A Full-Scale Test of the McDonnell Douglas Advanced Bearingless Rotor In the NASA Ames 40- by 80-Ft Wind Tunnel

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Abstract

The McDonnell Douglas Helicopter Company and NASA have tested a full-scale, advanced bearingless rotor in the 40- by 80- foot wind tunnel at Ames Research Center. The project goals were to obtain performance, loads, stability, and acoustics data for a state-of-the-art rotor system over a wide range of operating conditions, and also to measure the effects of open-loop Higher Harmonic Control (HHC) inputs on these attributes. The five-bladed, bearingless rotor was a pre-production version of the MD Explorer rotor system. The nominal "1g" thrust of the rotor was taken to be 5800 lbs for this test. The rotor was successfully tested over a wide range of operating conditions including speeds of over 200 knots, an advance ratio of 0.49, and thrusts of over 10,000 lbs, a C_T/σ of 0.13. The HHC test conditions included a transition flight case, a blade-vortex-interaction case, and a typical cruise flight case. The data are now part of the Rotor Data Reduction System (RDRS) database at Ames and the ASAP database at McDonnell Douglas.

Introduction

Advanced rotor developement has been a continuing Independent Research and Developement (IR&D) activity at McDonnell Douglas Helicopter Company for the last decade. Noteworthy projects include the Composite Flexbeam Tailrotor (CFTR) for the AH-64 (Ref. 1), and the highly successful Helicopter Advanced Rotor Program, or HARP, (Ref. 2). The HARP was a four-bladed bearingless rotor that was flown on the McDonnell Douglas MD500 in 1985. This rotor, like the Bell 680 , was characterized by single centrifugally loaded flexbeam; a torsionally stiff pitchcase that transfers blade control moments from the pitch link to the blade; and an elastomeric snubber/damper assembly that reacts the shear load due to the pitch inputs, helps control the deflection of the flexbeam, and also provides lead-lag damping. This design concept is now widely accepted as the standard in modern rotor design, Other flying examples of this rotor concept include Bell's Adanced Lightweight Rotor and 4BW Cobra (Ref. 3), the MBB BO-108 (Ref. 4), and, newest to fly, the McDonnell Douglas MD Explorer. This same rotor concept is also planned for use on the RAH-66 Comanche.

After the completion of the HARP flight program, advanced rotor development activities continued on two fronts at McDonnell Douglas. The first was a series of ongoing IR&D projects directed at improving analytical capabilities in the areas of performance, loads and stability, acoustics, and flexbeam design and optimization. The second front consisted of the product directed research and developement work for the McDonnell Douglas/Bell Helicopter Textron LH proposal and for the McDonnell Douglas MD Explorer.

Bearingless rotor technology has also long been of interest to NASA. The first full-scale wind tunnel test of a bearingless rotor was conducted by NASA Ames in the early 1980's (Ref. 5). The rotor tested, the BO-105 BMR, was a four-bladed, damperless design that used two back-to-back flexbeams per arm for blade retention and a torsionally-stiff torque tube to transmit pitch inputs to the blade. This rotor was successfully tested to over 165 kts. This damperless rotor was, however, subject to structural and dynamic difficulties that are greatly reduced in the modern bearingless rotor with its snubber/damper and external pitchcase. NASA has maintained an active research program

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directed toward furthering bearingless rotor technology.

In 1989, NASA and McDonnell Douglas recognized that the test data needed to validate new bearingless rotor analytical capabilities was lacking. A joint wind tunnel test program was planned to provide this data. The project was named "McDonnell Douglas Advanced Rotor Technology", or MDART. The program was governed by a Memorandum of Understanding (MOU) between NASA and McDonnell Douglas.

The project goals were to obtain performance, loads, stability, and acoustics data for a state-of-the-art rotor system over a wide range of operating conditions, and also to measure the effects of open-loop Higher Harmonic Control (HHC) inputs on these attributes. High speed and high thrust conditions, where blade stall is important, were of particular interest. Under the MOU, McDonnell Douglas was to provide an instrumented bearingless rotor and test stand; NASA was to provide the wind tunnel and the data acquisition hardware and software. The MOU allows NASA to release the data to domestic third parties beginning one year after the completion of the test.

Because the existing rotor test stand at McDonnell Douglas was well suited for a HARP-sized rotor, the original plan was to test a "Super Harp". This rotor would have incorporated the aerodynamic and structural improvements that McDonnell Douglas has developed since the orignal HARP was designed. The problem with this plan was that it would have been very expensive due to the design, tooling, and fatigue testing costs required to produce a new, one-of-a-kind rotor. There was a much better, and less expensive, way to achieve the research goals. It was found that by modifying the test stand in key areas, it could accomodate the larger MD Explorer rotor that was already in developement. This state-of-the-art bearingless rotor already had the same technological improvements relative to the HARP that were envisioned for the Super HARP. The Explorer project plan also called for a pre-production rotor to be built and whirl tested, but not flown. By using this rotor the MDART project was able to achieve the same test objectives at lower cost, and also obtain data that is directly relevant to a key McDonnell Douglas product. This, along with the teaming between NASA and McDonnell Douglas, gave the MDART project budget a great deal of leverage toward satisfiying the needs of all of the parties involved. The test remained, however, a research test, not an MD Explorer development and qualification effort.

This paper describes the rotor, test equipment, and instrumentation used for the test. The test procedures used are discussed and the scope of the test accomplishments are shown. Finally, samples of the various types of data acquired are presented.

Hardware

The Rotor

The MDART rotor is a pre-production version of the MD Explorer main rotor. A schematic of the rotor head is shown in Fig. 1. This five-bladed, bearingless rotor system has a 16.9 ft radius. The nominal "1g" thrust for the rotor was taken to be 5800 lbs for the MDART test. The key components of the rotor are the flexbeams, the pitchcases, the blades, and the snubber/damper assemblies. The leading and trailing legs of the flexbeams mount to the metalic hub in an over/under arrangement.

The blades and flexbeams are made of fiberglass. The pitchcase, for which high stiffness is essential, is made of graphite. The snubber damper assembly consists of upper and lower elastomeric dampers, each of which attaches to the pitchcase and to the metal snubber. The snubber is attached to the hub via an elastomeric bearing. This bearing allows pitch and flap angular motions of the pitchcase relative to the hub. The snubber restricts the vertical displacement of the pitchcase root. This, together with the high pitchcase flapping stiffness, forces the virtual flapping hinge to be very near the snubber location for any flight condition. The high pitchcase chordwise stiffness, the

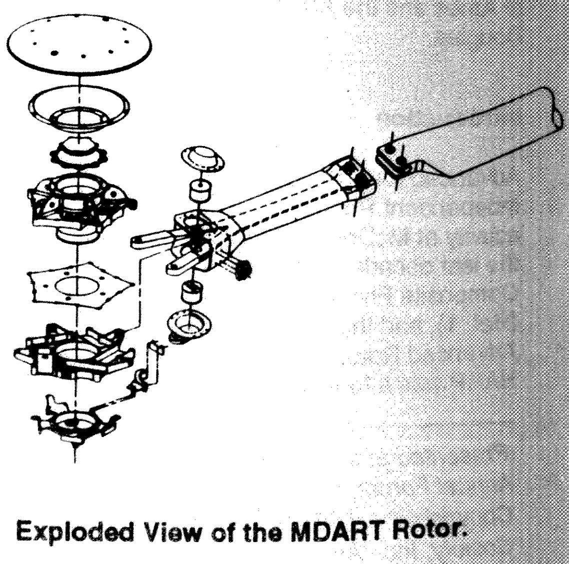

Fig. 1 Exploded View of the MDART Rotor.

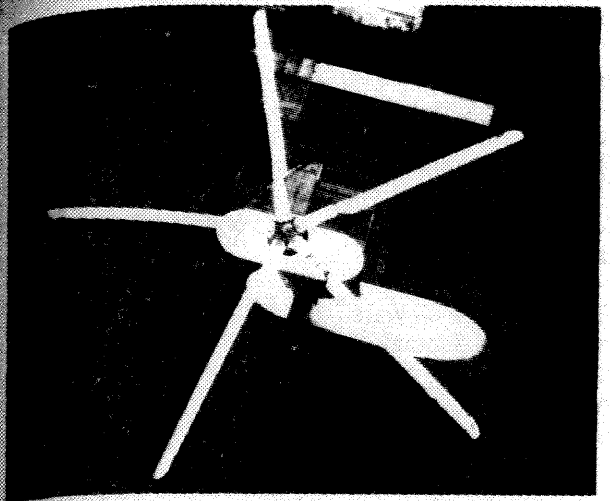

Fig. 2 MDART Rotor Seen From Above.

carefully tailored chordwise stiffness of the flexbeam, and the relative softness of the elastomeric damper combine to yield a large amount of damper shearing motion per degree of blade lead-lag deflection. The damping force that results from shearing the high-loss-factor elastomer effectively stabilizes the rotor.

The flexbeam geometry and stiffness were tailored to allow the required blade flap, lag, and pitch motions while keeping the first flapping frequency at approximately 1.05/rev. Obtaining a flap frequency this low from a bearingless rotor is a challenging design problem that was solved with optimization techniques (Ref. 6). The result is a rotor that has high agility and crisp handling qualities without the large control cross-couplings, high gust sensitivities, and high vibration levels that are often associated with stiffer rotors.

The rotor is shown in Fig. 2. The blades use the HH06 airfoil section inboard and the HH10 airfoil outboard. The blade tips have a parabolic leading edge sweep for aerodynamic and acoustic benefits.

More information on the rotor and its developement and testing prior to the wind tunnel test are given in Ref. 7.

The Test Stand

Figure 3 shows the rotor and test stand installed in the wind tunnel. The MDART rotor was mounted to a static mast. The rotating drive shaft passed through the static mast and applied the driving torque to the top of the hub. The advantage of this system is that the rotor flight loads are taken as static loads in the mast rather than as fatiguing 1/rev loads in the drive shaft. The static mast was mounted to a five-component rotor balance. A vertical stand strut runs downward from the balance housing to the top of the transmission. The transmission and a 1500 HP electric motor are mounted to a "sled". The balance housing, controls and the static mast were enclosed in the upper fairing. The sled, motor and transmission are enclosed in the large lower fairing. An airfoil-shaped fairing surrounds the vertical stand strut. Cross-arms extend from the base of the vertical strut, and another arm extends aftward from the end of the sled. These arms mount the test stand to the wind tunnel supports.

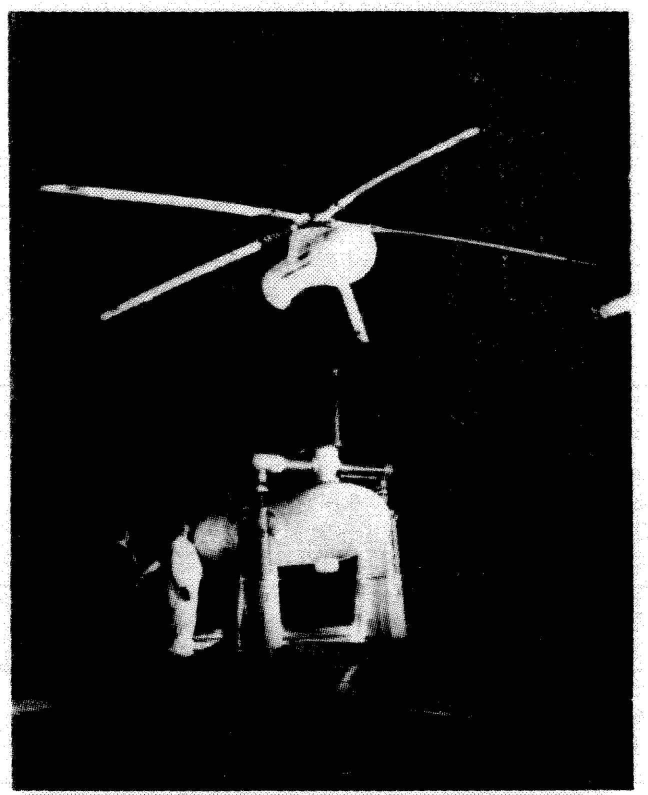

Fig. 3 The MDART Rotor and Test Stand Installed in the 40- by 80-ft Test Section.

The swashplate was driven directly by three hydrualic actuators spaced 120 degs apart in azimuth; no mechanical control mixing was used. Each actuator was fed by a hydrualic manifold that restricted the rate of large control motions, for safety, but still allowed high rate, small amplitude inputs. This high rate capability was used to oscillate the swashplate at the nonrotating lead-lag frequency for stability testing, and at 5/rev for HHC testing.

The Rotor Control Console, RCC, electronically converted the collective and cyclic inputs from the operator into the appropriate individual actuator displacements. The operator flew the rotor by monitoring the primary flap bending signal. This signal was resolved into sine and cosine components and displayed as circular trace. When this trace was centered on the display, the 1/rev flapping was zero. A backup flap bending signal and the rotor balance pitch and roll signals were also available to guide the rotor operator in case the primary signal failed.

Instrumentation

The MDART rotor and control system were extensively instrumented. A slip ring was used to transmit the forty-four analog channels of rotating instrumentation. The blade flap bending moment was measured at six radial stations, the chord bending moment at four stations, and the torsion moment at three stations. The trim tab bending moment was also measured. The pitchcase flap, chord, and torsion moments were measured at one location each. The flexbeam had one flap, one chord, and two torsion moment measurements. Single-strain measurements were also made at twelve key locations on the flexbeam.

All of the above instruments were installed on the number one arm of the rotor. The flap, chord, and torsion moments at one location each were also measured on the flexbeam on arm number two. These measurements served as back-ups for the safety-critical gages on the first flexbeam, allowed a data consistency check between two blades, and allowed the interblade phasing to be determined for rotor dynamic modes.

The blade number one flap angle, pitch link load and the swashplate drive scissors bending moments were also measured. The flap angle transducer failed early in the test, though, and the pitch link measurement was not completely reliable.

The shearing displacement of the damper was measured, as were the vertical and horizontal forces at the snubber support. These allow the effective spring and damping properties of the damper to be determined at any flight condition. The damper is non-linear, with its spring and damping characteristics depending on the strain level of the elastomer, its temperature, and the frequencies of the motion.

The five-component rotor balance measured the net rotor forces and moments at a location 37 inches below the rotor plane. The lateral and longitudinal bending moments in the static mast were also measured. The drive shaft had dual torque gages.

Bending bridges on the non-rotating swashplate were used to measure the three actuator loads. Each actuator also had dual LVDT's to measure its motion. These measurements were then used to define the collective and cyclic pitch control inputs, both for use as test data and for the control console feedback circuits.

Five microphones were installed in the test section to measure the acoustic data. The microphones were placed upstream of the rotor, on the advancing side, to measure the high-speed impulsive and blade-vortex-interaction noise produced by the MDART rotor.

Critical measurements were monitored real-time on oscillographs, oscilloscopes, and the NASA Bar Chart Monitor. The steady and oscillatory monitoring limits for the parameters were determined by a combination of conservative analysis and structural test.

The Wind Tunnel

The MDART test was conducted in the 40- by 80-Foot Wind Tunnel at Ames Research Center. Although the wind tunnel is named the 40- by 80-Foot, the actual test-section dimensions are 39 feet high and 79 feet wide. This is because of an additional six-inch acoustic lining inside the wind-tunnel wall panels. The closed circuit, single return wind tunnel is driven by six 40 foot diameter fans, which are powered by six 22,500 horsepower motors. The maximum airspeed in the test section is 300 kt.

The MDART test sled was mounted in the tunnel on two 8-foot main struts and a single telescoping tail strut. The tail-strut height can be adjusted remotely to set the model pitch angle during a test. The main and tail struts were supported by a turntable mounted on the wind-tunnel floating frame. The wind tunnel scales system was connected to the floating frame to measure six components of forces and moments transmitted from the model. In addition, the floating frame was engaged to four hydraulic dampers to reduce the potential risk of ground resonance in rotor test. During the test, the rotor condition was closely monitored in the control room through four video cameras.

Data Acquisiton

The Rotor Data Reduction System (RDRS) was developed at Ames to facilitate the reduction of large nts of rotor data. The software system reads the generated by the wind-tunnel data acquisiton m, reduces the data, and provides tabulated data phical plots. The wind-tunnel measurements sted of static and dynamic data. The static data acquired at 800 Hz per channel for approximatley volutions. The dynamic data were acquired at 64 les per revolution for 10 revolutions.

onnell Douglas has installed the test data in its database management system. ASAP is a ietary system that is build on the commercially able PV-Wave programming language. ASAP s the user great flexibility in selecting, pulating, and plotting data items, and uses ive, "almost like English", commands.

Test Procedures

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the test stand was installed in the test section, efore the blades were installed, a set of check s were applied to the rotor balance. The results ved large interactions between the balance ing moment and axial force (drag) channels, and een the the roll moment and side force channels. interactions were very different from what the lab ration and previous test experience with the nce had found. These interactions were tually traced back to the flexible coupling in the train. This coupling was a new part that replaced fter coupling that had been used in previous tests. higher power needs of the larger MDART rotor ssitated a stronger, and therefore stiffer, coupling. stiffness of the new coupling was high enough that erted significant loads on the balance as it cted slightly with mast bending.

problem was solved by recalibrating the rotor nce in place. The forces between the coupling the balance were then accounted for implicitly. ng this calibration the loads were applied by hts and hydrualic actuators hung from the head crane. A load cell at the rotor hub was used ccurately measure the input force, and the cables transmitted the load to the hub were carefully hed to minimize cross coupling. A least squares fit e input loads to the balance output was then ormed. When this calibration was then applied to input data the residual errors were somewhat se than for the original laboratory calibration without the drive coupling installed, but the results were acceptable.

After the rotor balance was proven to be working correctly, a stand shake test conducted. The shake test was needed primarily to determine the low frequency dynamic properties of the installed test stand. A frequency range of 0-16 Hz was appropriate for this purpose. The stand frequencies and damping values were needed for use in the coupled rotor-body stability analysis of the system. Three configurations were tested: with the wind tunnel scales system locked out; with the wind tunnel scales active but without the scales dampers installed; and with the scales active and the scales dampers installed. The rotor was not installed during the shake test, but it was simulated by a hub weight equal to half the rotor mass. For each configuration, lateral and longitudinal shakes were used. A random force was input to the hub by a hydraulic actuator hung from the crane. The primary data were taken by hub inplane accelerometers. The transfer functions between the measured input forces and the hub accelerations were then used to determine the stand properties. The stability analysis showed the MDART rotor stable for all of the configurations tested. The configuration with the scales active and the dampers installed was used for the rotor test.

The shake test was also used as a "poor man's" dynamic calibration of the balance. For this purpose lateral, longitudinal, and three different vertical shakes were used. One of the vertical inputs was at the hub center, for a pure vertical load input. The other two vertical inputs were offset from the centerline so that a combined vertical force and pitching moment or vertical force with rolling moment was applied. The frequency range for these tests was 0-64 Hz. This data is sufficient to determine the 5/rev dynamic amplification factors for the balance. A sample result is shown in Fig. 4. This plot shows the balance vertical response to vertical force input at the hub center. The magnitude of the transfer function at 33.6 Hz shows that the 5/rev vertical loads measured by the balance are actually 88% of the true rotor 5/rev vertical loads. While this data is very useful when evaluating the fixed system rotor dynamic loads, it suffers from one problem: all of the shake tests were conducted at with rotor shaft vertical, while the rotor test was conducted over a range of shaft angles. The amplification factors will change somewhat with shaft angle.

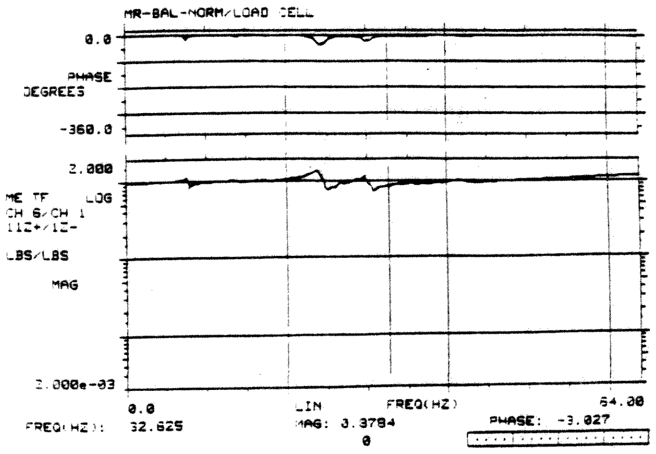

Fig. 4 Sample Shake Test Result; Balance Vertical Response to Vertical Force.

Measuring the needed tares was the final step before the actual rotor testing could begin. Three types of tares were required: rotor weight tares, shaft rotation tares, and hub aerodynamic tares. The rotor weight tare simply accounts for the change in the rotor balance outputs, from the zero point, as the test stand angle is changed.

The shaft rotation tare was needed to account for a slight eccentricity in the drive shaft. This eccentricity was evidenced as small rotor balance 1/rev side and axial forces when the shaft was turning. These forces average out during a test point with the shaft spinning, but not during the nonrotating pre-test zero point. This introduces a bias to the measured rotor balance forces. The shaft rotation tare needed to correct this bias was determined by running the bare hub at the normal rotor speed and measuring the rotor balance outputs for this case. As the actual hub forces and moments must be zero for this condition, the measured values are the tares that need to be subtracted from all of the rotor data.

The hub aerodynamic tares were used so that the performance of the rotor blades alone could be separated from the performance of the complete rotor. The tares themselves are the rotor balance loads and the shaft torque as functions of shaft angle and wind tunnel speed. To measure these tares, the hub, flexbeams, and pitch cases were spun at the normal rotor speed and the wind tunnel speed was brought up in steps to 190 kts. At each speed the rotor forces were measured over a range of shaft angles. The results, in the form of either simple functions or look-up tables, were later applied to the forward flight performance data. All of the rotor performance data are available both with and without the aero tares applied.

Hover Testing

Hover testing was conducted with the large test section overhead doors open to reduce recirculation. The pre-test zero point was taken with the number one blade over the tail and with 10 degrees of collective pitch. The MDART flexbeams were designed to have no elastic twist when the blade pitch was 10 degrees. The rotor was started with the collective pitch set at 4 degs, and with zero cyclic pitch. The rotor speed was then increased in steps to the normal operating speed, 392 rpm. The rotor operator would use cyclic inputs as needed to trim the 1/rev flapping to zero. During the initial runs, the rotor track and balance were adjusted as necessary, and rotor stability testing was conducted at the intermediate rotor speeds to ensure that it was safe to continue. After reaching full rotor speed a hover reference data point was taken on each run. These reference points were test conditions for which data were acquired on every run. The data for these points were compared with the data from previous runs to identify any instrumentation or other problems that may have come up. These reference points provided a valuable data quality check.

The shaft was then tilted forward to -10 degrees to help reduce the recirculation before taking further data points. Hover data included performance, blade loads, acoustics, and stability as functions of rotor speed and collective pitch. The rotor control power in hover was also determined by measuring the the hub moment due to cyclic pitch inputs.

Even with recirculation reduction measures mentioned above, the flow in the test section was very unsteady at high thrust in hover. Oscillatory loads were quite large at 10 degrees collective pitch, the highest pitch run in hover.

To obtain stability data the swashplate was used to excite the blade fundamental lead-lag mode. This was done by oscillating the swashplate in an advancing nutation at the regressing lead-lag frequency. The flexbeam chord bending moment and the damper displacement were monitored as the excitation level was increased. When these responses reached the desired levels, or when any other load reached its limits, the excitation was cut-off. The ensuing transient decays were recorded and analyzed real-time using the moving block technique. The stability trends were monitored to ensure that it was safe to proceed to next test condition.

rward Flight Testing

r forward flight runs the wind tunnel was started with rotor shaft angle 10 degrees forward and with 6 grees collective. The wind speed was then reased to give an advance ratio of 0.15, about 62 . The rotor operator would continually make cyclic uts to keep the 1/rev flapping trimmed to zero. On ch run, a forward flight reference data point was n taken at this speed. As with the hover reference ta point, comparison of these data from run-to-run s used as a data quality check.

bility testing was conducted as part of any pansion of the speed, thrust, and shaft angle velope. The stability test proceedures in forward ht were identical to those used in hover. While the lk of the forward flight data were taken at a hover tip ach number of 0.623 and with the cyclic flapping nimized, the effects changing tip Mach number and cyclic flapping were investigated.

oustic data were acquired for a wide range of rward flight test conditions. Partial power descents re simulated at various shaft angles to investigate ade-vortex-interactions.

r HHC testing the control console was used to input rev collective, lateral cyclic, and longitudinal cyclic tch inputs to the rotor. For each input axis the HHC ase was swept from 0 to 315 degrees in 45 degree ps. For each phase angle an amplitude of between 25 and 0.5 degrees pitch input was used. The dimentary open-loop control system did not allow a nstant input amplitude to be maintained during the ase sweeps.

Accomplishments

he MDART test was the first full-scale wind tunnel st of a modern, five-bladed, bearingless rotor. The DART test envelope, as a function of advance ratio nd C_t/σ, is shown in Figure 5. The highest thrust oints correspond to over 1.7 times the nominal thrust f the rotor. The maximum speed tested was 201.3 ts, the highest yet attained by a helicopter rotor in the 0- by 80-ft wind tunnel. A wide range of shaft angles as tested within this thrust-speed envelope.

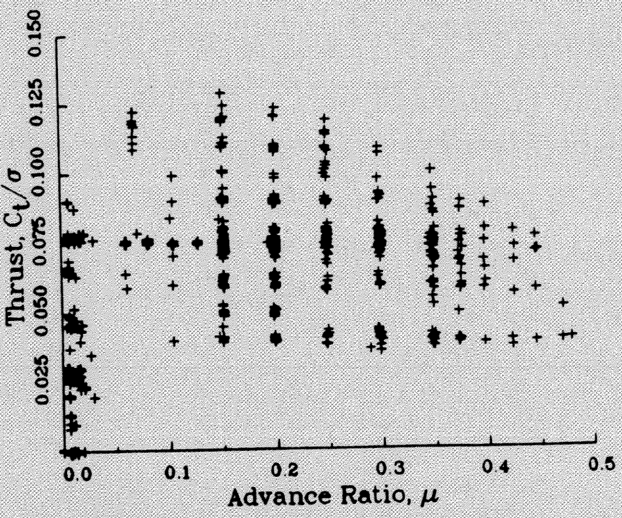

Fig. 5 MDART Test Envelope.

he rotor itself behaved very well throughout the test. fter the blades were tracked in hover, using pitch link adjustments only, no further tracking adjustments were required. The track was virtually perfect up to 124 kts, and then began to split slightly, but not enought to warrant making any tab adjustments.

Most of the test data were acquired with the 1/rev flapping zeroed, the standard wind tunnel trim technique. In addition, lateral and longitudinal cyclic pitch sweeps were performed in hover and at 0.05 advance ratio increments in a 1g speed sweep up to 155 kts (an advance ratio of 0.375). These data define the control power of the rotor and show the effects of 1/rev flapping on performance and loads.

The bulk of the forward flight data were taken with the hover tip Mach number held constant at 0.62. Hover tip Mach number sweeps were also conducted at 0.35 advance ratio for a range of thrusts. A wide range acoustic data were acquired, with special emphasis on high speed impulsive noise and blade-vortex-interaction conditions.

A comprehensive survey of the rotor's lead-lag stability was conducted. The stability test envelope is shown in Fig. 6. Stability data were acquired to the limits of the thrusts tested, and up to 0.45 advance ratio.

The first use of Higher Harmonic Control on a bearingless rotor was a noteworthy MDART achievement. Open loop Higher Harmonic Control effects were investigated at three flight conditions: moderate speed cruising flight at an advance ratio of 0.30; a simulated partial power descent at 82 kts with the shaft angle selected for maximum blade-vortex-

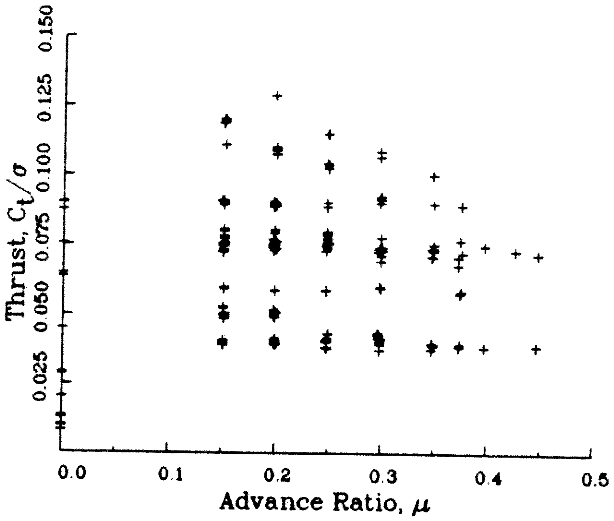

Fig. 6 Stability Test Envelope.

interactions; and a simulated landing flare at 30 kts with the shaft angle selected for high vibration. For each of these conditions the thrust was 5800 lbs. Performance, loads and acoustic data were acquired with the HHC operating.

Sample Data

Figures 7 and 8 show samples of the rotor performance data acquired during the MDART test. These data are for an advance ratio of 0.30, and the rotor hub aerodynamic tares have been removed from the data. The maximum scatter in the rotor lift, drag, and torque measurements was found to be similar to that experience in other large-scale rotor tests in the 40- by 80-ft (Ref. 8)

Figure 9 presents a sample of the dynamic rotor balance loads data obtained. The rotor balance 5/rev vertical loads are plotted vs. advance ratio for a nominal 1g level flight speed sweep. The shake test results (Fig. 4) indicate that these loads should be increased by a factor of 1.14 to get the true rotor 5/rev vertical hub load. Including this factor, the 5/rev vertical hub load is 4% or less of the steady thrust, up to 155 kts.

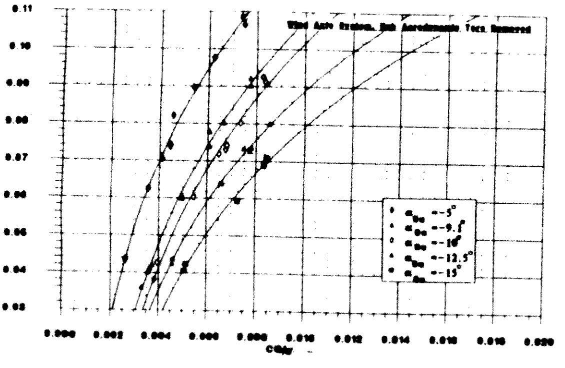

Fig. 7 Rotor Lift vs. Torque at Advance Ratio of 0.30, Rotor Hub Tares Removed.

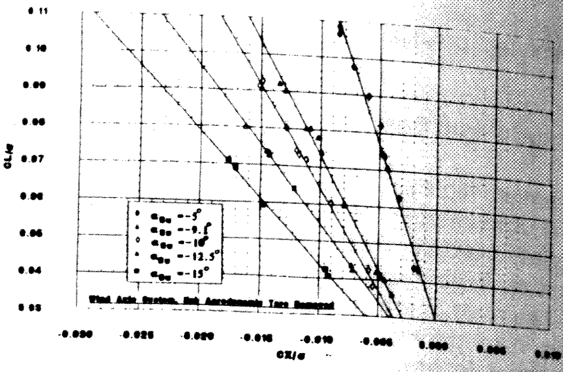

Fig. 8 Rotor Lift vs. Propulsive Force at Advance Ratio of 0.30, Rotor Hub Tares Removed.

Sample blade loads are shown in Figs. 10 and 11. The flap bending harmonics that can contribute to fixed system vibration are shown in Fig. 10. The data are at the 34% radial station, and for a nominal 1g level flight speed sweep. The distribution of flap bending loads over the blade and pitchcase is shown in Figure 11. The data are for an advance ratio of 0.35. Both the measured steady and 1/2 peak-to-peak loads are shown, along with the predicted values from the McDonnell Douglas DART analysis. The blade and pitchcase are joined at the 20% radial station.

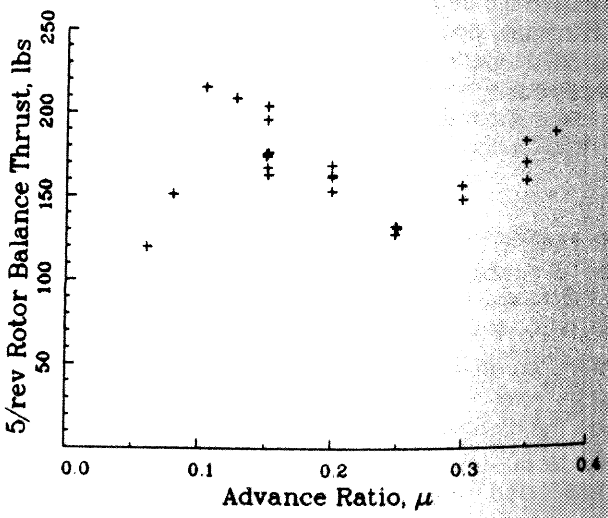

Fig. 9 Rotor Balance 5/rev Oscillatory Thrust vs. Advance Ratio at 5800 lbs Steady Thrust.

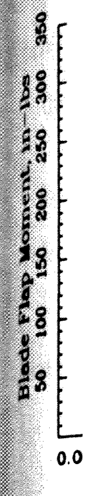

Fig. 10
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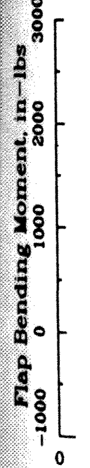

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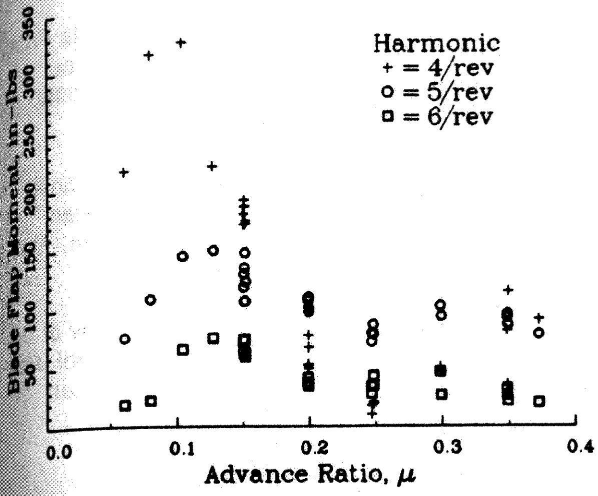

Fig. 10 **Blade Flap Bending Moment at the 34% Radial Station vs Advance Ratio; Contributors to Fixed System Vibration Shown.**

The lead-lag stability data acquired for the 1g speed sweep are shown in Fig. 12. The results obtained from both the damper motion and the flexbeam chord bending are shown. Reference 9 discusses the MDART stability data in more detail.

Finally, a sample result with HHC is shown in Fig. 13. The effect of HHC inputs on the rotor balance 5/rev pitching moment for the 30 kt transition flight condition is shown. The HHC input was used 0.4 degrees longitudinal cyclic, at 270 degrees phase. This relatively small HHC input reduced the fixed system vibration by over 50%. Reference 10 had indicated that, for hingless and bearingless rotors, up to four degrees of HHC might be optimum. It is believed that the lower levels of HHC are effective for the MDART rotor because of its low flapping frequency, 1.05/rev as opposed to 1.12/rev in the reference.

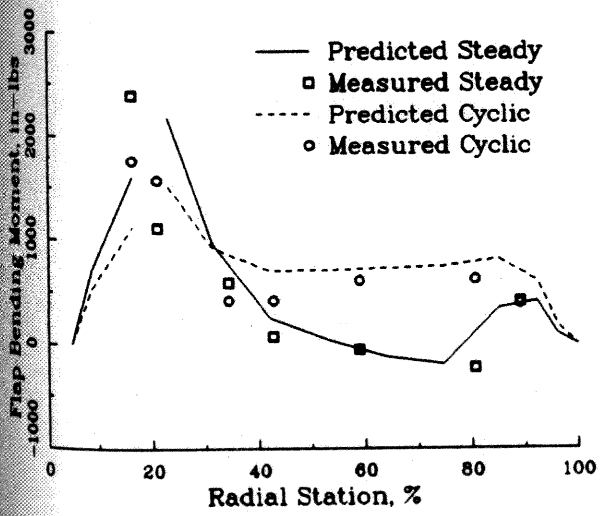

Fig. 11 Blade and Pitchcase Flap Bending Moment Distributions at Advance Ratio of 0.35 and 5800 lbs Thrust.

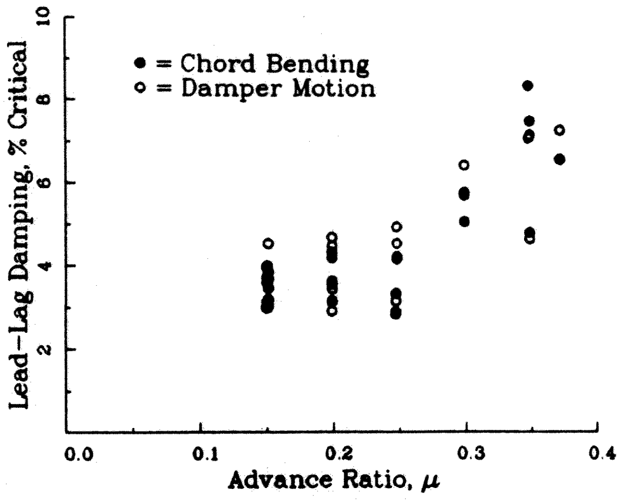

Fig. 12 Lead-Lag Damping vs. Advance Ratio at 5800 lbs Thrust.

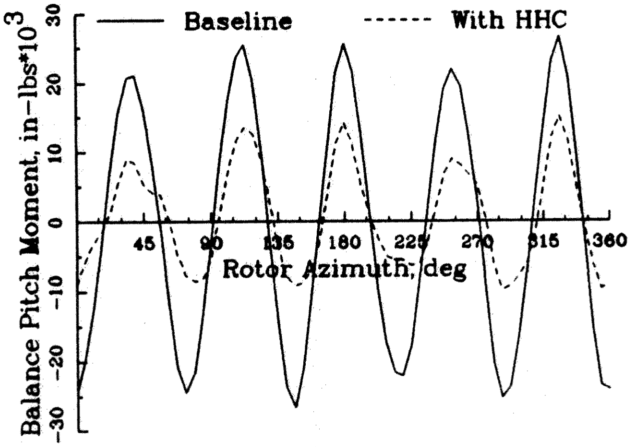

Fig. 13 Effect of 0.4 Deg of 5/rev Longitudinal Cyclic Pitch on Rotor Balance Oscillatory Pitch Moment for the 30 kt Transition Flight Condition.

Future Plans

The cooperative research agreement between NASA and McDonnell Douglas calls for a second MDART test entry. For this follow on test, the rotor will be equiped with a pressure instrumented blade. The preliminary design calls for over 200 pressure transducers. The test will also employ a closed-loop HHC control system.

Concluding Remarks

The MDART test was a very successful cooperative effort between McDonnell Douglas and NASA. The test produced a wealth of full-scale bearingless rotor aerodynamics, loads, stability, and acoustic data. For the first time, Higher Harmonic Control was employed on a bearingless rotor.

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