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PREDICTION OF AEROELASTIC RESPONSE OF A MODEL X-WING ROTOR*

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ABSTRACT

The purpose of this paper is to describe comparisons of predictions from an aeroelastic analysis with test data for a model X-Wing rotor to demonstrate the applicability of the analysis to the X-Wing. The analysis is the Rotorcraft Dynamics Analysis (RDYNE), developed by Sikorsky Aircraft, which was modified to incorporate Circulation Control airfoil aerodynamics and a pneumodynamic analysis, developed by the David Taylor Naval Ship Research and Development Center (DTNSRDC). Test data were derived from a representative X-Wing with a 10 ft diameter rotor tested in the Boeing-Vertol Wind Tunnel. A small number of comparisons were also made with data for a 25 ft diameter X-Wing rotor tested in the NASA Ames 40 x 80 ft Wind Tunnel. Several flight regimes were investigated, including hover, transition, and conversion to a fixed wing mode of flight. The comparisons indicate that the analysis is able to give satisfactory predictions of X-Wing behavior. Basic control power effects and the effects of Higher Harmonic Control on vibratory bending moments are predicted accurately. Forward flight vibratory flatwise bending moment and push rod load comparisons were as good as comparisons for conventional rotors. The analysis is able to accurately represent vibratory and steady responses in rotor thrust, blade bending moments, and hub rolling and pitching moments for conversion to a fixed wing flight mode. Refinements which were identified as leading to significant improvements were variable rotor induced flow and acoustic pressure wave delay in the pneumodynamic model.

INTRODUCTION

The X-Wing vehicle is an aircraft which utilizes a rotor to take off (and land) as a helicopter. The aircraft transitions to forward flight and converts to a fixed wing flight mode at a high subsonic flight condition, with the rotor first slowed and then stopped as a fixed wing with an X-planform. Advances in several technologies make more practical the realization of the concept, which has evolved to

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where NASA awarded Sikorsky Aircraft a contract in December 1983 to design, build, and test an X-Wing on the Rotor Systems Research Aircraft (RSRA). The Circulation Control Rotor (CCR) is a key technological solution incorporated in the X-Wing enabling the rotor to behave satisfactorily at high advance ratios and stopped conditions. Jets of air are ejected from slots at leading and trailing edges of the aerodynamically smooth airfoil section to achieve lift augmentation and cyclic control of lift, as well as vibration reduction through Higher Harmonic Control (HHC).

Prior to the Sikorsky contract, small scale and full scale tests were conducted with three models to verify the X-Wing concept and to acquire data (Reader, 1984). Data were obtained on a 6.7 ft. diameter Reverse Blowing Circulation Control Rotor (RBCCR), a Lockheed 25 ft. diameter X-Wing rotor, and a Boeing-Vertol 10 ft. diameter X-Wing rotor. To support the design of the RSRA/X-Wing, Sikorsky modified the Rotorcraft Dynamics Analysis (RDYNE) to model the pneumodynamic and aerodynamic behavior of CCRs, and this was followed by studies to validate the analysis. Comparisons were made with the Boeing-Vertol and Lockheed test data to study the ability of the analysis to predict basic phenomena, consisting of control power relationships, the effects of HHC, and the vibratory response of the rotor in forward flight and conversion to a fixed wing mode. The purpose of the paper is to describe the performance of the RDYNE aeroelastic analysis by comparing predictions from analysis with results from test data in X-Wing regimes of flight.

Acknowledgements are due to Robert H. Blackwell, Sikorsky, and Kenneth R. Reader, DTNSRDC, for their contributions.

AEROELASTIC METHODOLOGY

The methodology utilized to predict the aeroelastic behavior of the X-Wing rotor is the Rotorcraft Dynamics Analysis (RDYNE), developed by Sikorsky Aircraft. This is an analysis which integrates the equations of motion for a dynamical system with respect to time (Sopher and Hallock, 1986). The software is segregated along component lines. Components consist of distinct types of dynamical substructures, aerodynamic representations, trim solutions, and processing capabilities such as table specification and plot variable selection components. The components selected for the application of the analysis to predict the aeroelastic responses of X-Wing rotors were the following:

1) The elastic blade is based on a set of coupled flatwise, edgewise, and torsion equations (Arcidiacono, 1969). Blade mass and stiffness properties are used to calculate uncoupled bending and torsion normal modes, and blade displacements are expressed in terms of these modes to reduce the basis of the blade equations to normal modes coordinates.

2) The section aerodynamic component was developed by the David Taylor Naval Ship Research and Development Center (DTNSRDC) and yields the blade element characteristics of Circulation Control (CC) airfoils for specified values of blowing momentum coefficient, angle-of-attack, and Mach number. Incorporated with this component is a pneumodynamic analysis which calculates blade duct pressures and temperatures, for specified plenum pressure ratios, and allowing for losses and centrifugal pumping in the duct.

There is also a module for calculating the slot deflection height of the flexible slot. The slot height is utilized with duct pressure and temperature to calculate jet velocity and mass flow through the slot, and jet momentum coefficient, which in turn are used to obtain from a set of tables established from tests on CC airfoils the values of C_L, C_D, and C_m applicable to the airfoil state. The effects of acoustic pressure wave delay are represented in RDYNE by calculating the pressure at an orifice at a specified radial station from the pressure at a valve opening in the plenum at an earlier time, by accounting for the time taken for the wave to travel between these points.

The data were derived from tests on two types of CC airfoils consisting of 20% thickness ratio dual slotted cambered airfoil and a 15% thickness ratio uncambered dual slotted airfoil. The 20% thickness ratio airfoil was subsequently used at the root of the Boeing-Vertol X-Wing rotor and the 15% airfoil was used at the tip of the rotor, with intermediate sections obtained from straight line generators extended between root and tip.

3) Rotor induced variable inflow is represented by a procedure which utilizes geometric influence coefficients relating rotor blade circulations to induced velocity, which are calculated by a program external to RDYNE and then transmitted to RDYNE for calculation of the inflow. The geometric influence coefficients are based on the analysis of Landgrebe and Egolf (1976) and are functions of advance ratio and the angle (CHI) assumed between the rotor wake and rotor tip path plane. This angle may be calculated from momentum inflow considerations or may be input to reflect an empirical or arbitrary wake inclination. An iterative procedure is used in RDYNE to ensure that rotor blade circulations, motions, and rotor induced inflow are consistent with each other in the final vibratory state used for the predictions.

DESCRIPTION OF TESTS AND ASSUMPTIONS IN ANALYSIS APPLICATIONS

The objective of the Boeing-Vertol test was to obtain data from the model of an aircraft with a representative X-Wing rotor, for several flight regimes including hover, transition (10 to 100 kn), and high speed rotary wing flight to 200 kn. Fundamental effects of blowing inputs on steady hub moments and vibratory bending and pushrod loads (torsion moments) were studied, including the effects of HHC blowing.

The test was conducted in the Boeing-Vertol Wind Tunnel (BVWT) which has a 20 x 20 foot working section and a conventional closed circuit. The 10 foot diameter rotor is described in table 1. The circulation control airfoils have an aerodynamically smooth contour achieved by means of flexible slots at leading and trailing edges. Leading edge or combined leading edge and trailing edge (dual) blowing is achieved by a blowing system consisting of a plenum to which air is supplied by a

TABLE 1 - BOEING-VERTOL MODEL X-WING ROTOR

- **Rotor**
  - **Diameter** = **10 ft**
  - **Tip Speed (Ω R)** = **600 ft/sec**
  - **Taper ratio** = **0.5**
  - **Solidity** = **0.159**
  - **Airfoil** = **20% t/c at root**
    15% t/c at tip
  - **Slots** = **Dual openings vary with pressure**
  - **Twist** = **0 degrees**
- **Control system**
  - **Pneumodynamic control of leading and trialing edge blowing and**
    - **Mean**
    - **1-5 per rev harmonics**
  - **Mechanical collective**

compressor. The plenum is connected through ducting to leading and trailing edge slots in the blade. Sixteen throttling valves in the nonrotating system control the mean and cyclic variations of trailing edge pressure supplied to the slots, up to the fifth harmonic. Nine valves control the pressure in the leading edge.

The typical rotor loading in comparisons of theory and test in hover was CT/Sigma of .074 at a tip speed of 602 feet per second and a plenum pressure of 14 psig. The RDYNE analysis was run with measured control angles and pressures selected from a station between the 20 to 25 percent radial positions to define input variables for the control power comparisons in hover. Bending moment responses to these inputs were measured at the 29 percent radial position in hover.

To determine the potential of the analysis to predict reductions in vibrations induced by cyclic blowing, comparisons were made of the effects of blowing harmonic excitation (1P to 5P) on the 1/2 peak-to-peak flatwise vibratory bending moment in hover. Flatwise bending moments were compared at the 17 percent radial station, and harmonic pressures were measured at the 25 percent station. In the analysis application, the rotor speed was held at 750 rpm and the harmonic number, n, was varied from 1 to 5. Test data were measured at several different RPMs and harmonic numbers. The normalized frequency used for comparing the results is defined as n.(RPM/60).(1/f) where f is the ratio of flatwise frequency at a specified RPM used in the test or analysis to the flatwise frequency at zero RPM. The nonrotating flatwise natural frequency of the blade is 35 hz.

Comparisons were made in the transition flight regime of 10 to 100 knots to evaluate the ability of the analysis to predict steady rotor lift, torque, and hub rolling and pitching moments. Conditions selected were 20 through 60 knots with single trailing edge blowing and a plenum pressure of 17 psig. The analysis was run with fixed control angles from the test data and with variable inflow. Three sets of analytical cases were specified to determine the effect of the rotor wake inflow angle (CHI) on correlation of hub steady pitching moment with airspeed. The CHI angle is defined as the uniform inflow (determined by the lift, shaft angle, airspeed and tip speed) divided by the forward airspeed. The theoretical uniform inflow downwash angle and values of this angle reduced to 0.75 and 0.5 of the uniform angle value were specified to study the sensitivities of the predicted results to CHI.

For the comparisons of vibratory loads in forward flight, the tip speed was 602 feet per second, the plenum pressure 14 psig, the rotor loading (CT/Sigma) was .074 and the airfoil had single trailing edge blowing. The analysis was run with specified test control angles, blade pressures from test at 23 percent span, and variable inflow. For all cases the bending moments were compared at the 29 percent blade station.

All analytical cases for the Boeing-Vertol rotor were run with two flatwise, one edgewise and one torsion mode. Figure 1 is a calculated frequency diagram for the blade modes.

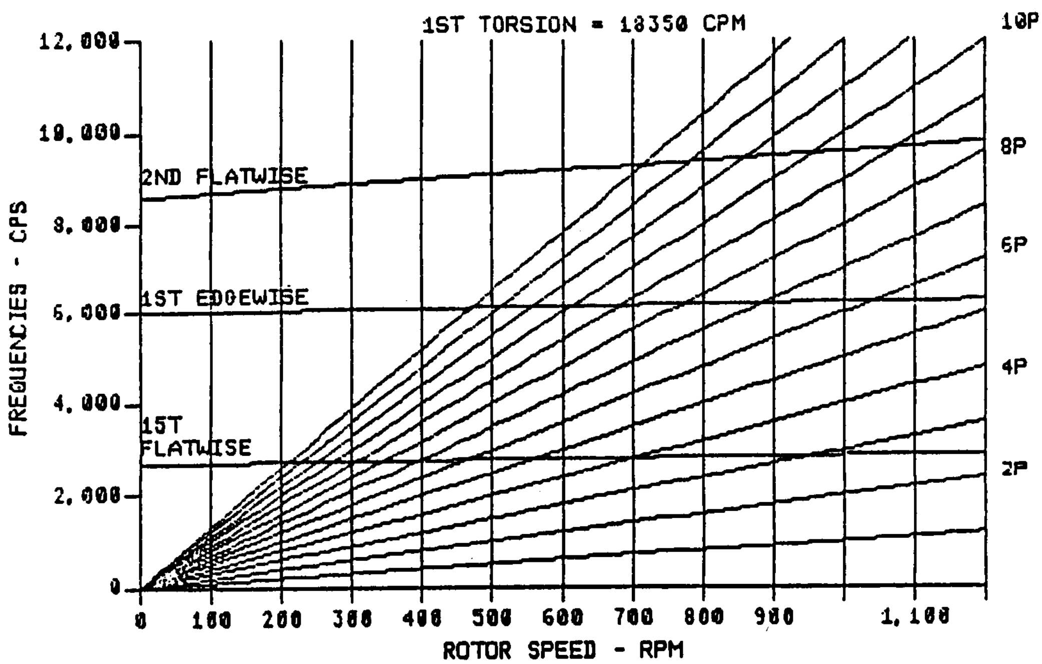

Figure 1 - Frequency Diagram for Modes for Boeing-Vertol Blade

The Lockheed rotor is a dual slotted 25 ft diameter X-Wing rotor which was tested in the NASA Ames 40 x 80 ft Wing Tunnel during the spring of 1979, for flight conditions including conversion, where the rotor was slowed from 90% NR (372 RPM) to a stopped condition at 180 kn. Figure 2 is a frequency diagram for the blade modes for the Lockheed blade.

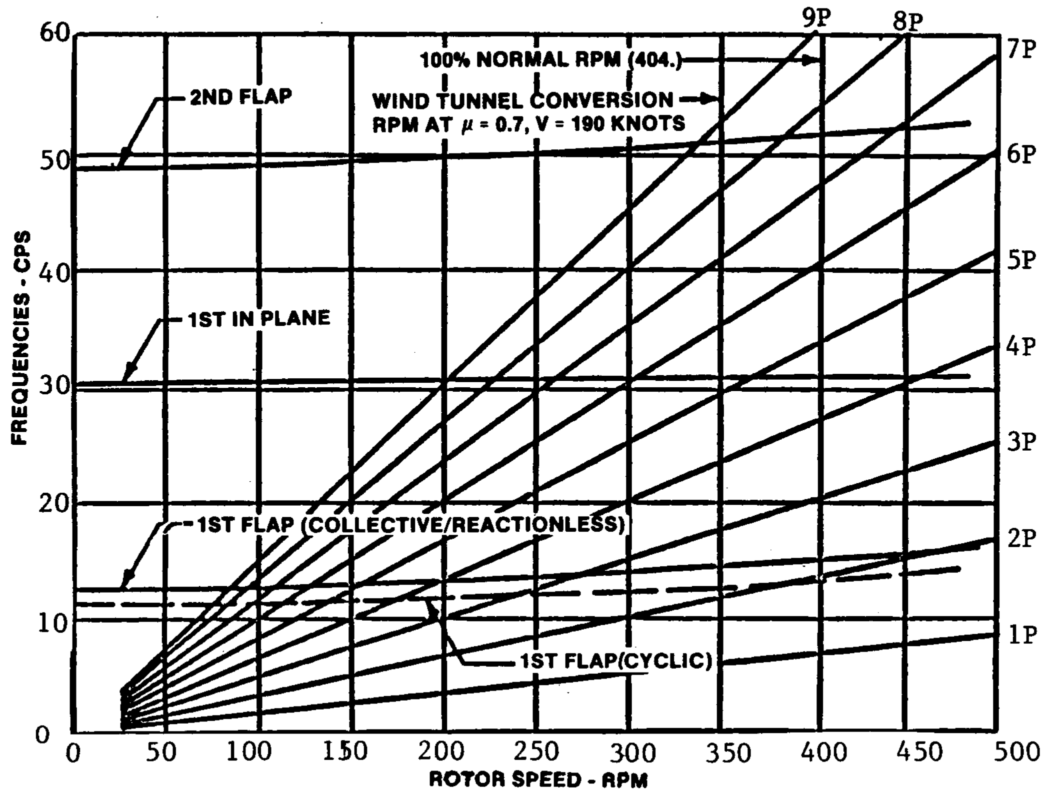

Figure 2 - Frequency Diagram for Modes for Lockheed Blade

The RDYNE analysis was run using uniform inflow to simulate a test conversion. The control angles were fixed at the values measured at the start of the run. The analysis used two flatwise modes and one edgewise mode and varied the blade modal frequencies as functions of rotor speed but used the same mode shapes throughout conversion. The blade torsion mode was omitted to enable the analysis to be run with a large time integration interval. This was felt to be justified based on the very high torsional stiffness and frequency of the Lockheed blade (torsion frequency was on the order of 20P). The test run was made under closed loop hub moment control which continuously adjusted the rotor steady hub moments to zero values. The analysis did not have a feedback hub moment control. Conversion to a stopped rotor condition was performed with blade dual blowing, a plenum pressure of 8.8 psig, 2 degrees shaft angle, and -5 degrees collective (Run 43, point 9).

All comparisons discussed below apply to the Boeing-Vertol X-Wing rotor, unless stated otherwise.

CONTROL POWER AND HIGHER HARMONIC CONTROL IN HOVER

A basic test of the analysis is its ability to predict the effects of once per rev (1P) blowing on hub trimming moments. Figure 3, which shows steady hub moment versus 1P blowing amplitude, demonstrates that the combination of an aeroelastic blade, rotor induced variable inflow, and acoustic pressure wave delay between the pressure source in the plenum and the blade orifices, succeeds in bringing the RDYNE

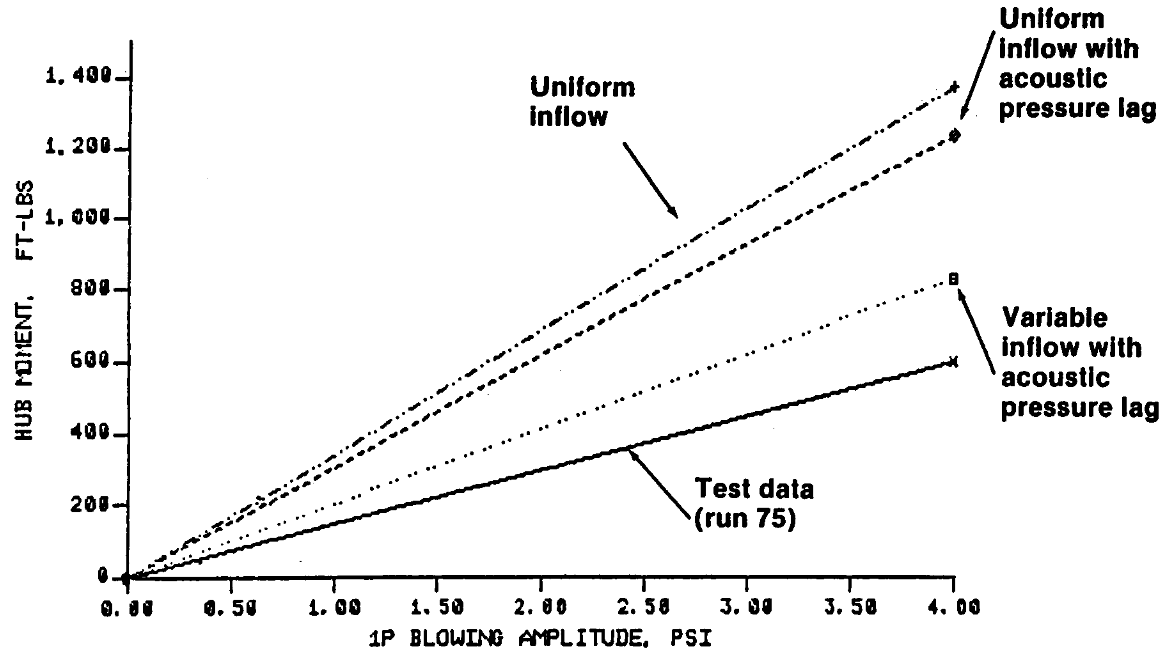

Figure 3 - Effects of 1P Blowing on Steady Hub Moments in Hover

analysis into good agreement with Boeing-Vertol test data. Figures 4 and 5 illustrate the agreement in the blade flatwise bending moment time histories and the harmonically analyzed bending moments. Interestingly, the 1P flatwise blade moment agrees exactly with the test data while the steady hub moment shows the analysis to overpredict the response by approximately twenty percent. This may indicate a slight discrepancy in the test data, since the steady hub moment is only generated from the 1P blade flatwise bending moment.

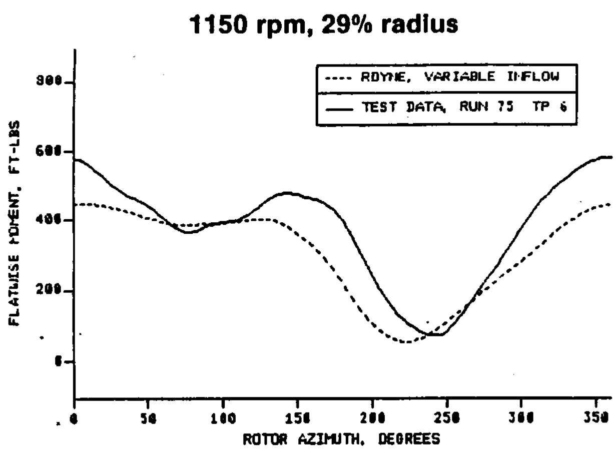

Figure 4 - Effects of 1P Blowing on Flatwise Bending Moment in Hover

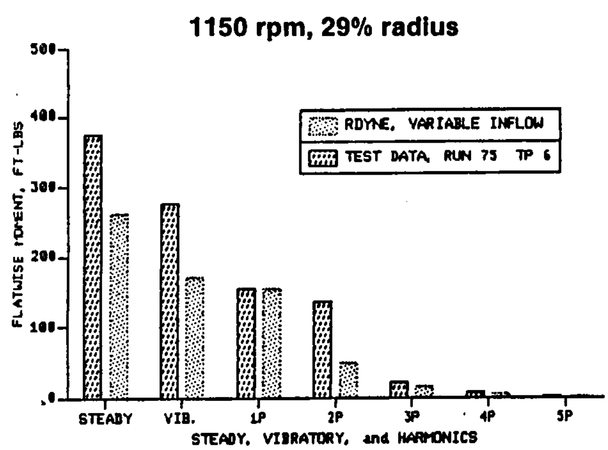

Figure 5 - Harmonic Content of Flatwise Bending Moment Response to 1P Blowing in Hover

Figures 6 and 7 demonstrate that the analysis is able to predict the effects on vibratory bending moments of Higher Harmonic Control of blowing. Variable inflow enables the amplitude to be predicted to within 20 to 30 percent and phase to be predicted almost exactly. Through blade resonance the phase of the response changes 270 degrees instead of the typical 180 degree phase shift associated with a single degree of freedom system. This was demonstrated analytically to be the effect of the acoustic pressure wave delay. Without this wave delay incorporated into the RDYNE analysis, the predicted phase shift approximated 180 degrees (figure 8).

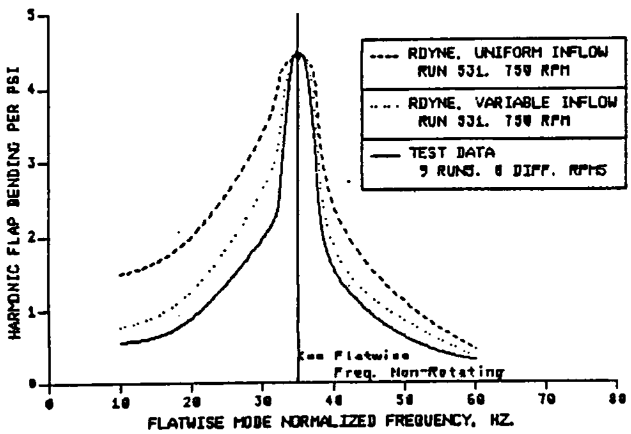

Figure 6 - Effects of Higher Harmonic Blowing on Amplitude of Flatwise Bending Moment in Hover

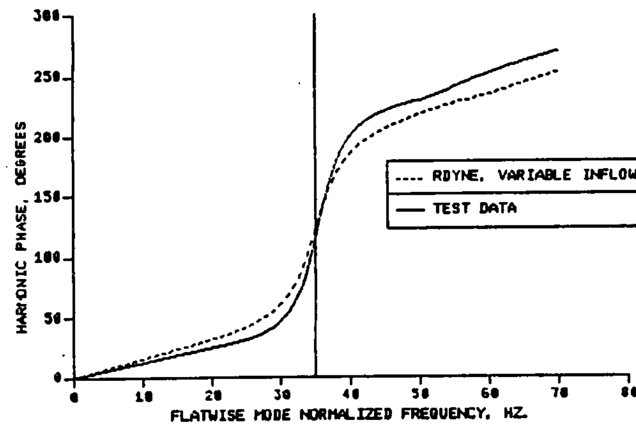

Figure 7 - Effects of Higher Harmonic Blowing on Phase of Flatwise Bending Moment in Hover

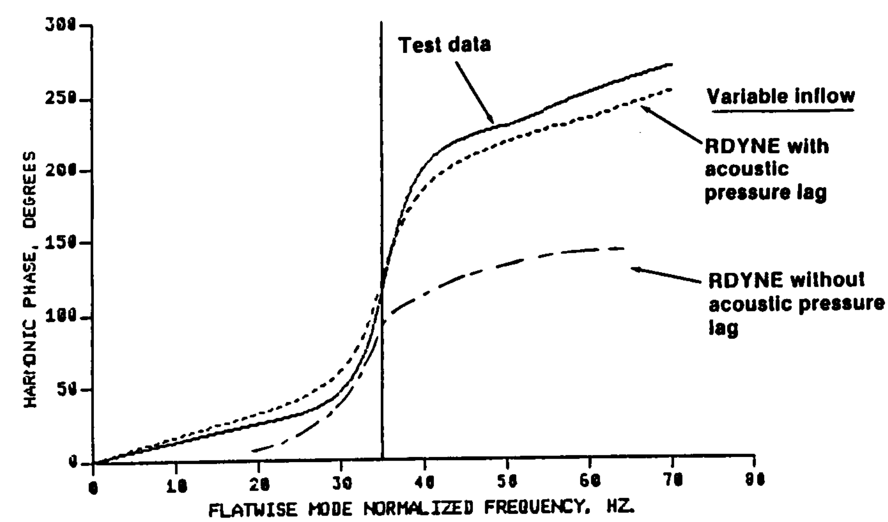

Figure 8 - Effects of Accoustic Pressure Lag on Phase Angle of Flatwise Bending Moment Response to Blowing Harmonic in Hover

TRANSITION FLIGHT

The RDYNE analysis satisfactorily predicts rotor lift (figure 9) and torque (figure 10) in the transition flight region, where the X-Wing has to achieve steady level flight. The CHI angle had little effect on the prediction of rotor lift and rotor torque, but clearly demonstrates that the prediction of the hub steady pitching moment is controlled by the selection of CHI (figure 11). The results showed that good agreement in steady hub pitching moment was obtained by reducing the empirical CHI angle as the airspeed is increased. This reduction brings the rotor wake vertically closer to the rotor, and causes an increase in the downwash in the rear portion of the disc. This in turn increased the hub pitching moment in the nose up direction.

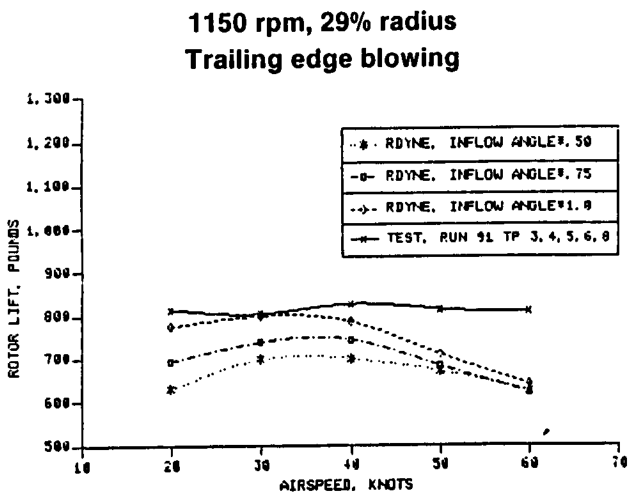

Figure 9 - Variation of Rotor Lift with Transition Airspeed

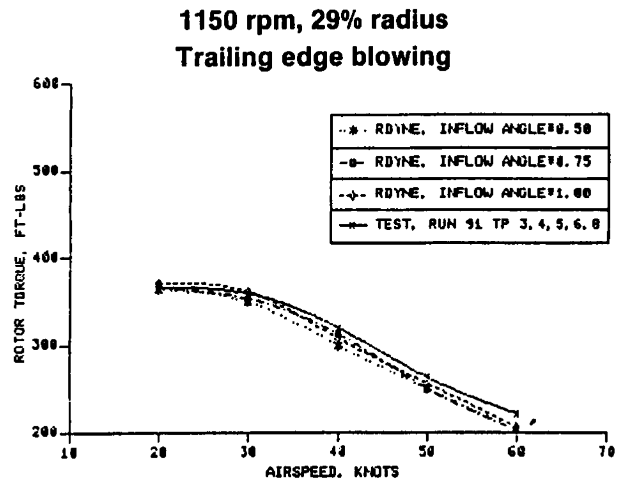

Figure 10 - Variation of Rotor Torque with Transition Airspeed

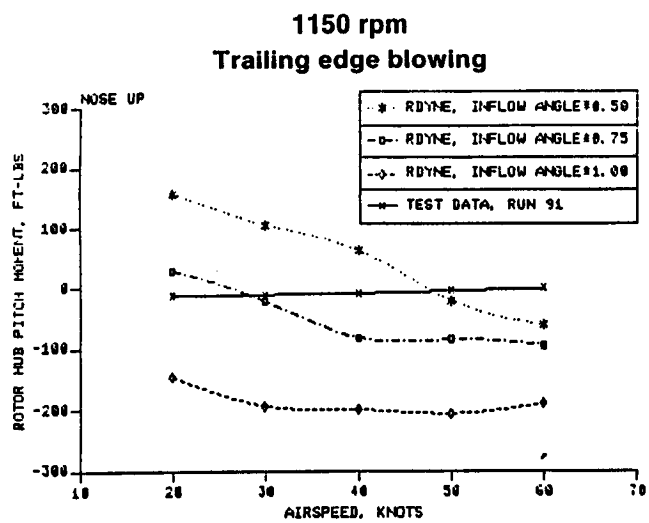

Figure 11 - Variation of Rotor Pitching Moment with Transition Airspeed

VIBRATORY LOADS AT FORWARD SPEED

Many of the comparisons of predicted vibratory loads are as good as comparisons for conventional rotors, and in some cases are better, indicating that a credible tool has been developed for predicting the vibratory loads on X-Wing rotors.

Figures 12 and 13 show the test and predicted blade flatwise bending moment versus blade azimuth at 100 and 120 knots. The overall 1/2 peak-to-peak response agreement is good and in general the time history agreement is fair. At 150 knots (figures 14 and 15) the 1/2 peak-to-peak response agreement is still good and at the same time significant improvement in the predicted harmonics occurred. The bar charts in figure 15 clearly illustrate the excellent prediction achieved at 150 knots with variable inflow. The chart shows steady, vibratory and the first five harmonics of blade flatwise moment. The vibratory and harmonic bending moments matched almost exactly, while the steady prediction is poor. However, this 40 percent underprediction of steady moment may not represent poor predictive ability since the prediction of rotor lift was within ten percent of the measured value. In general, it is normal for measurement of steady blade bending moments to be less reliable than the vibratory moments. Also shown on the bar chart is the RDYNE prediction using uniform inflow. At this airspeed the prediction of vibratory load and all the harmonics improves with incorporation of variable inflow.

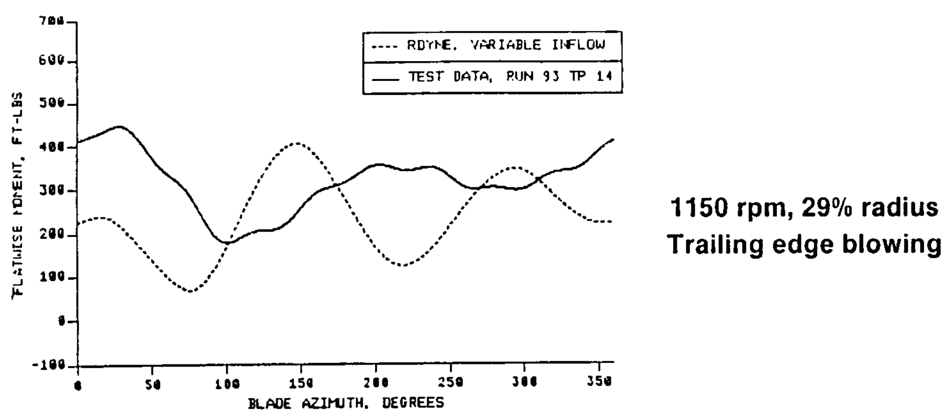

Figure 12 - Effect of Forward Speed on Flatwise Bending Moment at 100 Kn

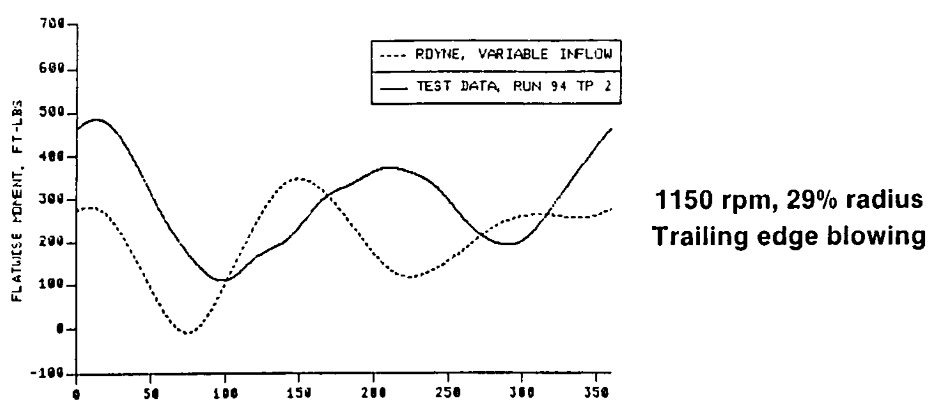

Figure 13 - Effect of Forward Speed on Flatwise Bending Moment at 120 Kn

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1150 rpm, 29% radius
Trailing edge blowing

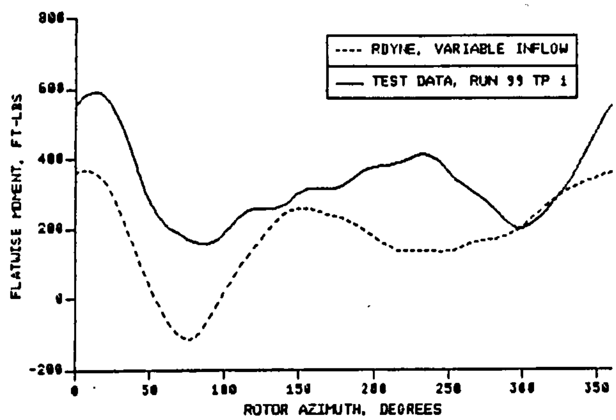

Figure 14 - Effect of Forward Speed on Flatwise Bending Moment at 150 Kn

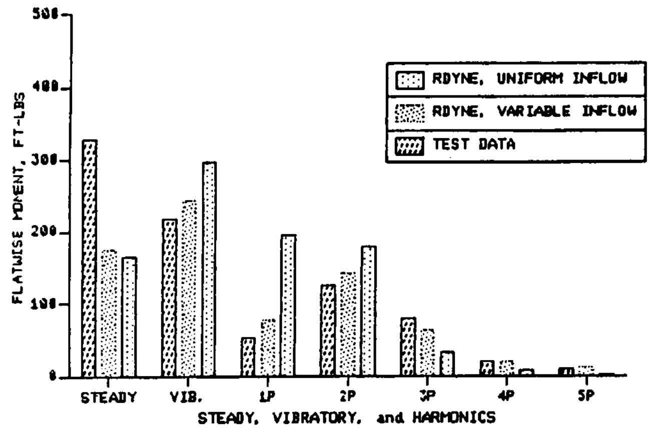

Figure 15 - Harmonic Content of Flatwise Bending Moment at 150 Kn

At the same flight condition of 150 knots, similar time history plots and bar charts are shown for edgewise blade bending moments and push rod loads. Again, both uniform and variable inflow results are shown for comparison. Figures 16 and 17 show that the agreement is quite good. The bar chart demonstrates that the variable inflow compared to the uniform inflow significantly improves the prediction of the vibratory load and all the harmonics of blade edgewise response. In general this edgewise comparison of harmonics is better than a majority of comparisons for conventional rotors.

1150 rpm, 29% radius
Trailing edge blowing

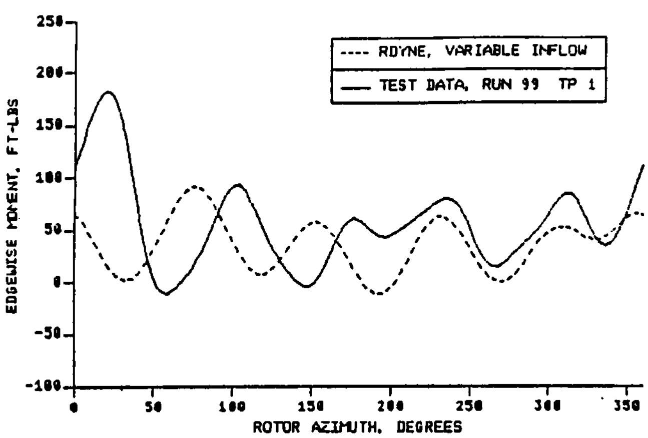

Figure 16 - Edgewise Bending Moment at 150 Kn

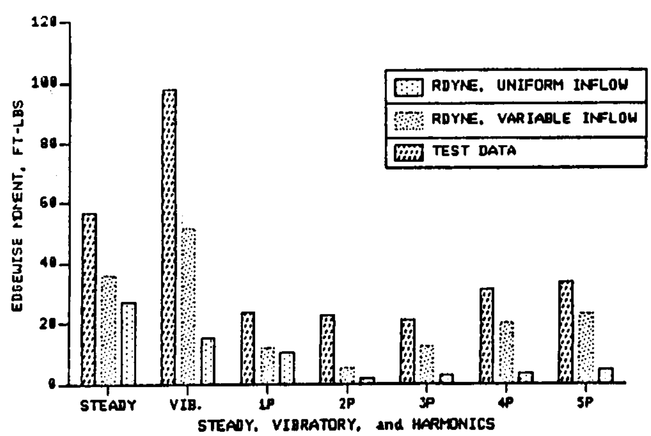

Figure 17 - Harmonic Content of Edgewise Bending Moment at 150 Kn

Figures 18 and 19 show the push rod comparison (derived from the torsional response of the blade). Again, agreement in the time history response and bar chart depicting harmonics of load is quite good. The comparison of variable and uniform inflow shows that both inflows yield good predictions of vibratory and 1P push rod load, with variable inflow improving the prediction of the higher harmonics.

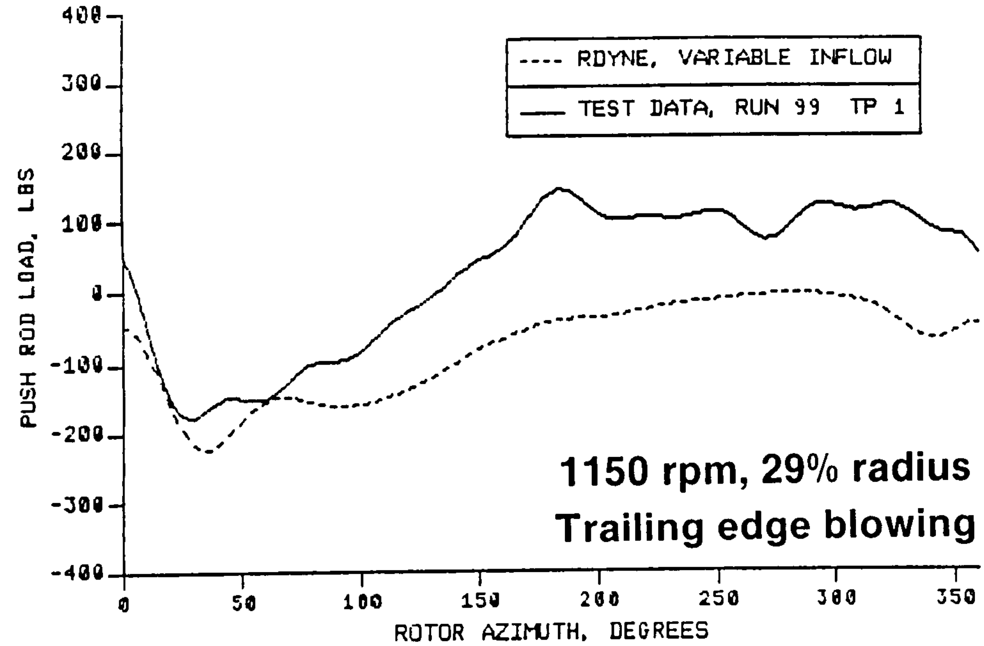

Figure 18 - Push Rod Load at 150 Kn

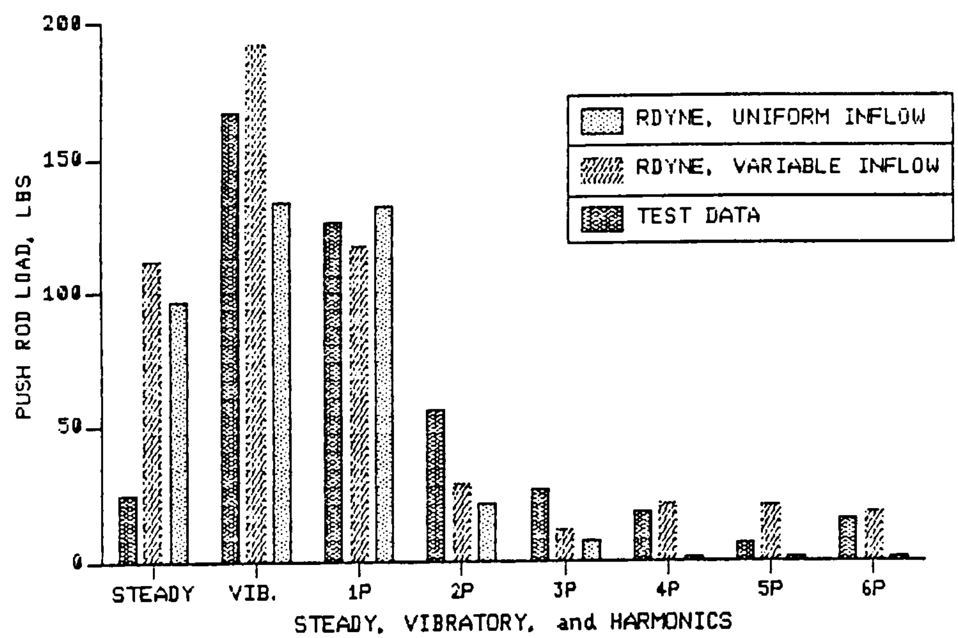

Figure 19 - Harmonic Content of Push Rod Load at 150 Kn

For the above conditions, figures 20 to 22 compare the variation of vibratory blade flatwise bending moments, edgewise bending moments, and vibratory push rod loads with increasing airspeed. Very close agreement was obtained by the RDYNE analysis with variable inflow for the vibratory (1/2 peak to peak) blade flatwise bending moment and the vibratory push rod load. For the edgewise moment, the analysis underpredicts the vibratory component by 50 to 75 percent. In general, the correlation of vibratory flatwise and push rod loads is as good as results obtained for conventional rotors (Arcidiacono and Sopher, 1982; Jepson et al, 1983).

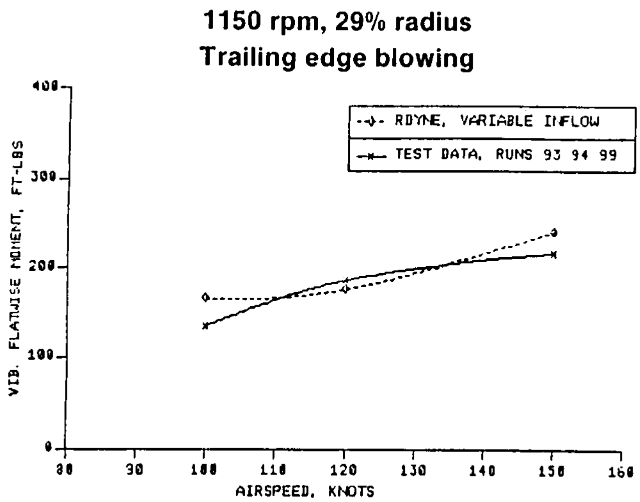

Figure 20 - Variation of Vibratory Flatwise Bending Moment with Airspeed

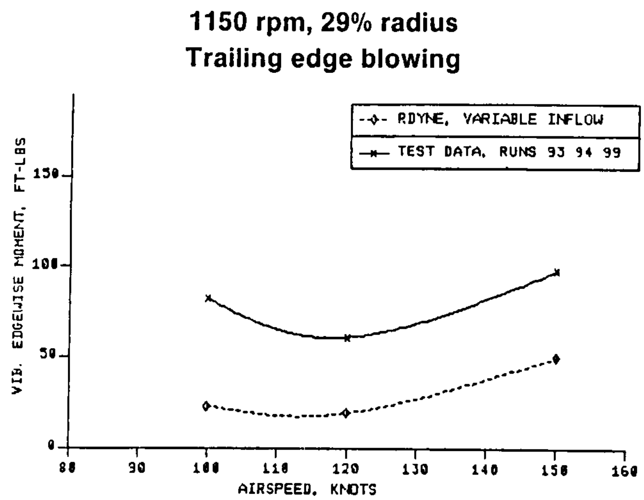

Figure 21 - Variation of Vibratory Edgewise Bending Moment with Airspeed

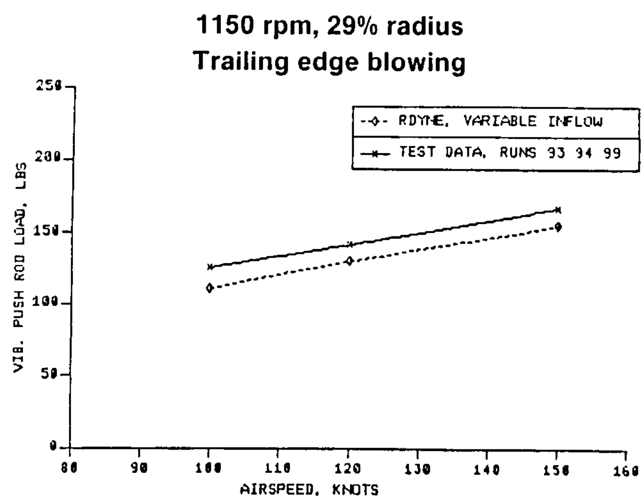

Figure 22 - Variation of Vibratory Push Rod Load with Airspeed

RESPONSES IN CONVERSION

The ability of the RDYNE analysis to predict vibratory blade loads and vibratory hub forces and moments during conversion is important to the design of an X-Wing rotor system. The vibratory levels will be the highest that the rotor will experience because the stopping of the rotor is done at high speed. The rotor system will experience the unique condition of being excited by airloads while the blade bending modes pass through resonance. This is a condition that conventional rotors are designed to avoid to minimize blade and hub loads.

Overall, the agreement in vibratory levels (figures 23 and 24) is good. The predicted thrust shows the same trend in mean values with decreasing rotor speed as the test data. Also the prediction of the mean thrust shows good agreement. The predicted maximum vibratory thrust occurs at approximately the same rotor speed as the test data but its level is underpredicted by 50 percent. The blade flatwise vibratory and steady levels show good agreement but the agreement in rotor speed at the point of maximum blade response cannot be clearly defined since the predicted moment does not show any distinct peaks. These peaks are clearly evident in the time histories of the hub roll and pitch moments for both the test data and the analysis. The predicted peaks are at a lower rotor speed (later time) than the test data. The predicted flatwise blade natural frequency versus rotor speed shown in figure 2 indicates that the test peaks occur at exactly the rotor speed for which the blade mode crosses a harmonic of rotor RPM. However, the analysis shows that the maximum response occurs just after passing through a harmonic of rotor speed (approximately 0.5 second lag) which is typical for a dynamic system being excited by a force with a decreasing frequency. The predicted increase in steady hub roll moment as the rotor slows down was expected due to the lack of an analytical closed loop hub moment control. The predictions of the maximum hub vibratory moments were in close agreement for the pitch direction and showed a slight underprediction for the roll direction.

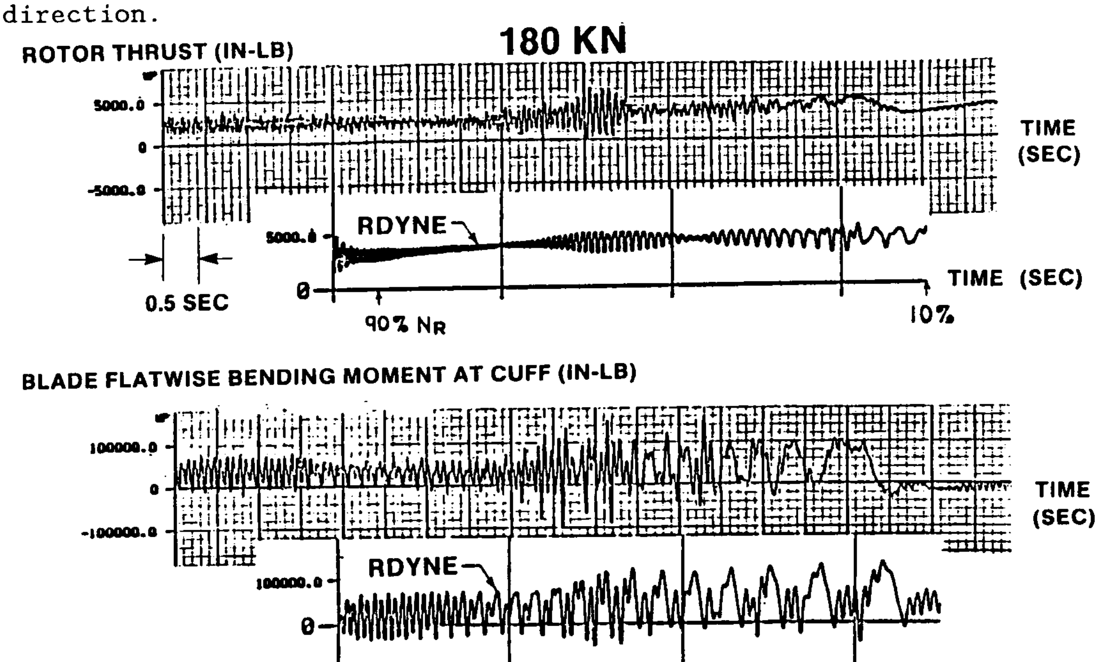

Figure 23 - Variations with Time of Rotor Thrust and Flatwise Bending Moment for Lockheed Rotor in Conversion

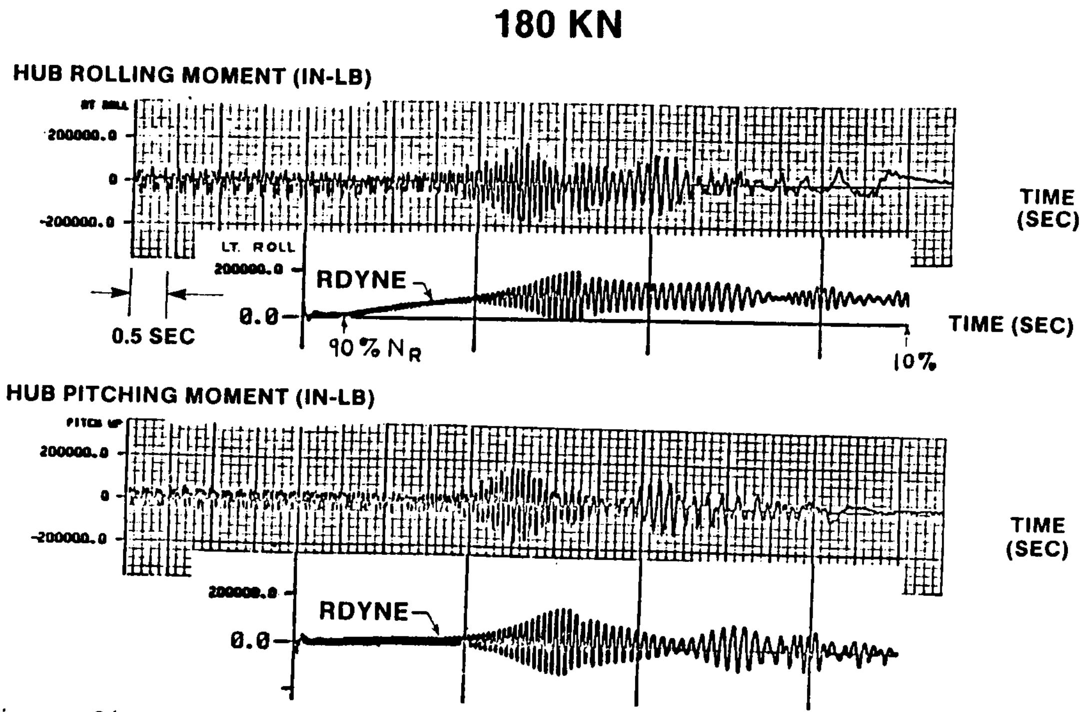

Figure 24 - Variations with Time of Rotor Hub Moments for Lockheed Rotor in Conversion

CONCLUSIONS

The RDYNE analysis was used to predict the aeroelastic responses of a representative X-Wing model with a 10 ft diameter rotor tested in the Boeing-Vertol Wind Tunnel. A small number of predictions were also made for a Lockheed X-Wing with a 25 ft diameter rotor tested in the NASA Ames 40 x 80 ft Wind Tunnel. Comparisons with test results indicate that the analysis is able to give satisfactory predictions of aeroelastic responses in X-Wing flight regimes.

For the Boeing-Vertol model, basic control power effects relating first harmonic blowing control inputs to steady hub loads, analogous to control relationships for mechanically controlled rotors, are predicted accurately in hover. The analysis is able to accurately predict the effects of higher harmonic blowing on blade bending moments, and shows potential for enabling rotors to be designed for reduced vibrations. Forward flight vibratory bending moments showed fairly good agreement with test data, and were as good as comparisons for conventional rotors. The comparisons of vibratory flatwise and push rod loads were better than results obtained for conventional rotors.

Good agreement between analysis and test was achieved for the Lockheed rotor in conversion flight for variations with time of rotor thrust, blade flatwise bending moment, and hub rolling and pitching moments at 180 knots with the rotor slowed from 90% NR to a stopped condition. The correlations establish the ability of the analysis to represent vibratory and steady responses for a mode of flight which is important to the design of the X-Wing.

Refinements which were identified as leading to significant improvements were variable rotor induced flow and acoustic pressure wave delays in the pneumodynamic model. Variable inflow improved the predictions of vibratory loads in forward flight and the amplitudes of vibratory bending moment responses to higher harmonic blowing in hover. Acoustic pressure wave delays significantly improved the predicted phase responses of blade bending moments to higher harmonic blowing in hover.

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