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GROUND VIBRATION TEST OF THE XV-15 TILTROTOR RESEARCH AIRCRAFT AND PRETEST PREDICTIONS

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Summary

The first comprehensive ground vibration survey was performed on the XV-15 Tiltrotor Research Aircraft to measure the vibration modes of the airframe and to provide data critical for determining whirl flutter stability margins. The aircraft was suspended by the wings with bungee cords and cables. A NASTRAN finite element model was used in the design of the suspension system to minimize its interference with the wing modes. The primary objective of the test was to measure the dynamic characteristics of the wings and pylons for aeroelastic stability analysis. In addition, over 130 accelerometers were placed on the airframe to characterize the fuselage, wing, and tail vibration. Pretest predictions were made with the NASTRAN model as well as correlations with the test data. The results showed that the suspension system provided good isolation necessary for modal measurements.

Introduction

This report documents the results of a ground vibration test of the XV-15 Tiltrotor Research Aircraft. The focus of the test was to acquire vibration data at the rotor hubs. In addition, the vibration of the fuselage was measured to characterize the complete aircraft dynamics.

Figure 1 shows the XV-15 Tiltrotor in flight in the airplane mode, steel-bladed configuration. This aircraft combines the hovering capability of a helicopter and the forward flight speed of an airplane. The XV-15 takes off in helicopter mode with the rotors tilted up. Then the pylons and rotors tilt down during flight to the airplane mode shown in figure 1. It is this airplane mode configuration in which whirl flutter instabilities are predicted to occur (ref. 1). The data acquired during the ground vibration test will be used to improve predictions of aeroelastic stability of the XV-15. The steel-bladed configuration was studied the most closely because the majority of documented XV-15 flight data was acquired with this blade set and can be used to validate stability predictions (refs. 1 and 2). A greater understanding of the instabilities unique to tiltrotors is important in the development of advanced high-speed tiltrotors (refs. 3–5).

In order to measure the vibration modes of the XV-15, a ground vibration test was conducted in January and February of 1992 at NASA Ames Research Center. Figure 2 shows the test setup. The aircraft was tested in both helicopter and airplane modes. In addition, measurements were taken for both steel and composite rotor configurations (simulated by dummy blade weights). This paper documents the results for the baseline configuration: the XV-15 in airplane mode with steel rotor blades.

Ideally, the aircraft should be in a free-free configuration which means that there are no constraints such as resting the aircraft on its landing gear. This was accomplished by suspending the XV-15 from the wings using bungee cords. The suspension system successfully isolated the aircraft, enabling the wings to move freely with minimal interference to the aircraft dynamics.

This test was the first comprehensive ground vibration test of the XV-15. An exploratory test was performed by Bell Helicopter Textron, Inc. in 1978 (ref. 6). However, the aircraft did not contain fuel or have complete pylons and transmissions. Another test was performed at NASA Ames Research Center in 1988. This test provided only a rough measurement of the XV-15 frequencies with the aircraft resting on jacks.

A NASTRAN finite element computer model of the XV-15 was used to predict the effectiveness of the suspension system in isolating the aircraft (ref. 7). The model was modified from a free-free configuration to predict the XV-15 vibration modes and also to determine the effect of the test setup on the results. In particular, the effects of the suspension system, dummy blade weights, and gravity were studied.

Ground Vibration Test

The purpose of the ground vibration test, or shake test, of the XV-15 was to experimentally characterize the structural dynamics of the aircraft. The XV-15 was tested in the helicopter mode with pylons tilted up and also in airplane mode with pylons tilted down. In addition, the XV-15 was tested with both steel and composite rotor blade weights.

The aircraft was configured to simulate in-flight conditions. It was fully fueled with 1500 lb of fuel and 180-lb weights were strapped in the pilot and copilot seats. Dummy blade weights replaced the rotors so that the rotor blades would not be damaged during the test. These weights are shown in figure 3 as three groups of steel plates offset 13.5 in. from the hub. They were placed as closely as possible to the hub so that they would add a minimal amount of rotational inertia to the pylons. This was important to match the assumption of aeroelastic analyses which model the rotor weight as a point mass located at the hub's center.

In order to model the free-free condition of zero airspeed flight, the aircraft was suspended with bungee cords. The suspension prevented the XV-15 from resting on the landing gear which would alter the test results. However, the landing gear were extended down as a safety precaution.

The suspension system consisted of an inverted-V system which lifted the aircraft from its wings by a crane 35 feet above the floor (fig. 2). The suspension was attached to the wings 6.8 ft from the centerline at locations designed for lifting the aircraft. Cables and turnbuckles comprised the lower 19 feet of the inverted-V. The turnbuckles allowed for adjustments in length to balance the aircraft left to right. Above the cables, bungee cords stretched to the top of the inverted-V. A total of 40 bungee loops were used, 20 per side, as shown in figure 4. They looped around upper and lower brackets stretching from 4 feet unloaded to 8 feet under the weight of the 14,100-lb aircraft.

The advantage of using bungee cords was that their low spring rate enabled the XV-15 wings to vibrate freely under the support. The combined stiffness of all forty bungee loops was 457 lb/in. which was well below the aircraft stiffness. In order to balance the XV-15 fore and aft, a bungee cord loop with a stiffness of 45 lb/in. stretched from the tail down to the ground.

To measure the vibration of the XV-15, 134 accelerometers were placed on the fuselage, tail, wings, and pylons. They measured acceleration in the vertical, longitudinal, and lateral directions. The most important accelerometers were located at each hub because hub dynamics are a key factor in determining aeroelastic stability. At these locations, rotational as well as linear accelerometers were used. The aircraft was excited using two electrodynamic shakers which applied force at the wing tips.

Figure 3 shows a shaker mounted on a stand applying a vertical force to the wing. The shaker was attached to the wing with a thin metal rod, or stinger, which applied the axial force. This vertical shaker configuration excited wing flapping and torsion modes. The shaker was also positioned to apply a horizontal force to excite in-plane, or chordwise, wing bending modes.

Two types of forcing methods were used. The first was a swept-sine method in which each shaker applied approximately 90 pounds of force sweeping in frequency from 2 to 40 Hz. The shakers could be made to act either in-phase or out-of-phase with each other to excite symmetric and antisymmetric modes, respectively. The second method used was random excitation from 0 to 37.5 Hz. This method used a lower force level and excited both symmetric and antisymmetric modes simultaneously.

The data acquisition system consisted of a Hewlett-Packard 3565S dynamic analyzer that used Vista software to acquire data (ref. 8). Signals from each of the 134 accelerometers and 2 load cells measuring shaker force were input to the analyzer. The Vista program then computed frequency response functions which provided the frequency and damping of the vibration modes.

Pretest Predictions

The NASTRAN finite element computer model of the XV-15 was used to determine the optimum suspension system configuration and ensure that the suspension modes were not coupled with aircraft modes. The model was also used to predict the XV-15 vibration modes before the ground vibration test began.

The NASTRAN model is shown in figure 5. The actual model is 1036 degrees of freedom and is a half-model taking advantage of the symmetry of the XV-15 about the longitudinal axis. The model was originally created by Bell Helicopter Textron, Inc. in the 1970s to predict free-free modes and frequencies of the XV-15. Modifications were made to this model to better simulate the shake test setup. The additions include the inverted-V suspension system, tail bungee, dummy blade weights, and gravity.

The major components of the suspension system were modeled to predict their impact on the overall system dynamics. The crane hook and cables were modeled using rigid beam elements. The bungee cords were modeled using an element with an axial stiffness of 228 lb/in. equal to the bungee stiffness on the left and right sides of the inverted-V. Weights for the suspension components were distributed onto each node point of the suspension model. The upper and lower brackets were 70 and 30 lb, respectively. The total bungee cord weight was 22 lb, and the combined weight of the cables, turnbuckles and wing hoist attachment was 80 lb on the left and right sides. The weight above the bungee (upper bracket and crane hook) was isolated from the aircraft due to the flexibility of the bungees. However, the weight below the bungees was effectively added to the system dynamics. For this reason, the suspension weight was minimized to prevent alterations to the modes.

The suspension configuration was determined using the NASTRAN model by minimizing the deviation from the free-free modes. It was found that the highest possible inverted-V should be used to minimize lateral forces acting at the wing attachment points. This also allowed the bungees to attach nearly perpendicularly to the XV-15 wings.

The dummy blade weights were modeled as three point masses representing the three steel blades weighing 181 lb each. The blade weights were modeled with an offset of 13.5 in. from the hub as shown in figure 5. This offset matches the distance of the blade weights from the hub in the shake test. The tail bungee, which opposed the nose-down moment of the aircraft, was modeled with a spring element with a stiffness of 45.5 lb/in., also matching the ground vibration test configuration.

Table 1 shows the NASTRAN results for the symmetric and antisymmetric mode shapes for the XV-15 configured in the airplane mode with steel rotor blades. The first column shows the free-free results, which is the baseline case. The second column shows the change in frequency when the suspension system and tail bungee were added. The third column includes the blade weights offset from the hub as compared with a single point mass at the hub. The modes in this last column which include the combined effects of the test setup, were used as a pretest prediction for the ground vibration test. The effect of gravity on the modes was negligible.

Table 1. The symmetric and antisymmetric NASTRAN modes showing the effects of the suspension system and dummy blade weights

Symmetric and antisymmetric modes (Hz)	Free-free XV-15	XV-15 with suspension	XV-15 with suspension and blade weights
Sym. wing flap	3.16	3.06	3.06
Sym. wing chord	5.71	5.55	5.54
Asy. wing flap	6.35	6.31	6.29
Asy. wing chord	7.52	7.10	7.04
Asy. wing torsion	8.13	7.84	7.81
Sym. wing torsion	8.20	7.81	7.73

A comparison of the first two columns in table 1 shows that the suspension system lowers the frequencies from the free-free model. The modes decreased an average of 2.4%. This decrease is due primarily to the added weight of the suspension system and in part to the physical interference of hanging the aircraft from its wings. This was determined by successive design iterations using the NASTRAN model. By comparing columns 2 and 3 it can be seen that the dummy blade weights had a smaller impact on the modes. They caused the frequencies to decrease an average of 1%. These blade weights affected the wing modes as a result of the rotational inertia transferred through the hub.

The support system also introduced low frequency suspension modes in which the XV-15 moves as a rigid body under the flexing of the bungee cords.

The highest frequency suspension mode predicted was 0.96 Hz which was well below the first bending mode of 3.06 Hz. This separation of the suspension modes from the aircraft dynamics was necessary to prevent coupling of the motion and an alteration of the XV-15 dynamics.

Figure 6 illustrates the motion of two modes predicted by the NASTRAN model. The dashed lines represent the mode shapes, whereas the solid lines are the undeflected model. The first is the 0.96 Hz suspension mode which couples a vertical bob of the aircraft with a pitching motion. The first symmetric wing bending mode is also shown. The XV-15 wings are able to vibrate unhindered by the support.

Test Results and Correlation With Predictions

Test results were obtained for both the swept-sine and random excitation methods. The Vista software was used to calculate the frequency response function shown in figure 7, which resulted from a random applied load in the vertical direction from 0 to 12.5 Hz. Each peak represents a vibration mode of the system. The Vista program is used to curve fit each peak and estimate the frequency and damping of each mode. For example, the symmetric wing chordwise bending and torsion modes are identified in figure 7.

A more complete listing of the symmetric and antisymmetric modes are shown in table 2. Here the test data obtained from the swept-sine and random methods are compared with the NASTRAN predictions. Both sets of measured results are higher than the predictions. The swept-sine results are an average of 9% higher whereas the random results are 11% higher than the NASTRAN frequencies. Despite this, the NASTRAN modes were a key means of mode identification and were used for comparison with test data. There was an antisymmetric mode at 5.9 Hz which the NASTRAN model did not predict. This was a faint mode combining lateral tail bending with antisymmetric pylon yaw. In addition, a small symmetric pylon yaw mode at 7.6 Hz was not predicted. However, the NASTRAN finite element model did predict all of the major modes shown in table 2.

It was expected that the XV-15 would exhibit nonlinearities in its structural dynamics. Tiltrotors are in general more nonlinear than airplanes due to the complexities of the wing pylon structure. Table 3 illustrates this nonlinearity by comparing the change in frequency for different force levels. A linear system should exhibit the same frequency despite changing the force applied by the shaker. However, as shown in the figure, the modes increase in frequency as the shaker force is increased.

Table 2. Correlation of test data with NASTRAN predictions. Dashed line indicates a mode not excited

Symmetric and antisymmetric modes (Hz)	NASTRAN model	Test data, swept-sine excitation	Test data, random excitation
Sym. wing flap	3.06	3.43	3.51
Sym. wing chord	5.54	6.41	6.71
Asy. pylon yaw	–	5.87	5.91
Asy. wing flap	6.29	7.47	–
Sym. pylon yaw	–	7.57	7.56
Asy. wing chord	7.04	7.99	–
Asy. wing torsion	7.81	8.31	8.59
Sym. wing torsion	7.73	8.22	8.37

Table 3. Comparison of modal frequencies with varying shaker force. Dashed line indicates a mode not excited

Symmetric and antisymmetric modes (Hz)	Swept-sine, full amplitude	Swept-sine, half-amplitude	Random excitation
Sym. wing flap	3.43	3.45	3.51
Sym. wing chord	6.41	6.70	6.71
Asy. wing flap	7.47	7.52	–
Asy. wing torsion	8.22	8.34	8.37
Sym. wing torsion	8.31	8.43	8.59

The forcing levels were 90 lb for the swept-sine full amplitude, 45 lb for the half-amplitude, and a lower random force for the random force. The differences between the full amplitude swept-sine and the random frequencies was an average of 3%, signifying a fair degree of system nonlinearity. It was for this reason that both swept-sine and random methods were used.

Conclusions

The shake test was a valuable means for determining the structural dynamic characteristics of the XV-15. Previous to this test, the estimated modal frequencies used to determine aeroelastic instabilities were lower than the true XV-15 dynamics. Now the actual modal frequencies measured in the ground vibration test will be used for further stability research. Although the NASTRAN predictions were an average of 9 and 11% lower than the swept-sine and random data, respectively, the finite element model was a valuable tool in modal identification. The major importance of the NASTRAN model was its use as design tool to study the effects of suspension system changes.

The modifications to the NASTRAN finite element model led to a better design of the suspension system. The model was also used to understand the effects of the test setup on the ideal, free-free configuration. The model predicted the effects of the dummy blade weights offset from the hub's center to be minimal. The offsets caused the frequencies to decrease an average of 1%. Moreover, the effect of gravity was negligible.

It was found that the suspension system used in the test gave a good approximation to the ideal, free-free configuration. The bungee cords effectively isolated the aircraft modes from suspension modes that were well below the first wing bending frequency. The inverted-V suspension system and tail bungee were predicted by NASTRAN to lower the frequencies an average of 2.4% from the free-free case. This change is attributed primarily to the weight of the cables and brackets above the wing rather than the bungee cords or suspension modes. However, the change due to the suspension is much less than that due to resting the XV-15 on its landing gear. Also, the degree of interference from the suspension was acceptable, given the system nonlinearity of the XV-15. This was illustrated by the average 3% difference between swept-sine and random forcing methods.

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Biographies

Karen Studebaker has worked for four years as an Aerospace Engineer at NASA Ames Research Center in Moffett Field, California. She works on research related to advanced, civil tiltrotor concepts as well as conventional helicopters. She received a B.A. in Physics from Colgate University in 1986 and an M.S. in Aerospace Engineering from Virginia Tech in 1988.

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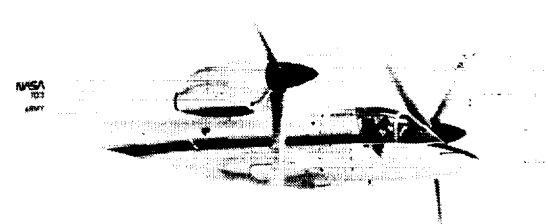


Figure 1. XV-15 Tiltrotor Research Aircraft in airplane mode with steel-bladed rotors.

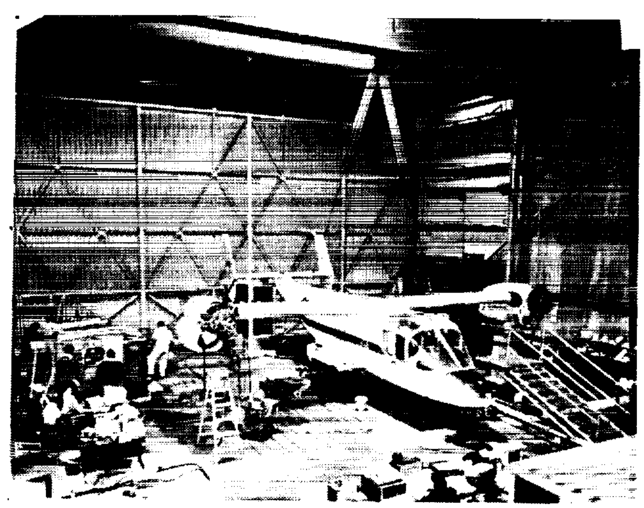


Figure 2. The XV-15 ground vibration test setup.

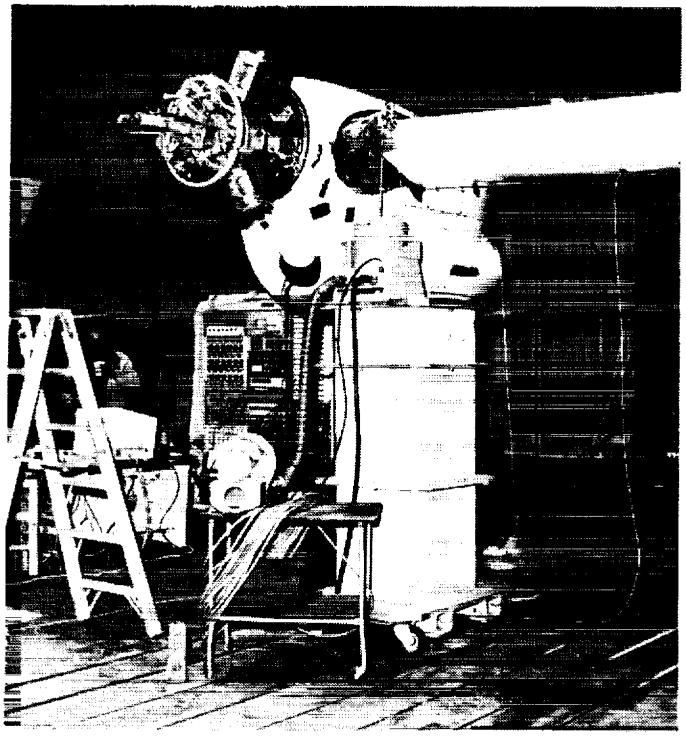


Figure 3. XV-15 hub showing the dummy blade weights and the electrodynamic shaker applying vertical force to the wing.

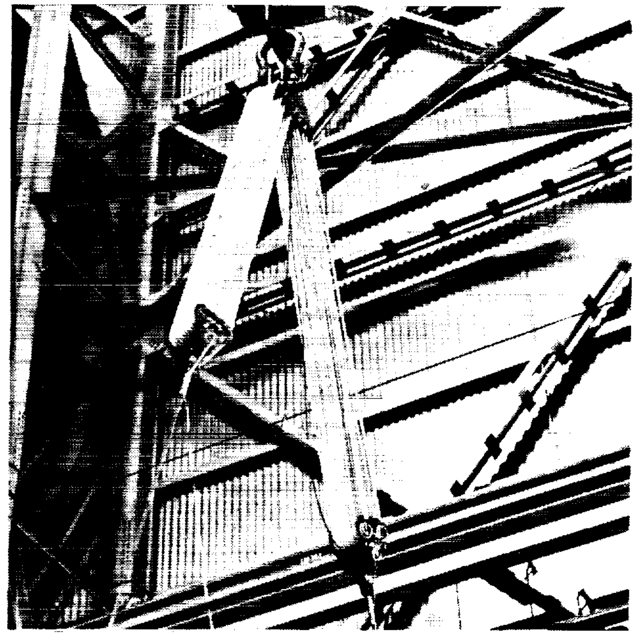


Figure 4. The 40 bungee loops which isolated the suspension system from the aircraft dynamics.

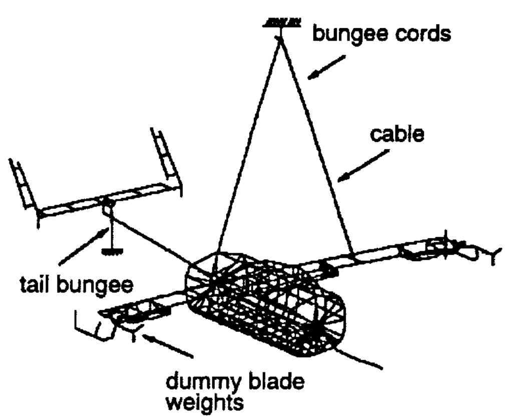
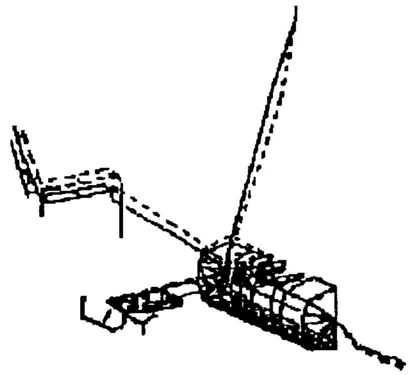
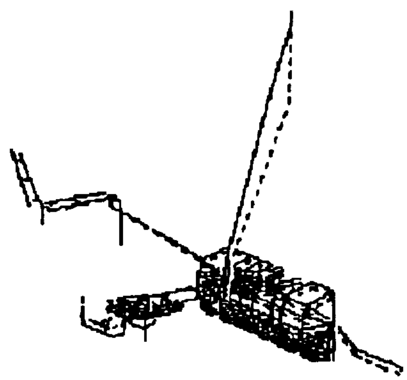


Figure 5. The NASTRAN finite element model of the XV-15.



Pitch rigid body mode, 0.96 Hz



Symmetric flapwise wing bending, 3.06 Hz

Figure 6. Two mode shapes predicted by NASTRAN.

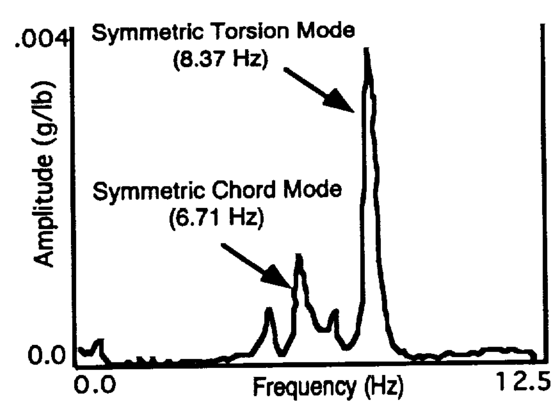


Figure 7. Frequency response function from random, vertical excitation.