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SUMMARY

A shake test was conducted in the 80- by 120-Foot Wind Tunnel at NASA Ames Research Center, using a load frame and dummy weights to simulate the weight of the NASA Rotor Test Apparatus. The simulated hub was excited with broadband random excitation, and accelerometer responses were measured at various locations. The transfer functions (acceleration per unit excitation force as a function of frequency) for each of the accelerometer responses were computed, and the data were analyzed using modal analysis to estimate the modal parameters.

INTRODUCTION

A shake test in the 80- by 120-Foot Wind Tunnel was conducted to determine the modal parameters—natural frequency, modal mass and damping—of a typical helicopter rotor set-up consisting of tunnel balance, turntable, struts and model (simulated by a load frame carrying dummy weights), as shown in figures 1(a) and 2. The primary objective of the shake test was to determine the amount of support system modal damping in this wind tunnel configuration for performing a rotor test using the Ames Rotor Test Apparatus (RTA) from the standpoint of potential ground resonance instability. If the damping coefficients of the resonant modes are below the analytically determined minimum values needed to ensure dynamic stability, then balance snubbers will be engaged to eliminate the balance mode thus increasing the stiffness of the system. An increase in the overall system stiffness implies an increase in natural frequency, which results in increased critical damping values at the remaining modes of vibration.

The location of the RTA rotor hub was simulated by structural beams without modeling of the hub or the blade mass, because this preliminary shake test was conducted to determine only the support system dynamic characteristics.The rotor-off hub accelerometer responses were measured in the longitudinal direction, i.e., longitudinal in-plane acceleration of the hub to the longitudinal in-plane applied force, and likewise in the lateral direction. The shake tests were performed parallel and perpendicular to the wind directions, i.e., at 0° and +90° yaw with respect to the wind tunnel flow direction, as shown in figures 3(a) and 3(b). For this study, longitudinal and lateral directions are defined relative to the load frame and model support system and therefore the model is re-oriented relative to the wind direction when the model is yawed.

The model was shaken at +90° yaw to determine the dynamic characteristics of this setup as a plausible hover test configuration to alleviate the rotor/wake interaction problem, which may alter rotor hover performance if the wake is not blown away. It was conceived that the RTA could be set at an angle of attack of +30° (nose up) and yawed to +90° position (figs. 3(a) and 3(b)) to remedy the rotor/wake interaction problem, thus discharging the rotor downwash out through the 80- by 120-Foot Wind Tunnel doors. To achieve these configurations, the RTA might be installed on a different set of struts.

The distance between the strut tip attachment points and the hub, and the strut lengths between this simulated model setup and the actual RTA configuration may not be identical. This would necessitate a separate shake test for each RTA configuration, since dynamic characteristics are dependent on the strut configuration and model mass.

TEST SYSTEM DESCRIPTION

Model

The model consisted of a 4,500-lb load frame, using dummy weights to simulate the RTA weight (29,200 lb). The load frame was mounted on a combination of 40- by 80-Foot (15-ft struts and 6-in. strut tips) and 80- by 120-Foot Wind Tunnel struts (21-ft), which positioned the model strut attachment points 36.5 ft above the tunnel floor. For all the shake test configurations, the tunnel balance and T-frame were not restricted from motion in any direction.

Test Apparatus

A hydraulic actuator was used to excite the model and the support system at the simulated hub position as shown in figure 1(b). One end of the hydraulic actuator was attached to a 5-ft-long extension arm. The other end of the actuator was attached to the dummy hub, approximately 45 ft above the tunnel floor (8.5 ft above the strut tips). The extension arm was attached to an 11,600-lb reaction mass hung from a gantry crane, as shown in figures 1(a), 1(b) and 2. The shaker was aligned with respect to the extension arm, which was in turn aligned parallel to each of the shake directions (longitudinal or lateral, 0° or +90° yaw; see figs. 3(a) and 3(b)) to minimize excitation of modes in directions orthogonal to the shake direction. After achieving rough alignment of the actuator and the extension arm using the gantry crane, finer alignment was achieved by applying tension to the guy wires attached between the reaction mass and tunnel floor. The guy wires also restrained swinging of the reaction mass during actuator excitation.

A load cell located between the hydraulic actuator and the hub measured the applied force. Accelerometers were mounted on various locations on the model/load frame and the balance T-frame in the longitudinal and lateral directions with respect to the coordinate system shown in figures 3(a) and 3(b). These accelerometer mounting locations were selected in order to provide large acceleration response to provide more information on the yaw modes of the model, balance frame, and the response of the load frame relative to the balance frame. These accelerometers were placed at the following locations, as shown in figure 2: 1) at the midpoint of the front struts on the T-frame (baseline), 2) at the midpoint of the T-frame between the front and the tail struts, 3) behind the tail strut on the T-frame, and 4) at the interconnection between the 40- by 80-Foot and the 80- by 120-Foot Wind Tunnel struts (see fig. 2).

Data Acquisition System

Transfer function data were acquired and stored on a 16-channel GenRad Model 2515 Computer-Aided Test System. It is a portable digital signal processing system for general purpose data acquisition and analysis. The data acquisition system is capable of analyzing data in the frequency range from DC to 25.6 KHz AC signal with alias protection on all channels.

Test Procedures

The GenRad acquisition mode was set to acquire data in the frequency range of 0 to 32 Hz to identify ground resonance, and up to 4/rev vibration modes of a typical four-bladed rotor system.

The test conditions for lateral and longitudinal shake tests at 0° and +90° yaw, shown in figure 3(a) and 3(b), were as follows:

1. Random excitation, bandwidth 0 - 32 Hz, nominal force (half peak-to-peak) = ±400 lb, 50 data averages, balance T-frame accelerometers (roving accelerometers) at baseline location (see fig. 2),

2. Random excitation, bandwidth 0 - 16 Hz, nominal force (half peak-to-peak) = ±400 lb, 50 data averages, roving accelerometers at baseline location (see fig. 2). Following the previous data acquisition procedure it was deemed unnecessary to acquire data on 0 to 32 Hz bandwidth, since there were no distinguishable support system natural frequencies in the 16 to 32 Hz bandwidth.

3. Random excitation, bandwidth 0 - 16 Hz, nominal force (half peak-to-peak) = ±400 lb, 200 data averages, roving accelerometers at baseline location (see fig. 2),

4. Random excitation, bandwidth 0 - 16 Hz, nominal force (half peak-to-peak) = ±400 lb, 50 data averages, roving accelerometers at the middle of the balance T-frame (see fig. 2),

5. Random excitation, bandwidth 0 - 16 Hz, nominal force (half peak-to-peak) = ±400 lb, 50 data averages, roving accelerometers on the T-frame behind the tail strut (see fig. 2),

6. Random excitation, bandwidth 0 - 16 Hz, nominal force (half peak-to-peak) = ±400 lb, 50 data averages, roving accelerometers on the left strut at the interconnection between 40- by 80-/80- by 120-Foot Wind Tunnel struts (see fig. 2),

7. Random excitation, bandwidth 0 - 16 Hz, nominal force (half peak-to-peak) = ±400 lb, 50 data averages, roving accelerometers on the right strut at the interconnection between 40- by 80-/80- by 120-Foot Wind Tunnel struts (see fig. 2).

TEST RESULTS

Data

Figures 4 to 7 present the hub response transfer functions for the four configurations tested. The shake directions are defined with respect to the coordinate system shown in figures 3(a) and 3(b). In figure 4 (longitudinal shake at 0° yaw) resonant peaks in the longitudinal response direction occur at 1.35, 1.92, 2.89, 6.70, 7.50, and 11.00 Hz. Resonant peaks shown in figure 5 (lateral shake at 0° yaw) occur at 1.78, 2.37, 2.87, 6.60, 8.50, and 12.00 Hz. The natural frequencies in figure 6 (longitudinal shake at +90° yaw) occur at 1.47, 2.15, 2.94, 5.50, 6.30, and 9.20 Hz. In figure 7 (lateral shake at +90° yaw) the resonant peaks occur at 1.50, 2.28, 2.77, 5.70, 7.20, 8.50, and 9.10 Hz.

The first three modes in each of the transfer functions were identified as support system structural modes, which were determined by comparing the magnitudes and phases between the hub accelerometers with those at other locations. In the absence of sufficient fixed system damping, coupling between the rotor and the model support system could cause potentially hazardous ground resonance.

The frequencies above 5 Hz could have been caused by the flexibility of the simulated hub and the rocking motion of the concrete blocks supported by the model load frame to simulate the RTA weight. The influence of these high frequency large amplitude vibrations on the lower frequency responses cannot be overlooked because they influence the transfer function curve fits of the latter as will be discussed later.

Analysis Techniques

The data were analyzed using the SDRC Modal Plus software package (ref. 1). Modal Plus provides four methods to determine the modal parameters from frequency response functions. The four methods are search peak, complex exponential, direct parameter and polyreference methods.

The search peak method computes a good estimate of the modal parameters and fits a smooth curve over the transfer function using these estimated modal parameters, provided the resonant peaks are well defined (i.e., at least 2 Hz apart and can be modeled as second-order single degree-of-freedom systems).

For resonant peaks that are close to each other, the complex exponential method, a time domain algorithm, computes a better estimate of modal parameters at the resonant peaks of the transfer function.

The direct parameter method is a frequency domain, multiple degree-of-freedom curve fitting algorithm which computes a global estimate of the modal characteristics from several response locations with respect to a single excitation or reference location.

The polyreference method is a time domain complex exponential algorithm capable of multiple degrees-of-freedom curve fitting that provides a global estimate of modal parameters with respect to two or more excitation or reference locations (refs. 1,2).

Since the resonant peaks in most of these transfer functions are only a few hertz apart, the complex exponential method provided better curve fits of the data than the search peak method in the frequency range of interest, i.e., 1.0 to 3.0 Hz. This method computes polynomial coefficients in each of the time subintervals and steps through all the subintervals of the total time record until the entire time history is curve fitted, using the specified resonant frequencies and the computed polynomial coefficients. These coefficients are then used to compute the residues corresponding to each of the specified resonant peaks on the original curve, from which the modal parameters are then computed (ref. 1, ch. 6).

In actual usage of the analysis software, only the frequency range of interest and the number of resonant peaks on the original transfer function need be specified to obtain a curve fit. During modal parameter estimation at the resonant peaks, the analysis method assigns a default number of roots greater than the specified number of resonant peaks. It has been determined that allowing the algorithm to compute the default number of roots (nonphysical mathematical and actual roots) leads to better estimates of natural frequencies, and consequently, more accurate modal parameters. These mathematical roots are distinguishable from the real roots on the complete list of roots, either because the magnitudes of the residues are very small or the phase is close to 0 or π radians. Once all the roots have been computed the mathematical roots can be suppressed, beginning with the most obvious mathematical roots. The final curve fit is obtained by adding residual corrections to the curve fit, away from the resonant peaks to better fit the original transfer function.

Discussion of Results

Figures 8 to 14 present the curve fits of the transfer functions presented in figures 4 to 7. The curve fit in figure 8 spans frequency range of 1.06 to 3.25 Hz of figure 4 (hub longitudinal transfer function for 0° yaw shake), which encompasses the three modes of vibration attributed to support system natural frequencies. In figure 8, the curve fit over the peak at 2.94 Hz does not match the original transfer function peak, therefore this peak was curve-fitted in figure 9 over the frequency range of 2.48 to 3.34 Hz. Table 1 illustrates the physical and mathematical roots estimated by Modal-Plus and their corresponding modal values. The root numbers with adjacent asterisks depict the mathematical roots computed by the algorithm, but these roots were suppressed prior to obtaining the final curve fits shown in figures 8 and 9. The root numbers with adjacent diamonds are the physical roots occurring at the three modes of vibration representing the model support system response. In this shake test configuration, the damping values at 1.36, 1.92 and 2.89 Hz resonant peaks were 5.39, 5.02, and 3.99% of critical damping, respectively.

The plot in figure 10 is a curve fit of figure 5 (hub lateral transfer function for 0° yaw shake) over the frequency range of 1.31 to 3.73 Hz. The balance lateral mode at 1.77 Hz is almost undetectable and seems highly damped due to its low response level. One reason could be that the mode was not excited with sufficient energy using a broadband random excitation method of shaking. The damping values in this test configuration at 1.78, 2.37, and 2.87 Hz modes were 12.66, 3.87, and 2.61% of critical damping, respectively.

Figure 11 presents the curve fit of the transfer function data shown in figure 6 (hub longitudinal transfer function for +90° yaw shake) only over the frequency range of 1.09 to 2.60 Hz, because a good curve fit could not be obtained through the last response peak at 2.89 Hz. Figure 12 represents the curve fit of the original transfer function over the last resonance peak at 2.89 Hz, which consists of two very closely located response peaks at 2.88 and 2.93 Hz. These modes essentially correspond to the same yaw mode of the balance or load frame yaw mode. The slight difference in the natural frequencies may be due to small structural stiffness asymmetry either at the hub or the model support system in the longitudinal and lateral directions. The estimated damping at 1.47, 2.15, and 2.94 Hz modes were 3.46, 8.54, and 1.69 % of critical damping, respectively.

Figure 13 shows the transfer function curve-fit of figure 7 (hub lateral transfer function for +90° yaw shake) over the entire frequency range covering all three resonant peaks of interest. The curve fit matches the original transfer function better at frequencies above 2.00 Hz than at lower values. This discrepancy was also noticed in the curve fit over the third resonant peak in figure 8. It may again be due to greater curve-fit weighting distribution over the higher frequencies than at lower frequencies. The occurrences of high frequencies were attributed to the rocking/impacting motion of the dummy weights or load frame structural flexibility at the hub. Figure 14 represents the transfer function curve-fit of figure 7 (hub lateral transfer function for 90° yaw) only over the first resonant peak in the frequency range of 1.12 to 1.76 Hz. This curve fit seems to provide a better estimate of the damping ratio at this mode than the value of modal parameters obtained from the curve fit in figure 13. The damping values at 1.50, 2.28, and 2.77 Hz modes were computed to be 6.02, 2.38, and 1.94% critical damping, respectively.

TABULATED MODAL PARAMETERS

Table 2 gives a composite listing of the modal parameters in physical units corresponding to the physical modes of vibration of the model support system structure. Some of the modal masses have very large values—and one explanation is that the modal mass is a function of the transfer function value at the resonant peak. If the transfer function values at the peak are small, then the modal masses tend to be very large.

CONCLUSION

The shake test revealed all the low frequency modes of vibration of the wind tunnel model support system for the simulated RTA mounted in the NASA Ames 80- by 120-Foot Wind Tunnel.

From the reduced data it has been determined that there is at least 1.7 % critical damping in all the modes of vibration.

REFERENCES

1. User's Manual for MODAL-PLUS 9.0. General Electric CAE International, 1985.

2. Reference Manual for MODAL-PLUS 9.0. General Electric CAE International, 1985.

Table 1 - Estimate of roots for hub longitudinal response at 0° yaw

Roots	Frequency, Hz	Critical damping ratio	Residue, g's/lb	Phase, rad
1*	1.07	0.097	6.37E-06	0.00
2◊	1.35	0.055	8.80E-05	1.88
3◊	1.92	0.052	1.00E-04	1.43
4*	1.38	0.641	2.77E-04	0.00
5*	1.95	0.073	4.32E-06	–0.714
6*	2.61	0.031	2.36E-06	0.06
7◊	2.89	0.038	3.30E-05	1.23
8*	2.95	0.040	5.49E-07	–1.99
9*	3.31	0.011	1.79E-06	0.00
10*	3.42	0.243	3.62E-04	–3.142

* - mathematical roots
◊ - actual roots

Table 2 - Dynamic characteristics of simulated RTA in the 80- by 120-Foot Wind Tunnel (model wt = 29,200 lb, installed on 15-ft 40- by 80- and 21-ft 80- by 120-Foot Wind Tunnel struts with 6-in. strut tips)

Mode									
Longitudinal	f, Hz	H, g/lb	C, lb-sec/ft	M, lb	Lateral	f, Hz	H, g/lb	C, lb-sec/ft	M, lb
0° Yaw shake									
Balance	1.36	0.000200	1403	49233	Balance	1.78	0.000130	4447	50586
Strut	1.92	0.000200	2339	62210	Strut	2.37	0.000300	1574	44049
Balance/load frame yaw	2.89	0.000060	10633	236927	Balance/load frame yaw	2.87	0.000650	775	26532
90° Yaw shake									
Balance	1.47	0.000300	825	41538	Balance	1.50	0.000080	5481	104682
Strut	2.15	0.000050	16944	236798	Strut	2.28	0.000650	706	33262
Balance/load frame yaw	2.94	0.000055	18146	942011	Balance/load frame yaw	2.77	0.000800	728	34711

f - frequency
H - transfer function magnitude
C - damping coefficient
M - modal mass

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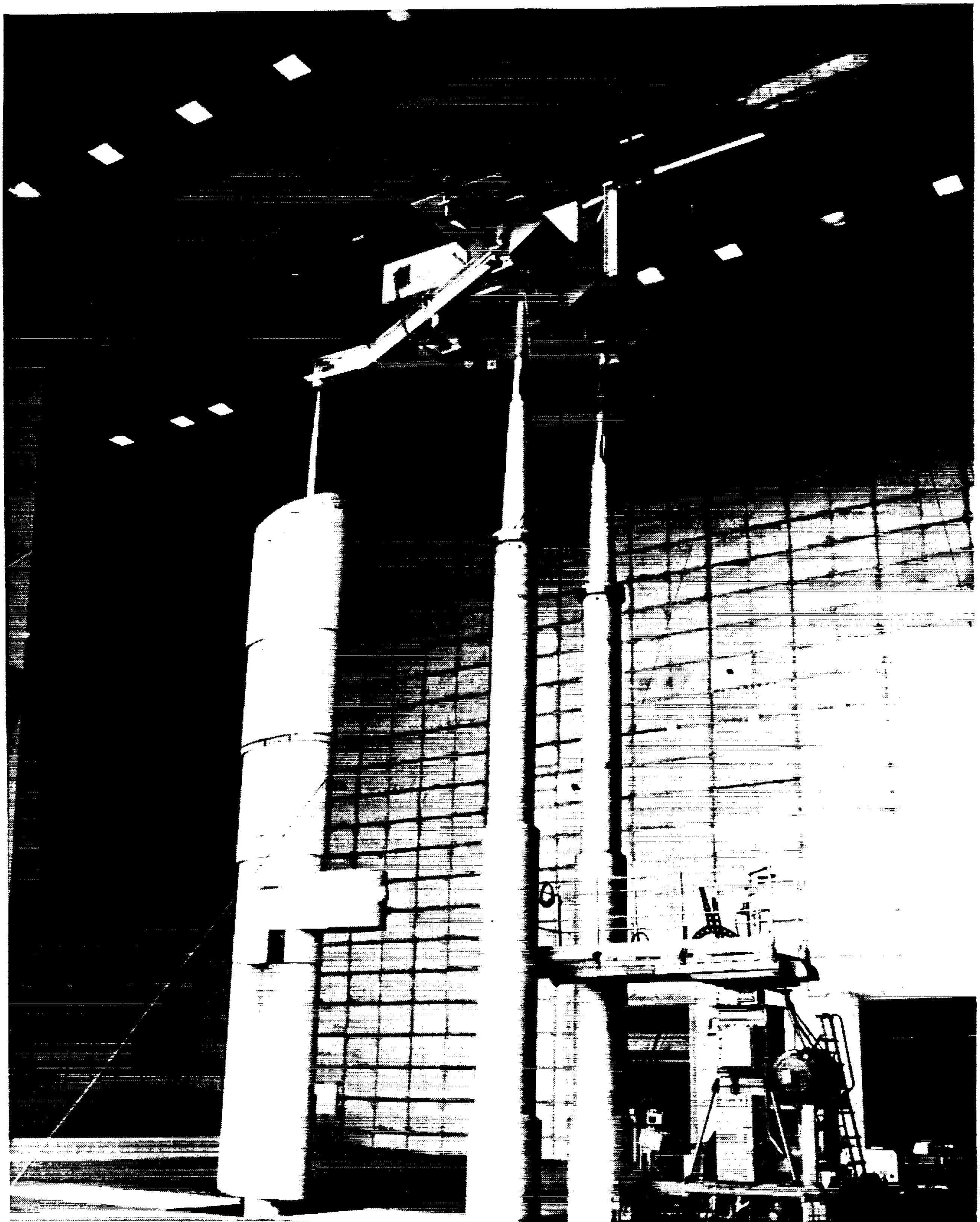

Figure 1(a). Shake test set-up of simulated rotor test apparatus in the 80- by 120-Foot Wind Tunnel.

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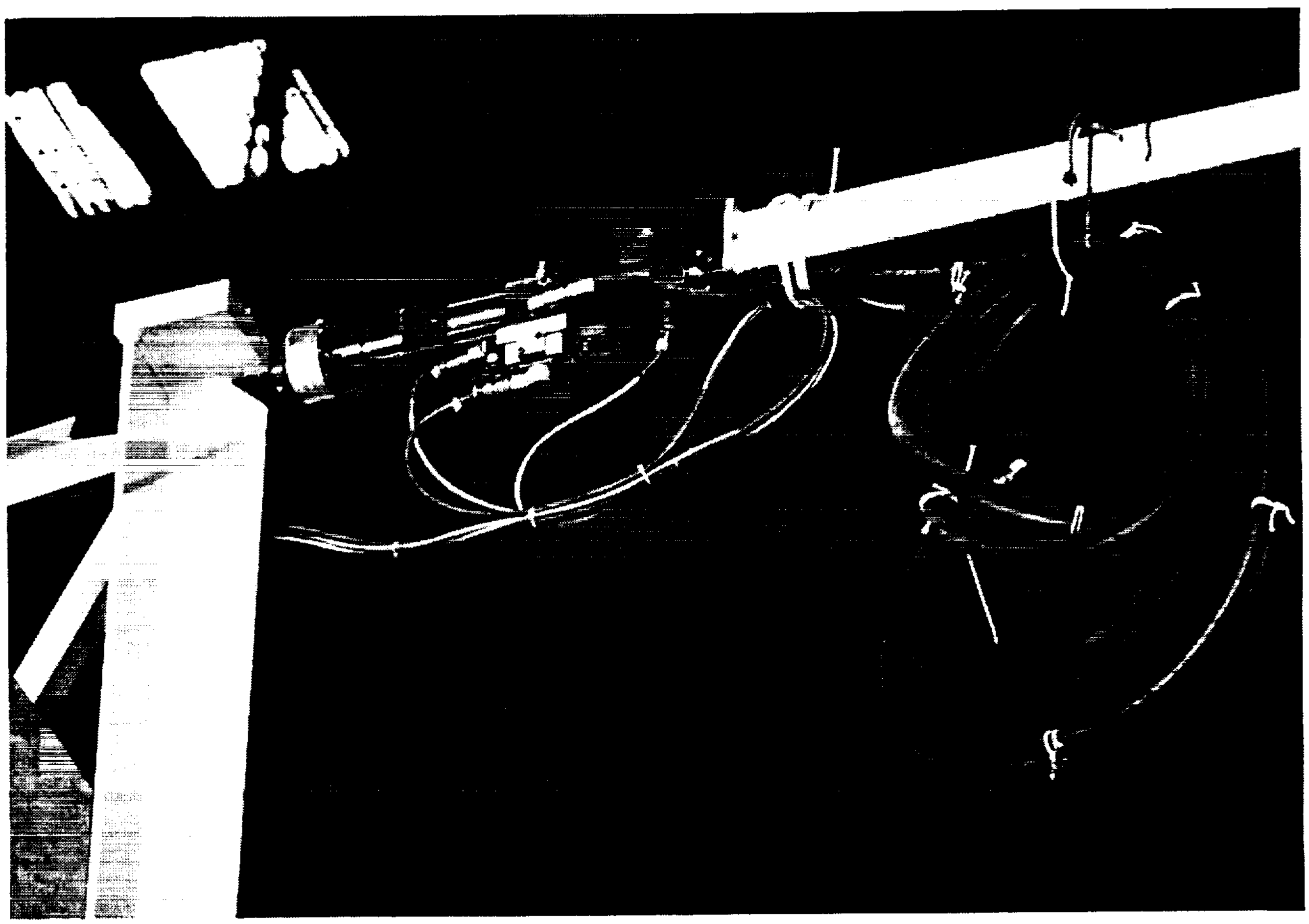

Figure 1(b). Load cell, extension arm, actuator and reaction mass set-up for the shake test in the 80- by 120-Foot Wind Tunnel.

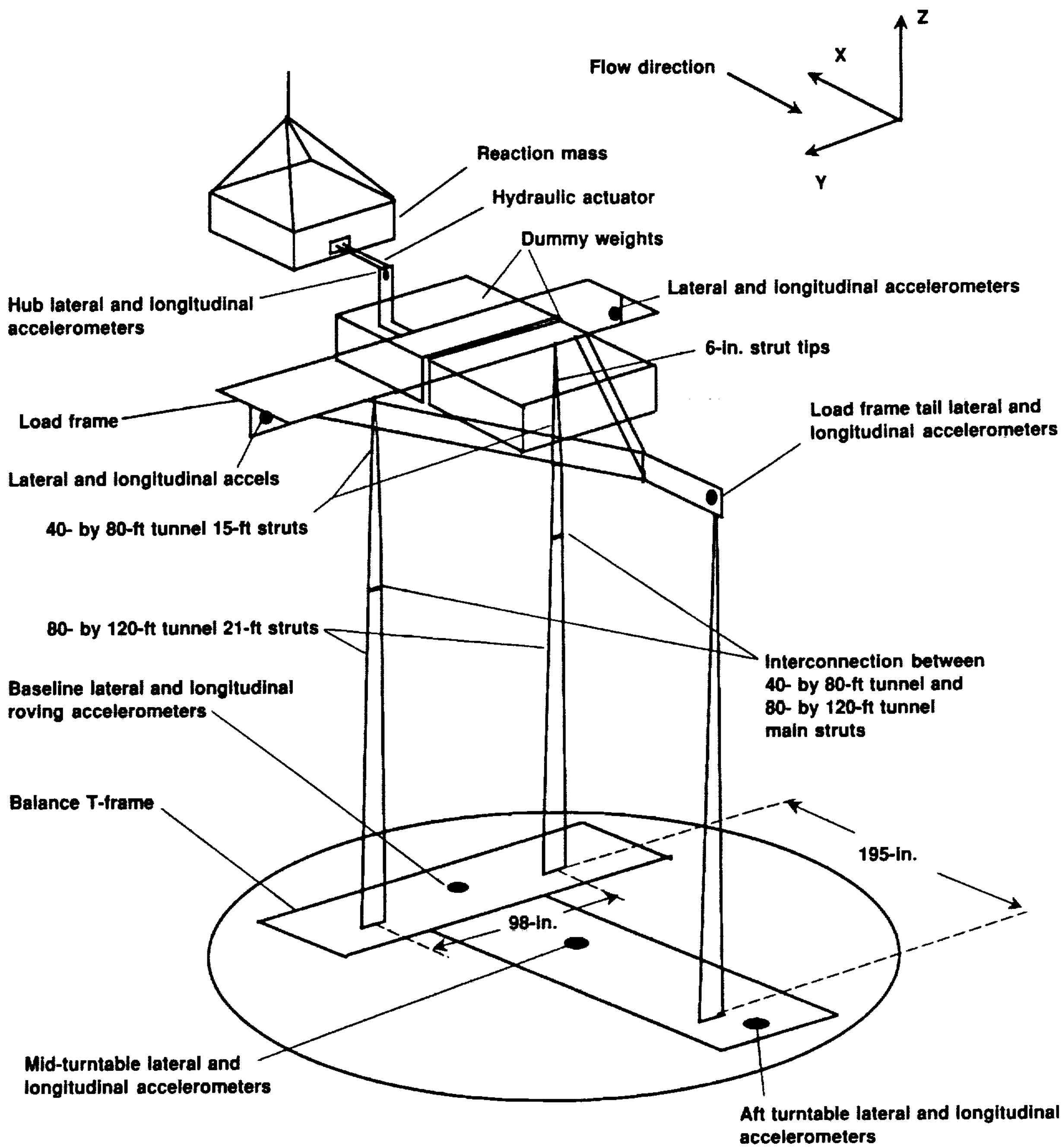

Figure 2. Shake test set-up of Simulated Rotor Test Apparatus (RTA) in the 80- by 120-Foot Wind Tunnel.

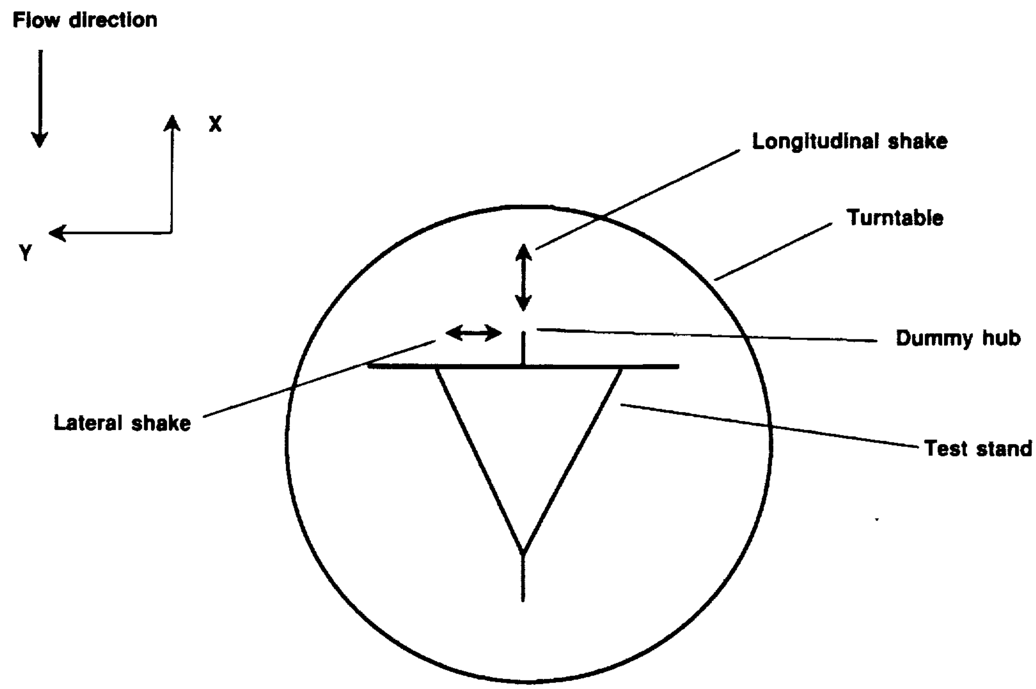

Figure 3(a). Longitudinal and lateral 0° yaw shake configuration.

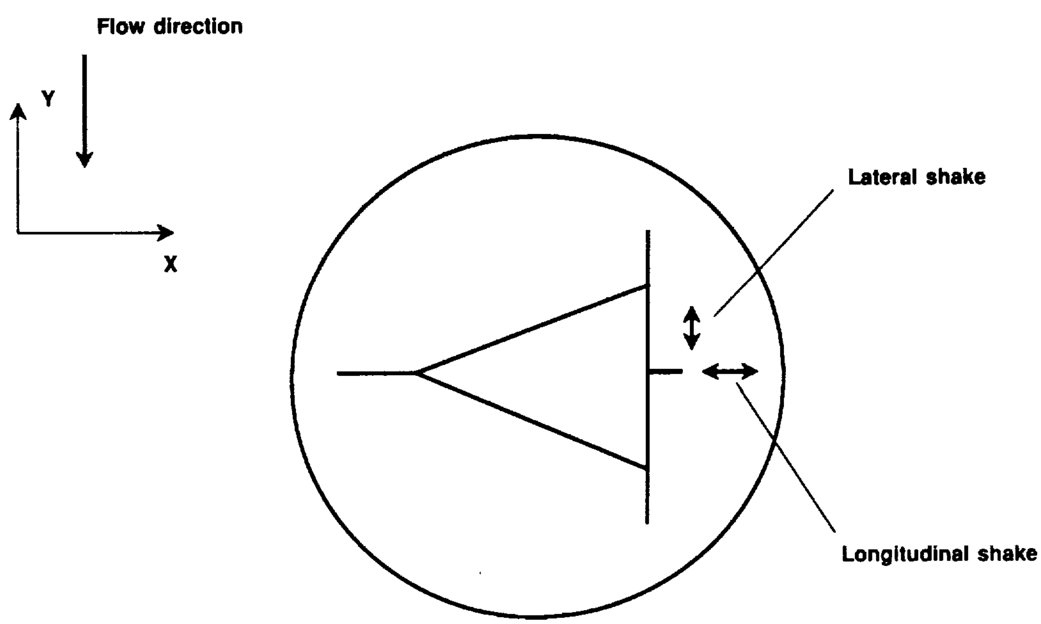

Figure 3(b). Longitudinal and lateral +90° yaw shake configuration.

Serial No.	Frequency, Hz	Phase
1	1.38	–219°
2	1.94	–297°
3	2.89	–213°

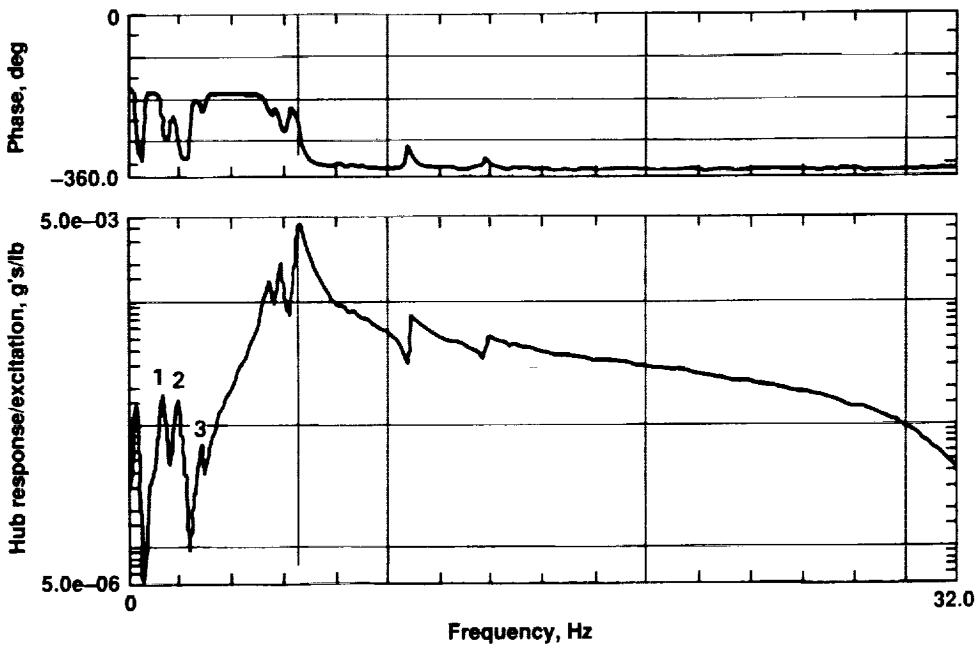

Figure 4. Transfer function of longitudinal hub response to longitudinal excitation, 0° yaw.

Serial No.	Frequency, Hz	Phase
1	1.78	–225°
2	2.37	–276°
3	2.88	–282°

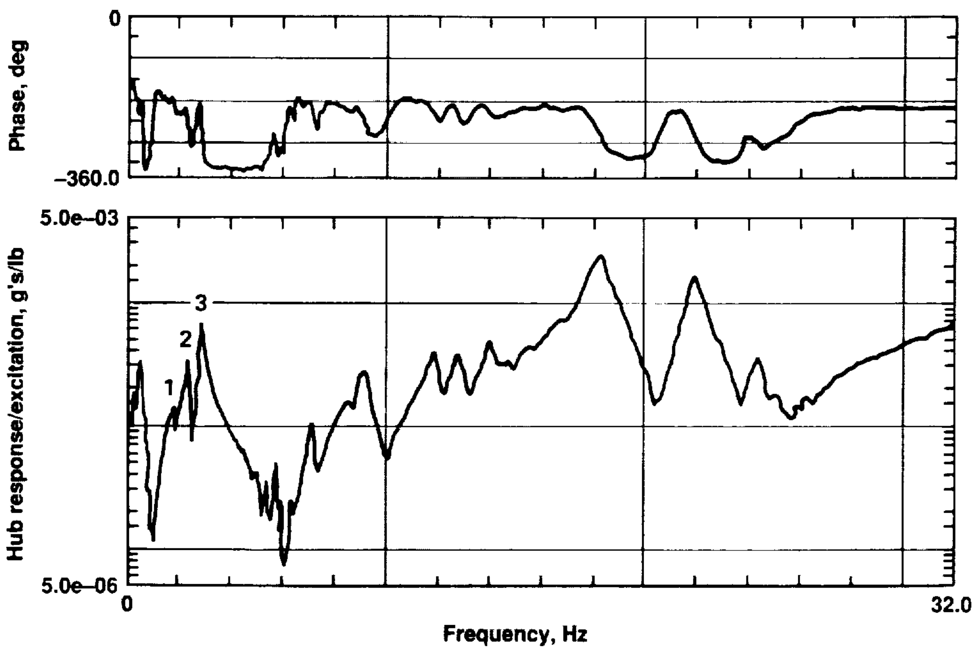

Figure 5. Transfer function of lateral hub response to lateral excitation, 0° yaw.

Serial No.	Frequency, Hz	Phase
1	1.44	−227°
2	2.19	−311°
3	2.94	−272°

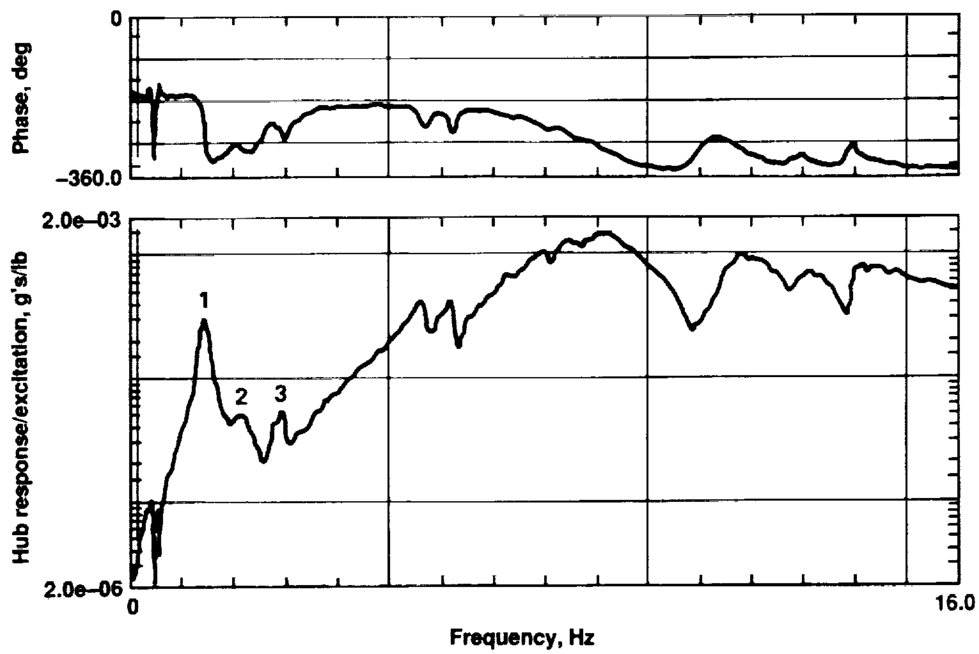

Figure 6. Transfer function of longitudinal hub response to longitudinal excitation, 90° yaw.

Serial No.	Frequency, Hz	Phase
1	1.49	–236°
2	2.28	–265°
3	2.78	–293°

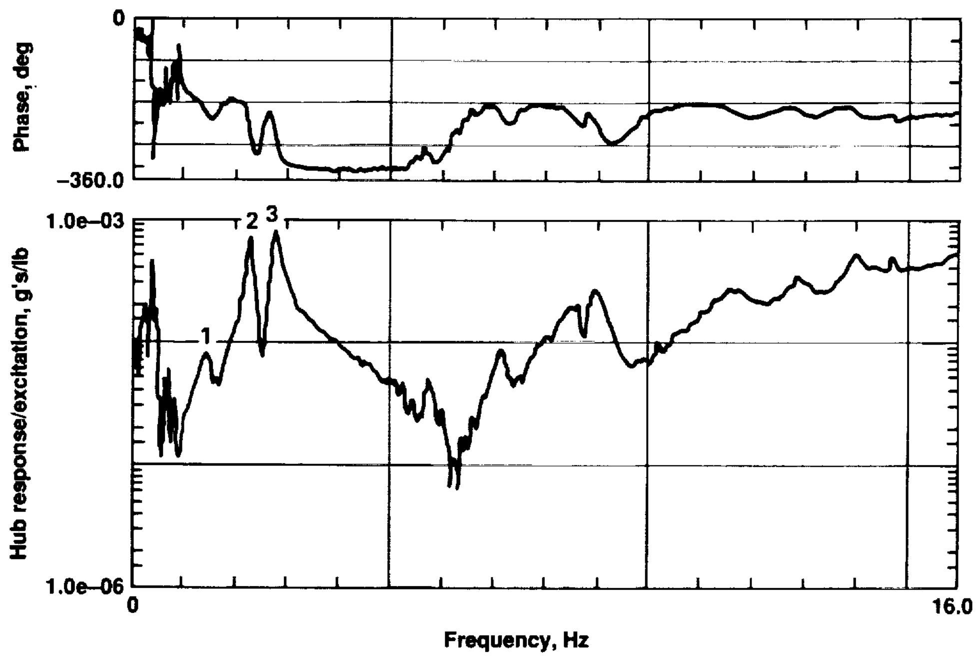

Figure 7. Transfer function of lateral hub response to lateral excitation, 90° yaw.

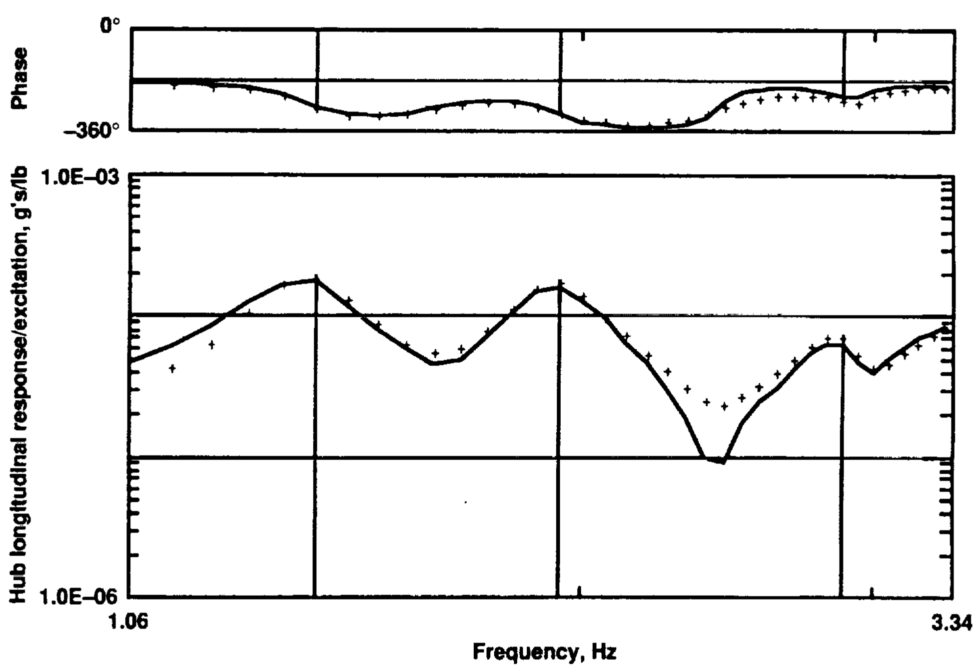

Figure 8. Curve fit of longitudinal hub response transfer function, 0° yaw (frequency range: 1.06 to 3.34 Hz).

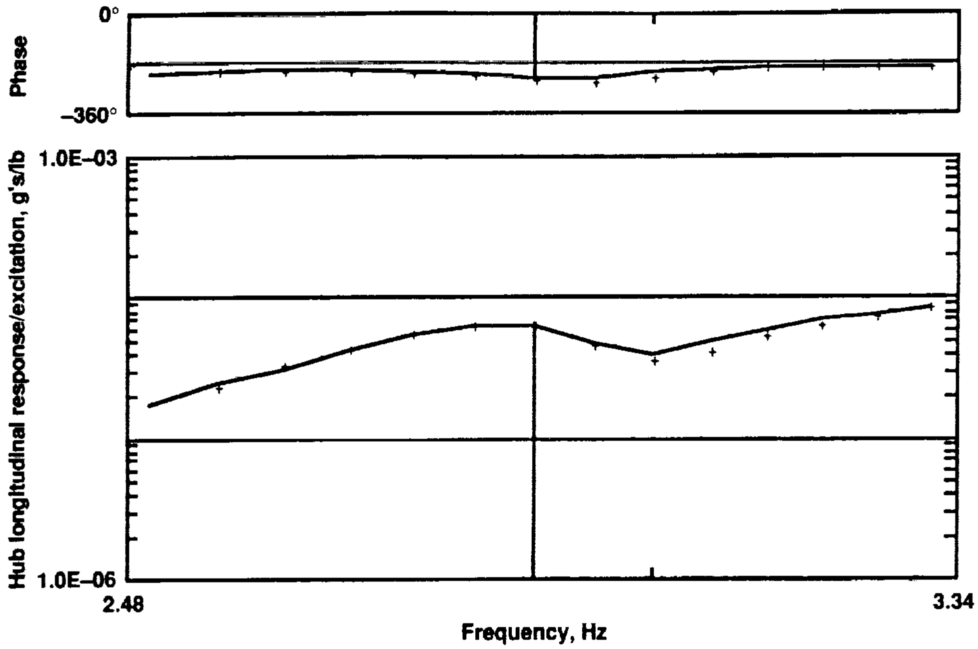

Figure 9. Curve fit of longitudinal hub response transfer function, 0° yaw (frequency range: 2.48 to 3.34 Hz).

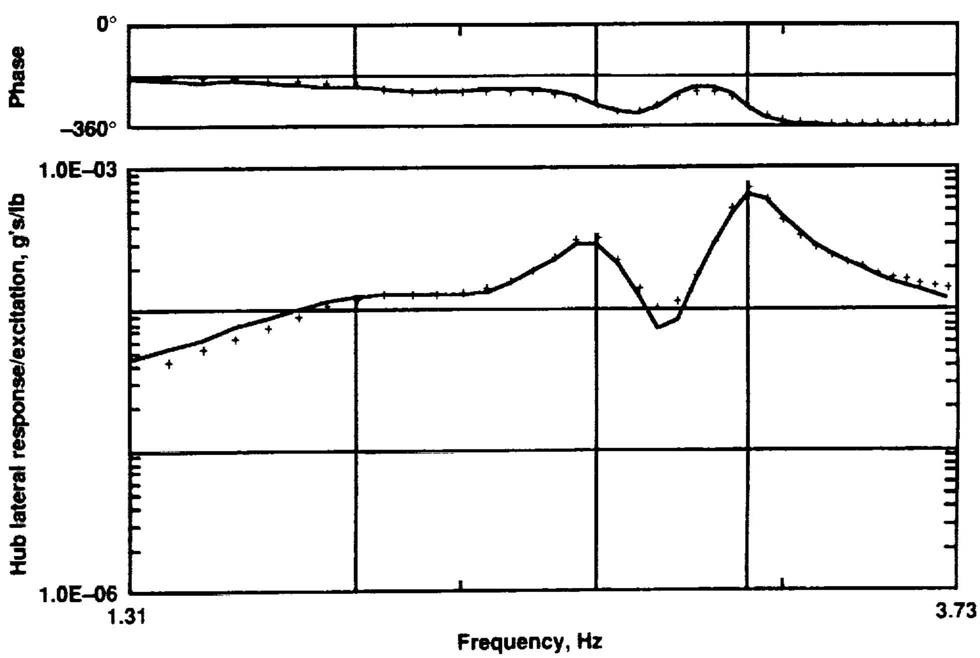

Figure 10. Curve fit of lateral hub response transfer function, 0° yaw (frequency range: 1.31 to 3.73 Hz).

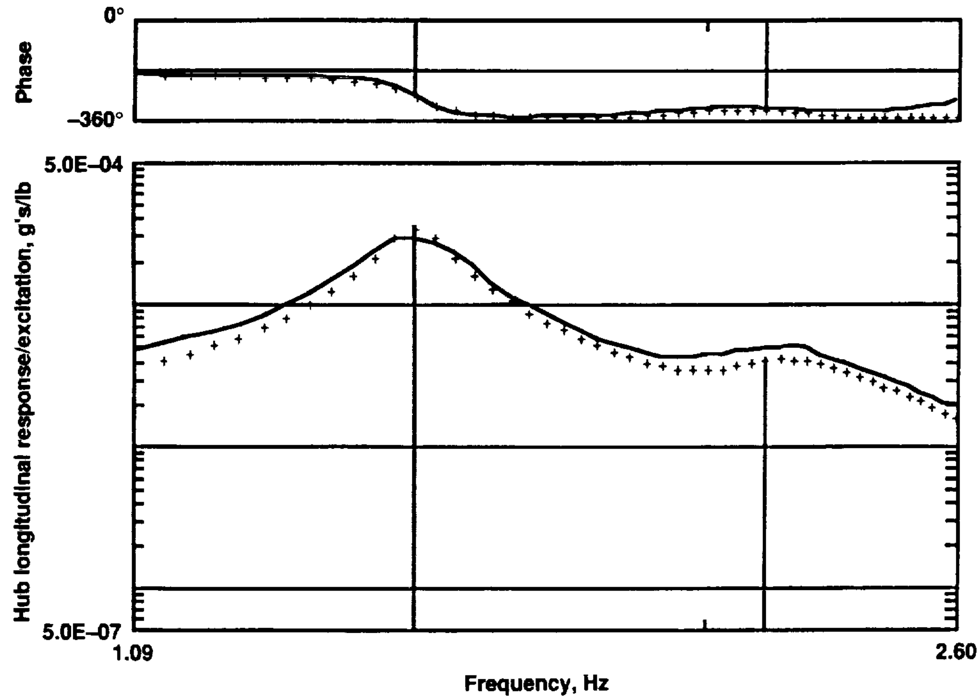

Figure 11. Curve fit of longitudinal hub response transfer function, 90° yaw (frequency range: 1.09 to 2.60 Hz).

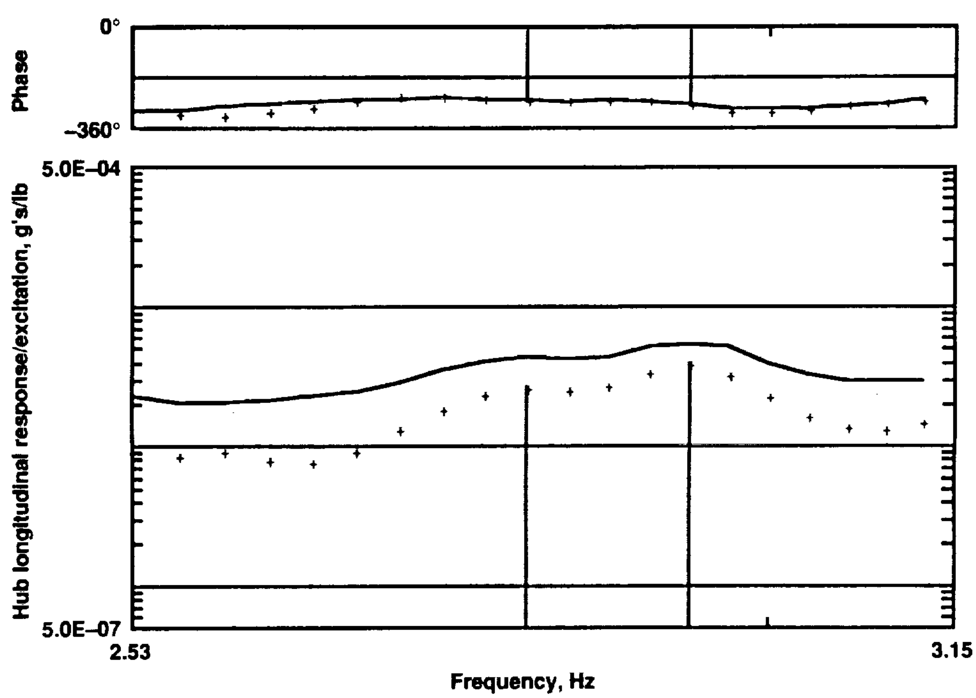

Figure 12. Curve fit of longitudinal hub response transfer function, 90° yaw (frequency range: 2.53 to 3.15 Hz).

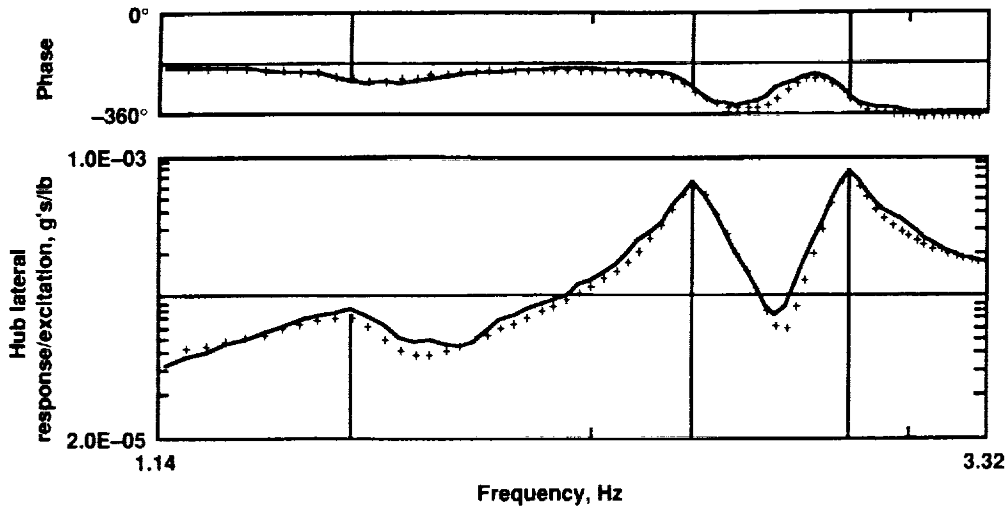

Figure 13. Curve fit of lateral hub response transfer function, 90° yaw (frequency range: 1.14 to 3.32 Hz).

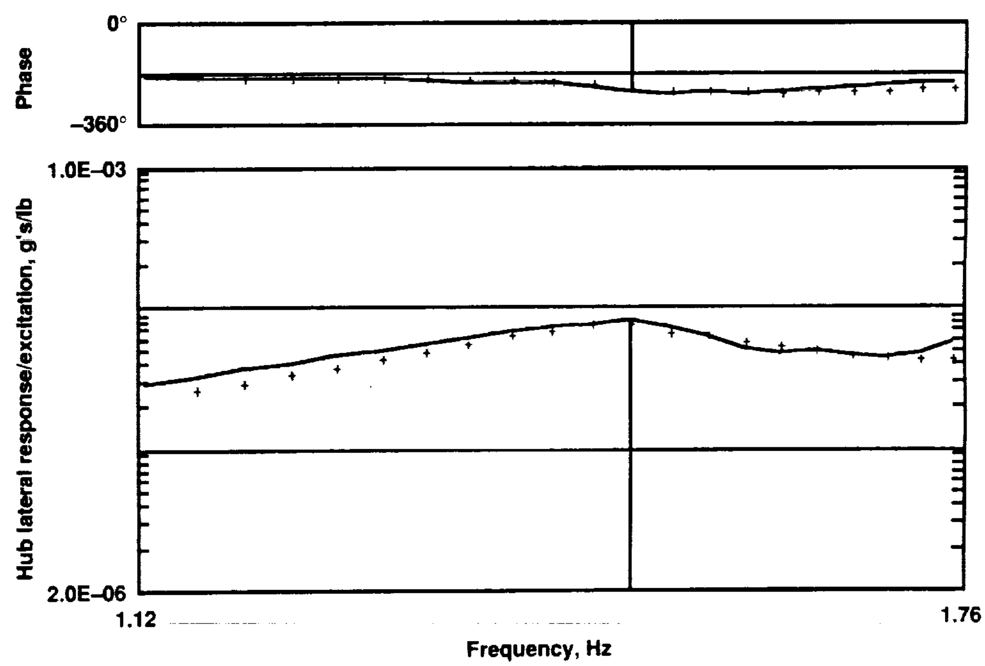

Figure 14. Curve fit of lateral hub response transfer function, 90° yaw (frequency range: 1.12 to 1.76 Hz)

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16. Abstract

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