Shake Test Results and Dynamic Calibration Efforts for the Large Rotor Test Apparatus

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Introduction

A shake test of the Large Rotor Test Apparatus (LRTA) was performed in an effort to enhance NASA's capability to measure dynamic hub loads for full-scale rotor tests. This paper documents the results of the shake test as well as efforts to calibrate the LRTA balance system to measure dynamic loads.

Oscillatory hub loads are the primary source of vibration in helicopters and other rotorcraft, leading to passenger discomfort and damage due to fatigue of aircraft components. There are novel methods being developed to reduce rotor vibrations, but measuring the actual vibration reductions on full-scale rotors remains a challenge. In order to measure rotor forces on the LRTA, a balance system in the non-rotating frame is used. The forces at the balance can then be translated to the hub reference frame to measure the rotor loads. Because the LRTA has its own dynamic response, the balance system must be calibrated to include the natural frequencies of the test rig.

For this test, a very large shaker system was used to excite the LRTA at known frequencies and magnitude. In addition to measurements from the balance and shaft bending gauges, the test rig was instrumented with accelerometers in order to measure the dynamic response of the entire LRTA. The intent of collecting accelerometer measurements was to provide data that could be validated against a finite element model of the LRTA. Results of the shake test, as well as comparisons with finite element and other reduced-order analyses are presented here. The ultimate goal is to use the shake test data, along with finite element models of the LRTA, to generate a dynamic calibration of the balance. This dynamic calibration would then be used to correct oscillatory hub load data acquired during the UH-60A Airloads wind tunnel test, documented in Ref. 1.

Test Description

The shake test was carried out in the 40- by 80-foot test section of the National Full-scale Aerodynamics Complex (NFAC). The LRTA was mounted on the same struts as it was during the actual wind tunnel test. The UH-60A shaft extender and hub were mounted on the LRTA output shaft, and the "instrumentation hat" was mounted on top of the hub, but the UH-60A blades were not present. In order to facilitate shaking in the vertical direction, an adapter was fitted to the hub. Two hundred pounds of lead weights were also attached to the vertical shake adapter to help evaluate the impact of hub mass.

To provide the shaking force, a hydraulic actuator system was used. The point of application of in-plane oscillatory loads was the hub bifilar. A 12,000 lb reaction mass was hung from the NFAC gantry crane and secured by guywires attached to the wind tunnel floor to support the hydraulic actuator. The test setup is shown in Fig. 1. Sinusoidal loads were generated by the actuator using a feedback control system. A swept sine signal ranging from 0 to 80 Hz was used as input.

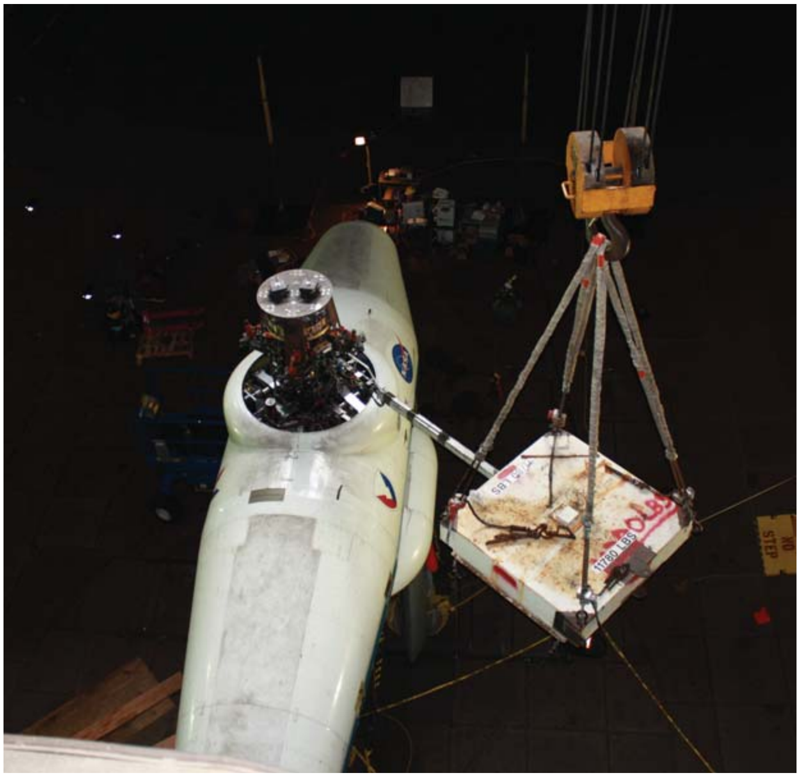

Figure 1. Shake test installation. In-plane shaking at 45° azimuth

The primary balance gauges were used to collect loads data, and the shaft bending gauges provided additional loads measurements. To help with validation of existing NASTRAN models of the LRTA, 49 accelerometers were placed at various locations on the test rig. These locations are shown in Fig. 2.

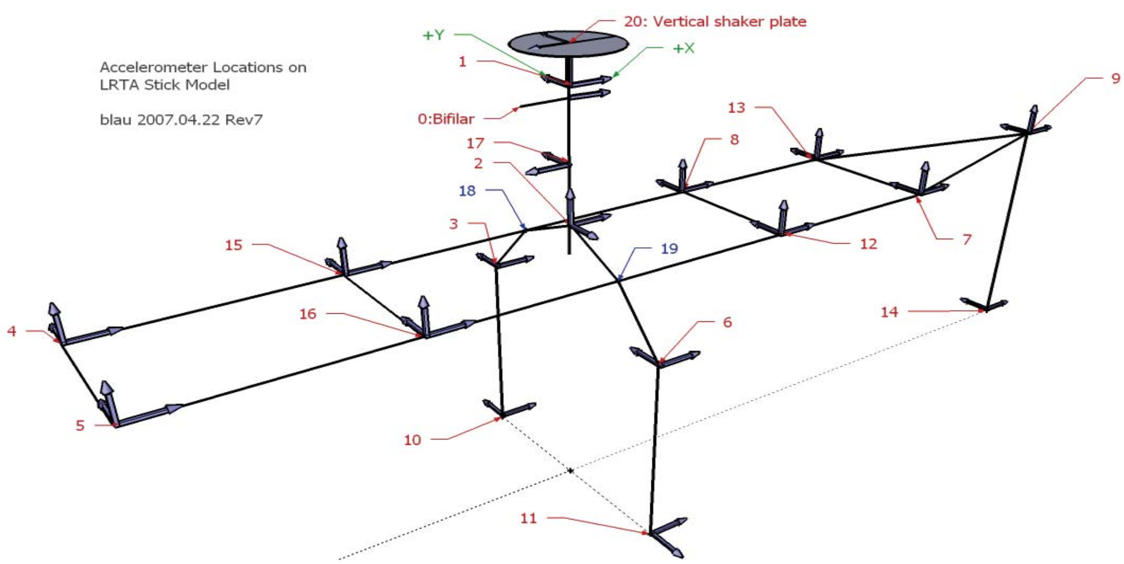

Figure 2. Shake test accelerometer locations

The test matrix is given in Table 1. The majority of testing was performed with the vertical shake plate adapter attached to the hub. Additional testing was performed with the shake plate removed to determine its effect on the frequency response and the tail strut was extended to see if there was any effect of changing angle of attack. Only a limited number of shake directions were tested for these additional scenarios.

Table 1. Shake test matrix. Shaking direction is indicated as in-plane (IP) or vertical (VT) along with the azimuth of shake application.

Configuration	IP 0°	IP 270°	IP 315°	IP 50°	VT center	VT 0°	VT 270°	VT 315°
With shake plate and 200lb mass	✓	✓	✓	✓	✓	✓	✓	✓
With shake plate and no 200lb mass	✓	✓	✓	✓	✓	✓	✓	✓
With shake plate and LRTA 10° nose down		✓						
Without shake plate	✓	✓						

Results

A calibration has been attempted and the results were used to reduce data taken during the recently completed UH-60A Airloads wind tunnel test. The main complication that has arisen during the data processing is that the mass of the hub (along with any hardware mounted to it) has a large impact on the dynamic response measured by the balance. This is a similar result to that observed during dynamic calibration efforts on the Rotor Test Apparatus (RTA), described in Refs. 2-3. The RTA dynamic calibration efforts also investigated the effects of pre-load and rotation of the rotor shaft, but found that hub mass had the largest effect.

Further complicating any attempts at using a dynamic calibration to correct the Airloads data is the fact that the strongest response of the LRTA is very close to the 4/rev frequency of the UH-60A rotor. The response to in-plane shaking at 0° azimuth measured by the axial balance gauges is shown in Fig. 3. The red and green curves show measurements taken with the vertical shake plate adapter in place both with and without the additional 200 lb weight on the hub. The blue curve shows the frequency response function when the shake plate (weighing approximately 380 lb) is removed. As Fig. 3 shows, changing the mass at the hub by only 200 lb has a very large impact on the dynamic response.

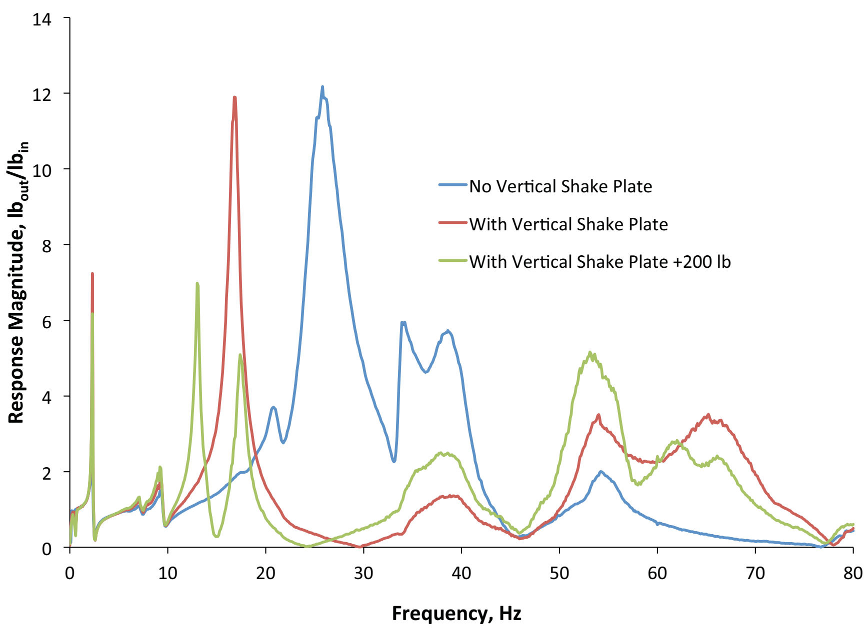

Figure 3. Frequency response measured at the LRTA balance in axial direction for axial shaking

Because the dynamic response of the LRTA is strongly affected by hub mass, generating a usable dynamic calibration with only the balance data may be an intractable problem. Another option is to generate a finite element model that can be tuned to replicate the behavior of the LRTA, and then generate transfer functions based on simulation results. Accelerometer data was used to compare the results of the shake test with an existing NASTRAN model of the LRTA. Several of the modes identified by analysis of the NASTRAN model were clearly visible in the shake test data. Figure 4 shows a comparison between one of the NASTRAN mode shapes and the corresponding shape measured by the accelerometers. The modes that are visible in both the NASTRAN model and the accelerometer data are identified in Table 2. Even though the shapes are similar, the frequencies are not identical. In general, NASTRAN overpredicts the frequency, and the amount of overprediction increases with the frequency of the mode. The data shows that the modes involving motion of the entire LRTA are not affected by the mass of the hub. The modes that involve only motion of the hub and rotor shaft, however, are very sensitive to the mass placed on the hub.

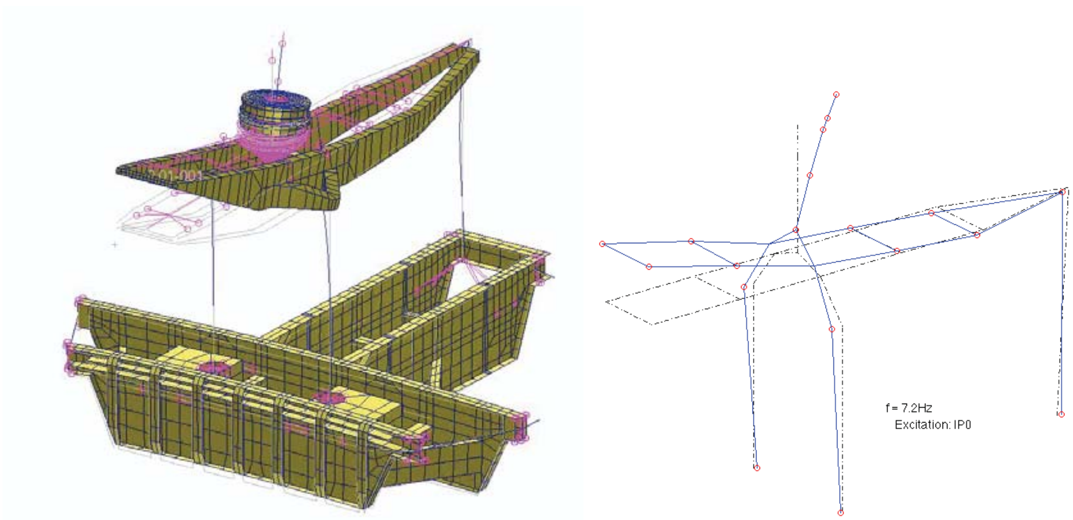

Figure 4. Comparison of NASTRAN model and accelerometer data mode shapes

Table 2. Modes and frequencies from both the NASTRAN model and accelerometer data

Mode Shape	NASTRAN Frequency (Hz)	Accel. Frequency (Hz)
Longitudinal strut bending	2.4	2.3
Chassis vertical bending	8.9	7.2
Chassis + T-frame vertical bending	13.4	9.3
Rotor shaft lateral bending	26.1	15.9
Rotor shaft longitudinal bending	29.9	16.9

The last two modes listed in Table 2 involve very little motion of any component except the rotor shaft and hub. In order to help determine whether bending of the rotor shaft was indeed the culprit in causing the large response near 4/rev, some lower-order calculations were made to estimate the natural frequencies of the rotor shaft. The assumptions were that the upper and lower bearings on the rotor shaft form rigid constraints. A Rayleigh-Ritz approximation was made to calculate the rotor shaft natural frequencies. A quadratic mode shape was assumed, and the resulting calculations gave a calculated frequency of 12.6 Hz assuming a hub weight of 800 lb. While not identical to the frequency observed in the shake test, this result further indicates that the oscillatory loads measured by the balance gauges were in fact being strongly affected by the first bending mode of the rotor shaft.

To explore whether a FEA model could be tuned to match the behavior of the test rig, a solid model was developed using the Creo mechanical design software suite. Because the shaft bending modes involve very little motion of the LRTA chassis, a simplified FEA model was used, including only the LRTA output shaft and UH-60A shaft extender. As with the lower-order calculations, it was assumed that the bearing constraints were rigid, with the lower bearing constrained in the axial and radial directions and the upper bearing constrained in only the radial direction. The shaft extender and output shaft were modeled together as a solid piece, and the hub was modeled as a point mass. Using only the mass of the hub (and ignoring the vertical shake adapter), the calculated frequency was 28.7 Hz, while the observed frequency in this configuration was 25.8 Hz. Changing the mass at the hub as well as adjusting the height of the hub above the top of the output shaft has a large effect on the first natural frequency observed, indicating that it will be possible to tune the FEA model to match the behavior of the LRTA. It appears that assuming the LRTA chassis is rigid and focusing only on the output shaft can produce an acceptable result, but further tuning of the model is required.

Initial Conclusions and Further Directions

The frequency response of the LRTA is strongly affected by the mass of the hub mounted on the output shaft. The variation in natural frequencies makes measuring vibratory hub loads of the full-scale UH-60A Airloads rotor very difficult, especially near 4/rev. The final paper will fully document the results of the shake test, including measurements for lateral, longitudinal, and vertical shaking.

There is promise in using an FEA model of the output shaft to calculate the response at the balance. By properly tuning the FEA model to match observed frequencies in the shake test data, it may be possible to generate transfer functions based on simulation. These transfer functions could ideally then be used to correct vibratory hub load data generated during the UH-60A Airloads wind tunnel test. More analysis is required and will be performed in the coming months.

References

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