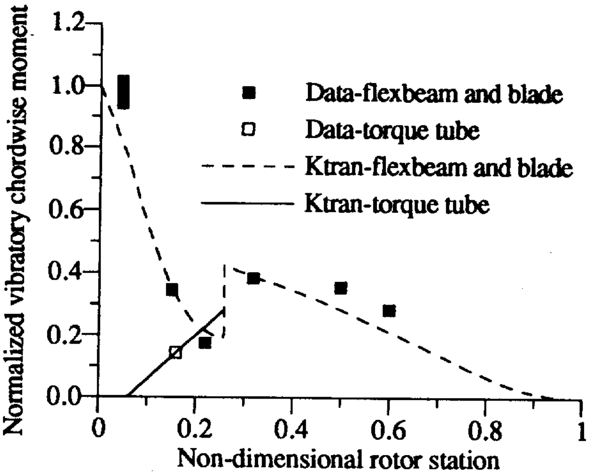

Figure 15. Comparison of spanwise vibratory chord moment with predictions, typical thrust/pitch moment, 315 RPM, 160 knots

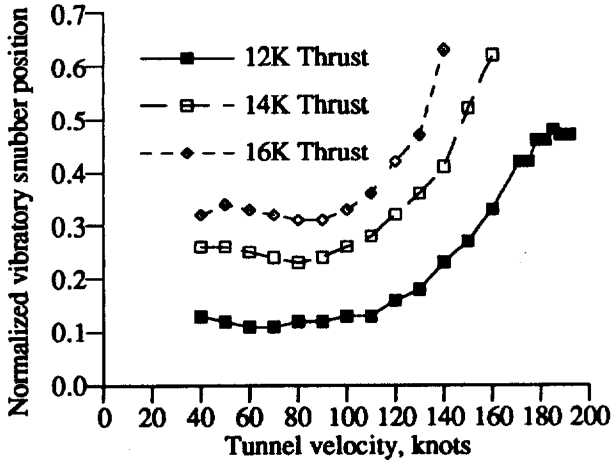

Figure 16. Vibratory snubber/damper position versus tunnel velocity for three thrust levels, 315 RPM

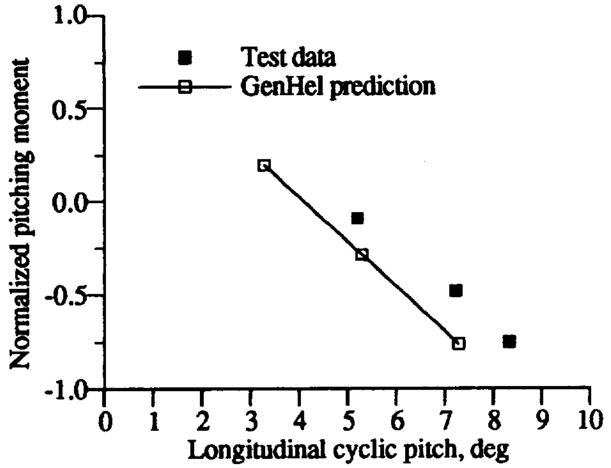

Figure 17. Effect of longitudinal cyclic pitch on hub pitching moment, 315 RPM, 85 knots, 14000 lb thrust

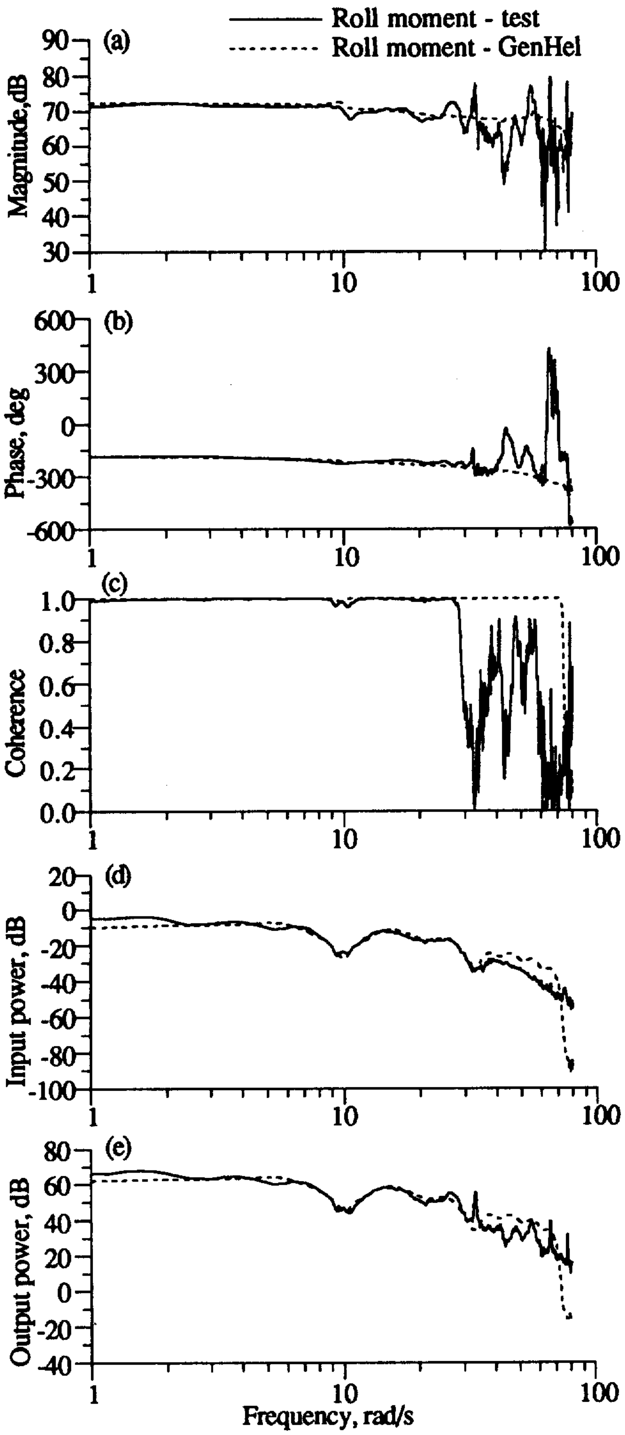

Figure 18. Comparison of CIFER results with GenHel predictions for roll moment response to lateral cyclic pitch input at 315 RPM, 100 knots, 14000 lb thrust. a) magnitude, b) phase, c) coherence, d) input power spectrum, e) output power spectrum

condition, chirp excitation was conducted only up to 5 Hz, explaining the drop-off in coherence of the test data above 30 rad/s (Fig. 18c). In general, the comparison indicates that GenHel adequately predicts the dynamics of the SBMR for this input/output pair. This test technique was also used to help identify rotor system natural frequencies. Figure 19 is the output power spectrum generated from the cosine lag time history when excited with a lateral cyclic pitch input. In addition to the rotor 1P, 2P, and 3P, this figure clearly identifies a number of rotor system lead-lag modes. Table 2 lists the measured frequencies of these modes, along with the predicted frequencies using UMARC. Of particular note is the experimental determination of the 2nd regressing and 2nd progressing of the first lag mode. The collective lag prediction is not accurate because it does not account for the RTA drive train flexibility.

Prior to blades-on aeroperformance tests, aero tare tests were conducted first for the bare hub and then with the torque tubes and flexbeams added. This allowed updating the aerodynamic analysis as the test was in progress to correct for differences between measured and predicted drag. After hub and torque tube aero tares were revised to reflect actual results, rotor performance analysis and test results were in good agreement, as shown in Fig. 20. The original aeroperformance test matrix was expanded to include a test to evaluate the effects of fairing the torque tube/blade joint and the outboard joint bolts. This fairing had a measurable effect on rotor performance, as shown in Fig. 21, and emphasizes the importance of the aerodynamic design of the torque tube in future rotor system development.

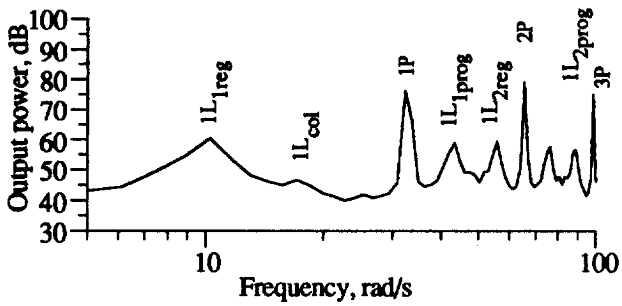

Figure 19. Output power spectrum from cosine lag time history showing identification of lag modes, lateral cyclic pitch excitation

Table 2. Predicted and measured frequencies for first lag mode

Lag Mode	Notation	UMARC Prediction (Hz)	CIFER Identification (Hz)
Collective	$1L_{col}$	3.68	2.7
1st regressing	$1L_{1reg}$	1.58	1.6
1st progressing	$1L_{1prog}$	8.93	8.9
2nd regressing	$1L_{2reg}$	6.83	6.8
2nd progressing	$1L_{2prog}$	14.18	14.2

The acoustics portion of the test addressed two major areas: blade-vortex interaction (BVI) noise, and high-speed impulsive (HSI) noise. During BVI testing, acoustic data were acquired using the ASA to map out the noise field on the advancing side of the rotor. A short ASA survey was performed at numerous shaft angles and tunnel speeds

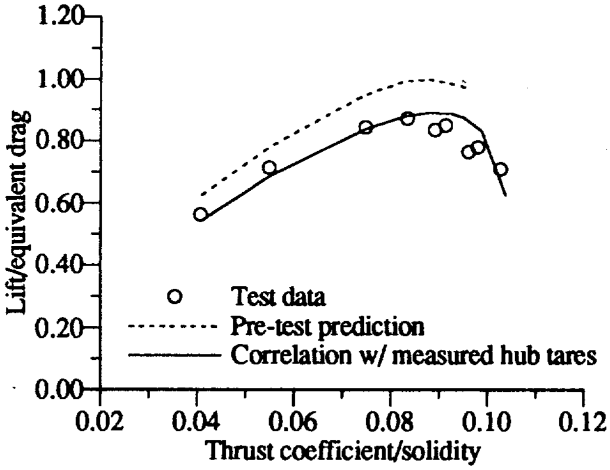

Figure 20. Comparison of rotor performance with predictions, 293 RPM, 150 knots, -5 deg shaft angle

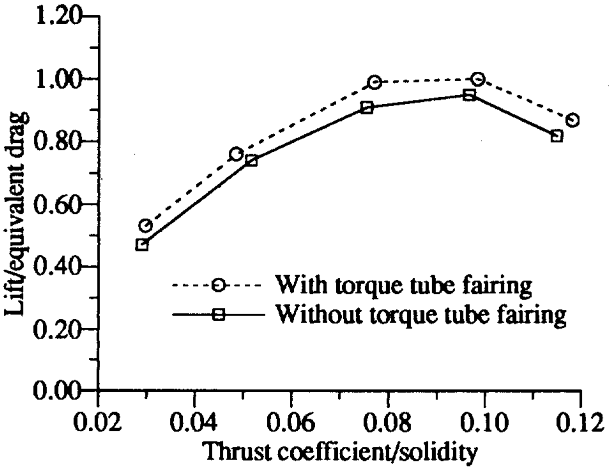

Figure 21. Effect of torque tube fairing on performance, 293 RPM, 120 knots, 0 deg shaft angle

(rotor thrust and RPM were held constant) to determine peak BVI conditions. A detailed mapping was then performed at each of these defined conditions. The ASA enabled a much more complete mapping of the acoustic field than would have been possible using fixed microphones. Unfortunately, full BVI mapping was not possible, due to the high directivity angle of the BVI, coupled with the relative rotor size in the wind tunnel. HSI noise data were acquired at locations in front of the rotor as a function of advancing tip Mach number (up to 0.927). This parameter was set by holding RPM constant and varying tunnel velocity (up to 195 knots). Data trends from this Mach number sweep were consistent with predictions, including the determination of the delocalization Mach number. Future efforts with both the BVI and HSI data will concentrate on comparisons with four-bladed data from other wind tunnel and flight tests.

In the active controls area, 5P open-loop HHC was shown capable of reducing dynamic hub loads and separately, reducing the noise due to BVI. During dynamics testing, airspeeds from 80-160 knots were tested with thrust held constant at 14,000 lb, while BVI testing was done at 60 and 80 knots and 12000 lb thrust. In both phases, testing was conducted with all three modes of control: collective, lateral, and longitudinal. The amplitude and phase angle in each of these modes were varied to determine their optimum values. For dynamics testing, it was found that from 120 to 160 knots, the 5P side force could be reduced up to 30 percent by lateral control at a 90 deg phase angle. For the BVI testing, each condition tested had a particular combination which was most effective at reducing BVI-related noise (defined as acoustic data between 200 and 800 Hz). For the 80 knot case, it was found that the lateral mode at 0.6 deg amplitude and 90 deg phase angle was the most effective. This can be seen in Fig. 22 and 23, which use data from a single microphone located in the BVI noise field. Figure 22 shows the effect of control mode and phase angle for a given amplitude and Fig. 23 shows the effect of amplitude for the optimum lateral control input and phase. Clearly, over 5 dB reduction in BVI noise has been achieved with the controls optimized. (It should be noted, however, that this decrease in BVI-related noise was met with an increase in low frequency noise levels for the first three rotor harmonics.) In addition to the positive 5P HHC results for dynamics and acoustics, 1P collective control was found to substantially reduce 1P normal forces and 1P cyclic control was shown to have the potential to improve rotor performance. All of these active controls results are discussed in more detail in Ref. 4.

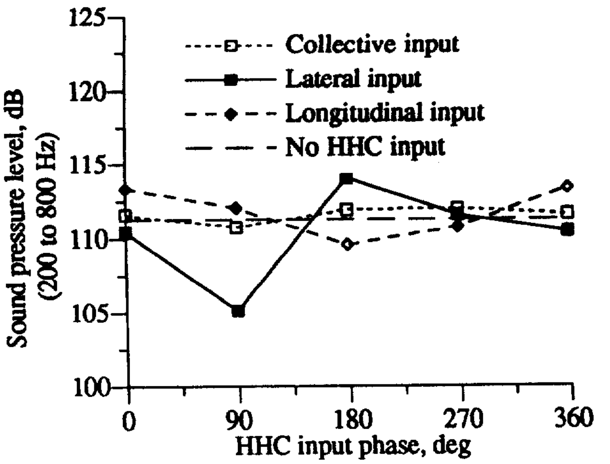

Figure 22. Effect of HHC control mode and phase angle on BVI noise, 293 RPM, 80 knots, 0.3 deg shaft angle, 11900 lb thrust

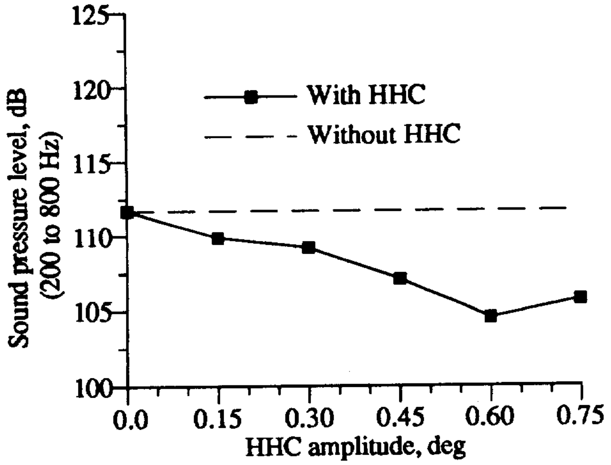

Figure 23. Effect of HHC amplitude on BVI noise with optimum lateral control, 293 RPM, 80 knots, 0.3 deg shaft angle, 11900 lb thrust

In addition to the primary research results listed above, the wind tunnel test provided significant insight in understanding the field operational requirements for a bearingless main rotor of this configuration. Inspection techniques used to support the test were modified and/or deleted based on observed test results. Post-test inspection of rotor hardware provided useful design information about wear patterns and performance of materials at critical interfaces.

Concluding Remarks

A highly successful wind tunnel test of the Sikorsky Bearingless Main Rotor (SBMR) was recently completed in the 40- by 80-foot test section of the NFAC. The test was conducted to obtain information about the SBMR in the areas of dynamics and stability, rotor structures and

loads, handling qualities, aeroperformance and acoustics. Effects of open-loop higher harmonic control on rotor loads, performance and acoustics were also evaluated.
As part of this test program, three new wind tunnel test methodologies were developed. The benefits of these new methodologies, along with the benefits of new NFAC test hardware, can be summarized as follows:

1) A new dynamic calibration methodology has been developed to allow accurate determination of dynamic hub loads using the new rotor balance on the RTA. This capability is a significant addition to the testing capabilities of the NFAC. Further refinement of the calibration methodology is planned.

2) A new on-line fatigue monitoring system has been developed which improves the efficiency of rotorcraft testing. Specific benefits include allowing real-time judgements concerning fatigue damage accumulation to be performed, allowing multiple parameters to safely exceed their endurance limits simultaneously, and reducing the workload of test personnel in preparation for the next test run.

3) A new frequency response test technique has been adapted for use in wind tunnel testing. This technique offers an excellent and time-efficient way to obtain an understanding of rotor dynamics, and also to obtain a large frequency domain database for model development and validation.

4) Testing capabilities in the NFAC have been greatly enhanced with the addition of new test hardware. This hardware includes the Steady/Dynamic Rotor Balance, two new rotor control consoles, and the Acoustic Survey Apparatus (ASA).

During this program, all significant test objectives were attained, including the generation of a large database for use in correlating with design analyses. Specific results discussed in this paper include the following:

5) In the dynamics area, rotor stability trends and rotor natural frequencies were generally close to predictions. The SBMR demonstrated positive stability in the regressive lag mode at all conditions tested in the wind tunnel. In addition, the rotor produced low flap moments at 4, 5 and 6 per rev frequencies at high velocities, which should lead to low vertical 5P vibration in an aircraft application.

6) During rotor structure testing, the SBMR was found to be quite robust resulting in low accumulated fatigue damage. In general, the testing was not limited by the rotor system, but rather by either RTA power or shaft bending-moment limits. Spanwise bending moments were found to correlate well with predictions in both flapwise and chordwise directions.

7) For handling qualities, generally good correlation of control derivative data with predictions was found. Rotor frequency response methods were used to provide a large database for comparison with predictions. Generally good correlation was found in the areas of control system modeling and rotor system natural frequency identification.

8) In the aeroperformance area, rotor performance analysis and test results were in good agreement after accounting for actual hub and torque tube tares. Fairing of the torque tube/blade joint had a measurable effect on rotor performance.

9) For acoustics, the ASA enabled a much more complete mapping of the acoustic field than would have been possible using fixed microphones. Unfortunately, full BVI mapping was not possible, due to the high directivity angle of the BVI, coupled with the relative rotor size in the tunnel. High speed impulsive noise trends, however, were generally consistent with predictions, including the determination of the delocalization Mach number.

10) In the active controls area, 5P open-loop HHC was shown capable of reducing dynamic hub loads and separately, reducing the noise due to BVI. In addition, 1P collective control was found to substantially reduce 1P normal forces and 1P cyclic control was shown to have the potential to improve rotor performance.

Acknowledgements

We would like to acknowledge the significant efforts of both the NASA and Sikorsky test teams in the conduct of this experimental investigation. From initial discussions to test completion, the success of this joint program is directly attributable to the dedication and commitment of all team members.

We would also like to acknowledge the support provided by the Army Aeroflightdynamics Directorate at Ames Research Center. Without their efforts, the new frequency response methodology would not have been implemented.

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