Evaluation of a Six-DOF Electrodynamic Shaker System

David O. Smallwood
Consultant
9817 Pitt Pl. NE
Albuquerque NM 87111
(505) 296-2931

Dan Gregory
Sandia National Laboratories
Albuquerque NM 87185
(505) 844-9743

The paper describes the preliminary evaluation of a 6 degree of freedom electrodynamic shaker system. The 8 by 8 inch (20.3 cm) table is driven by 12 electrodynamic shakers producing motion in all 6 rigid body modes.

INTRODUCTION

A small electrodynamic shaker system suitable for small component testing is described. The principal purpose of the system is to demonstrate the technology. The shaker is driven by 12 electrodynamic shakers each with a force capability of about 50 lbs (220 N). The system was developed through an informal cooperative agreement between Sandia National Laboratories, Team Corp. and Spectral Dynamics Corporation. Sandia provided the laboratory space and some development funds. Team provided the mechanical system, and Spectral Dynamics provided the control system. Spectral Dynamics was chosen to provide the control system partly because of their experience in MIMO control and partly because Sandia already had part of the system in house. The shaker system was conceived and manufactured by TEAM Corp. Figure 1 shows the overall system. The vibration table, electrodynamic shakers, hydraulic pumps, and amplifiers are all housed in a single cabinet. Figure 2 is a drawing showing how the electrodynamic shakers are coupled to the table. The shakers are coupled to the table through a hydraulic spherical pad bearing providing 5 degrees of freedom and one stiff degree of freedom. The pad bearing must be preloaded with a static force as they are unable to provide any tension forces. The horizontal bearings are preloaded with steel springs. The drawing shows a spring providing the vertical preload. This was changed in the final design. The vertical preload is provided by multiple strands of an O-ring material as shown in Figure 4.

Figure 1. Overview of 6-DOF Shaker System

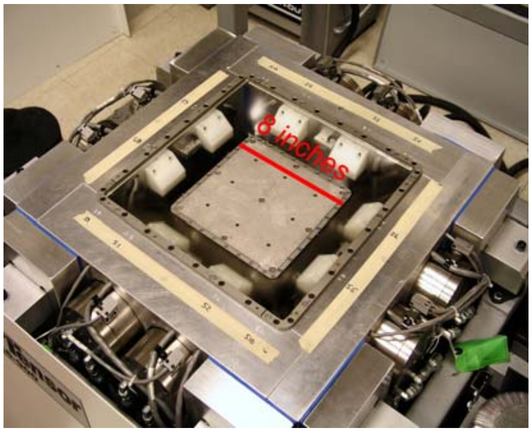


Figure 2. Top View of the Shaker Table

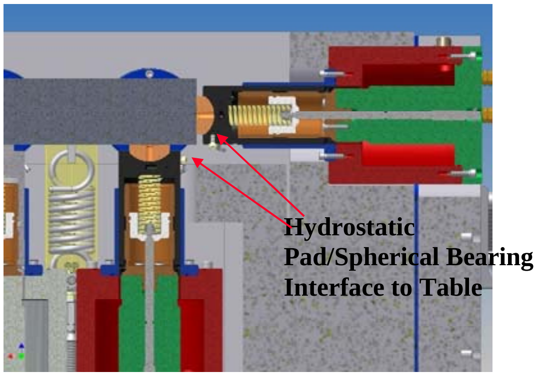


Figure 2. Drawing Showing the Shaker to Table Connections

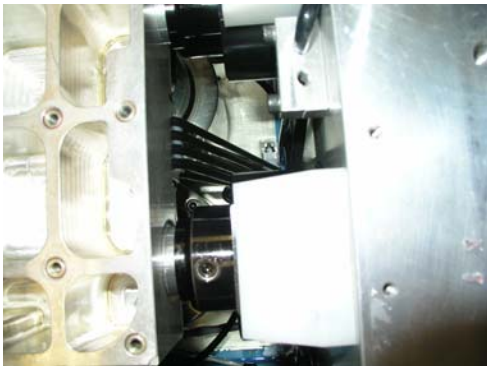


Figure 4. Top View of the Table Showing the Vertical Restraints

Four shakers provide excitation in each of the three orthogonal axes. The specifications of the shaker are outlined in Table 1. Four shakers provide inputs in each of the three orthogonal directions. By choosing the phase relationships between the shakers all six rigid body modes (three translation, and three rotations) can be excited. The system is over determined. There are more shakers than degrees of freedom. This provided an interesting control problem. The problem was approached using the input-output transformation matrices provided in the Spectral control system. Twelve accelerometers were selected for the control accelerometers (a tri-axial accelerometer at each corner of the table (see Figure 5). Figure 6 shows the nomenclature used to identify the shakers and control accelerometers. A fifth tri-axial accelerometer was placed at the center of the table, but it was not used for control. Thus we had 12 control accelerometers and 12 shakers to control a 6-dof shaker. The 12 control channels were reduced to a 6-dof control using a simple input transformation matrix. The control was defined by a 6x6 spectral density matrix. The six outputs in the control variable coordinates were transformed to twelve physical drive signals using another simple output transformation matrix. It was assumed that the accelerometers and shakers were well matched such that the transformation matrices were independent of frequency and could be deduced from rigid body considerations. The input/output transformations are shown in Equations 1 and 2.

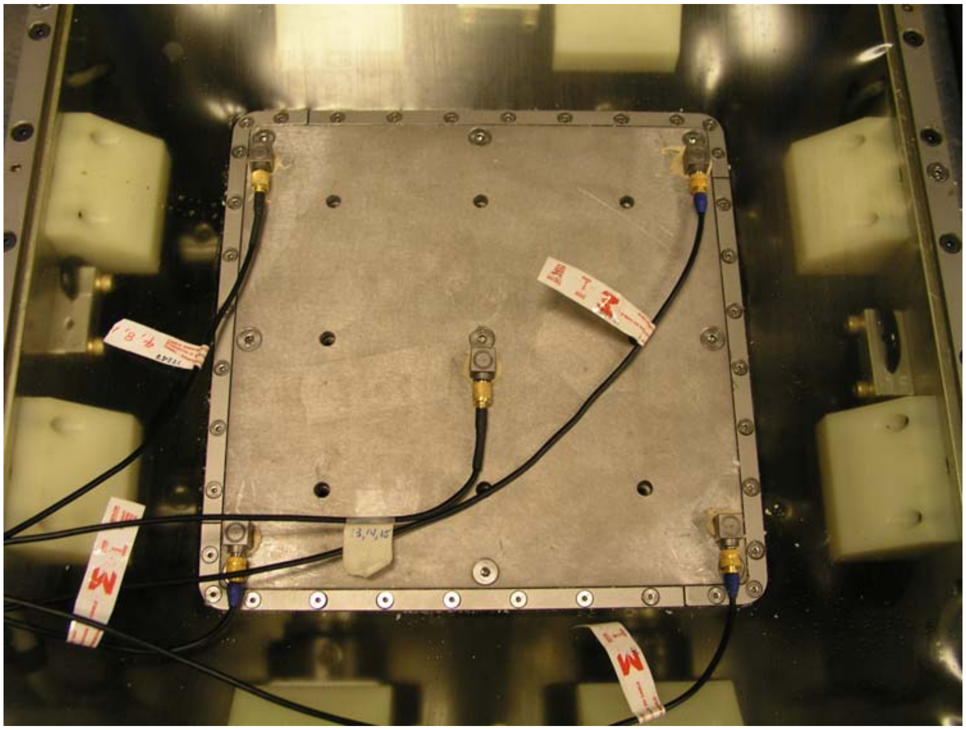
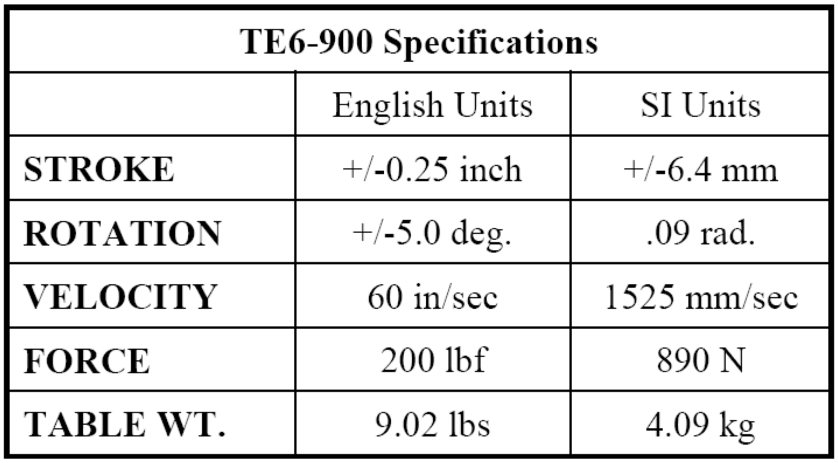


Figure 3. Accelerometer Locations Used for the Evaluation

Table 1. Specifications



TE6-900 Specifications		
	English Units	SI Units
STROKE	+/-0.25 inch	+/-6.4 mm
ROTATION	+/-5.0 deg.	.09 rad.
VELOCITY	60 in/sec	1525 mm/sec
FORCE	200 lbf	890 N
TABLE WT.	9.02 lbs	4.09 kg

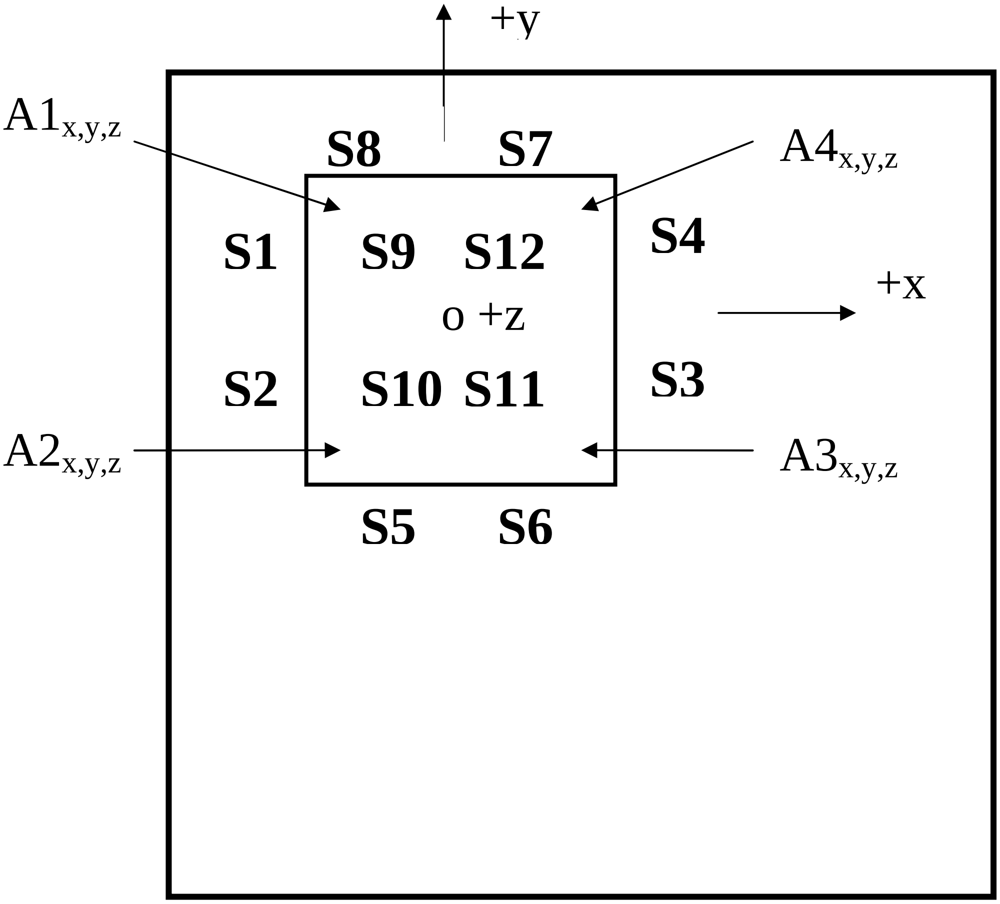


Figure 6. Accelerometer and Shaker Numbering Convention

The input transformation to define the control variables in terms of the physical acceleration measurements is:

$$\begin{Bmatrix} X \\ Y \\ Z \\ R_X \\ R_Y \\ R_Z \end{Bmatrix} = \begin{bmatrix} .25 & .25 & .25 & .25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & .25 & .25 & .25 & .25 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .25 & .25 & .25 & .25 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .25 & -.25 & -.25 & .25 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .25 & .25 & -.25 & -.25 \\ -.125 & .125 & .125 & -.125 & -.125 & -.125 & .125 & .125 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} A1_X \\ A2_X \\ A3_x \\ A4_X \\ A1_Y \\ A2_Y \\ A3_Y \\ A4_Y \\ A1_Z \\ A2_Z \\ A3_Z \\ A4_Z \end{Bmatrix} \qquad (1)$$

The output transformation to calculate the individual drives to the twelve shakers in terms of the computed drives in the control variable coordinates is:

$$\overset{\text{Drives to Shakers}}{\begin{Bmatrix} D1_X \\ D2_X \\ D3_X \\ D4_X \\ D5_Y \\ D6_Y \\ D7_Y \\ D8_Y \\ D9_Z \\ D10_Z \\ D11_Z \\ D12_Z \end{Bmatrix}} = \overbrace{\begin{bmatrix} .25 & .25 & -.25 & -.25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & .25 & .25 & -.25 & -.25 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .25 & .25 & .25 & .25 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .25 & -.25 & -.25 & .25 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .25 & .25 & -.25 & -.25 \\ -.125 & .125 & -.125 & .125 & -.125 & .125 & -.125 & .125 & 0 & 0 & 0 & 0 \end{bmatrix}^{-1}}^{\text{Inverse of Output Transformation Matrix}} \overset{\text{Drives in Control Variable Coordinates}}{\begin{Bmatrix} X_{drive} \\ Y_{drive} \\ Z_{drive} \\ R_{X-drive} \\ R_{Y-drive} \\ R_{Z-drive} \end{Bmatrix}} \tag{2}$$

TYPICAL IMPEDANCE FUNCTIONS

Figures 7 and 8 show typical impedance functions for the system as seen inside the transformation matrices (the 6x6 matrices of drive and control). As can be seen the system is well behaved from 20 to 5000 Hz. We did find two flexural modes below 5 kHz. One was a torsion mode at 2031Hz. In this mode the vertical accelerometers on opposite corners along a diagonal were in phase while the accelerometers on the other diagonal were out of phase. This mode was observable by the control accelerometers, but we did not try to control the mode. The other mode was a diaphragm mode at 4381 Hz where the four corners were in phase and the center of the table was out of phase. This mode was not observable by the control accelerometers and hence was not controlled.

TEST RESULTS

X-Axis Translation

The results of a typical test are presented. The test is x-axis translation specified as a flat spectrum of 0.025 g^2/Hz from 18.75 to 5000 Hz. The other degrees of freedom were specified as a flat spectrum about 4 decades lower. The rotations were not scaled in $(\text{rad/sec}^2)^2$/Hz but in the units given by the transformation matrix (a weighted sum of accelerations) (g^2/Hz). The results are shown in Figures 9 and 10. The results shown are for the control variable. The individual accelerometer signals varied from the reference at frequencies above 2 kHz as the control variable was an average of four accelerometers. As can be seen the reduction of translation in the y and z axes was better than suppression of the rotations. It is speculated that couplings between the rotations about the x and y axes are primarily coupled with the shaker input in the x-axis, but there is some coupling from shakers driving the x and y translations which are not accounted for in the output transformation matrix.

All Six Rigid Body Modes with Zero Coherence Between Inputs

The results of a test where all six rigid body modes were controlled to the same level with zero coherence between inputs is shown in Figures 11 and 12. The rotations were scaled in units of acceleration as determined by the input transformation matrix. The rotations were not scaled in radians. As in the previous example the plots are of the control variables which were a weighted average of 4 or 8 accelerometers. In each plot the green line is the reference spectrum and the black line the estimated control spectrum.

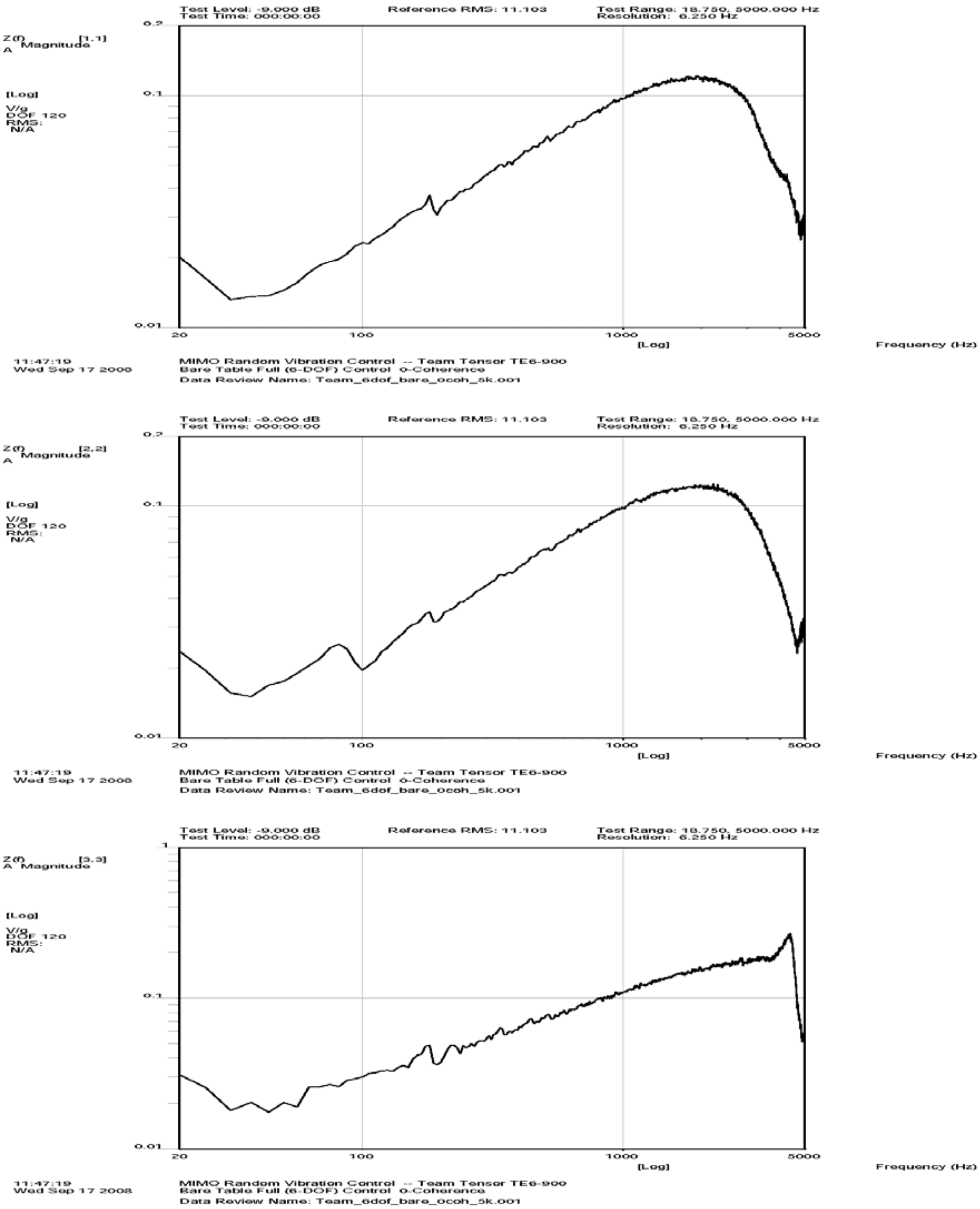


Figure 7 Typical Impedance Functions (v/G) in the Translation Directions, x y, z Respectively

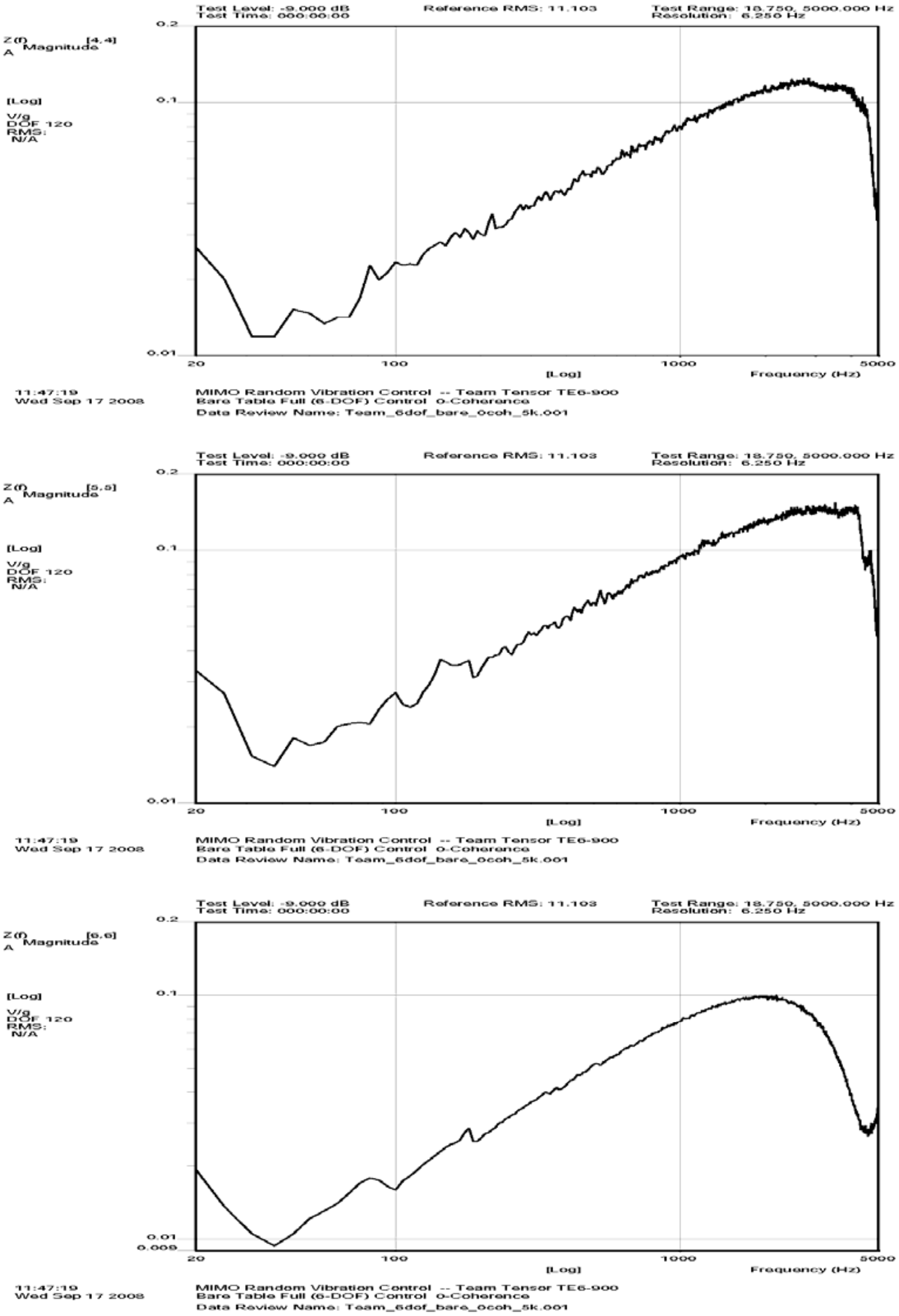


Figure 8 Typical Impedance Functions (v/G) in the Rotational Directions, Rotation about x, y, z, Respectively

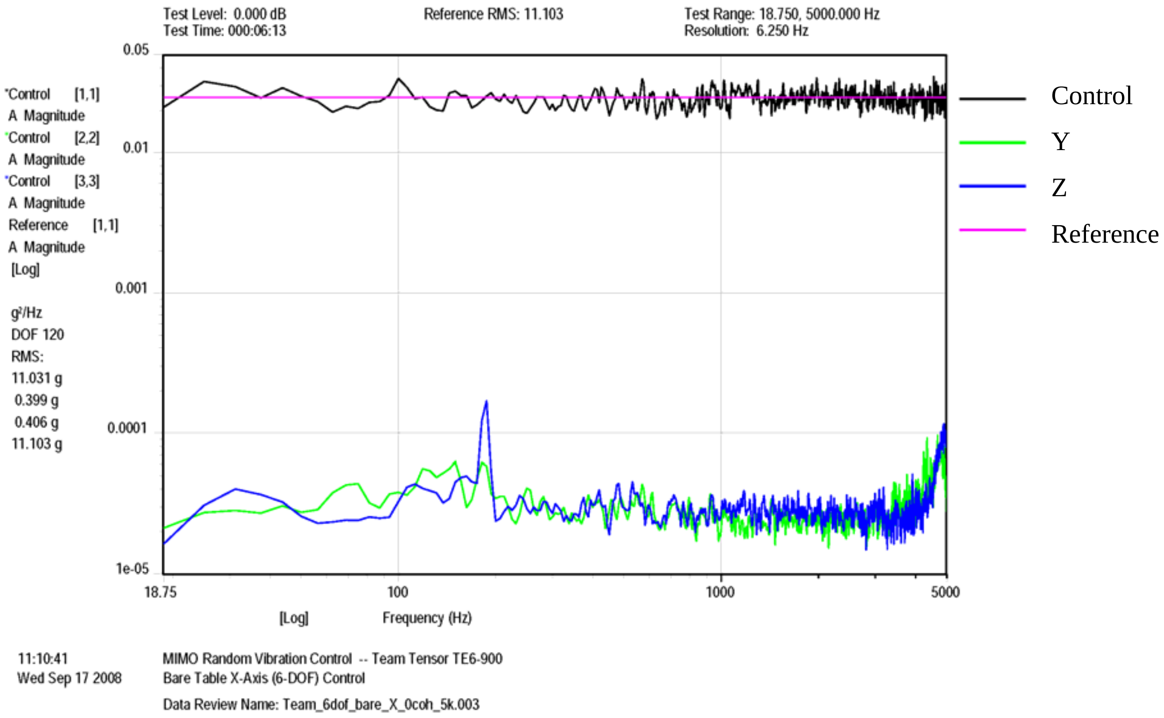


Figure 9 X-axis Test, Translations

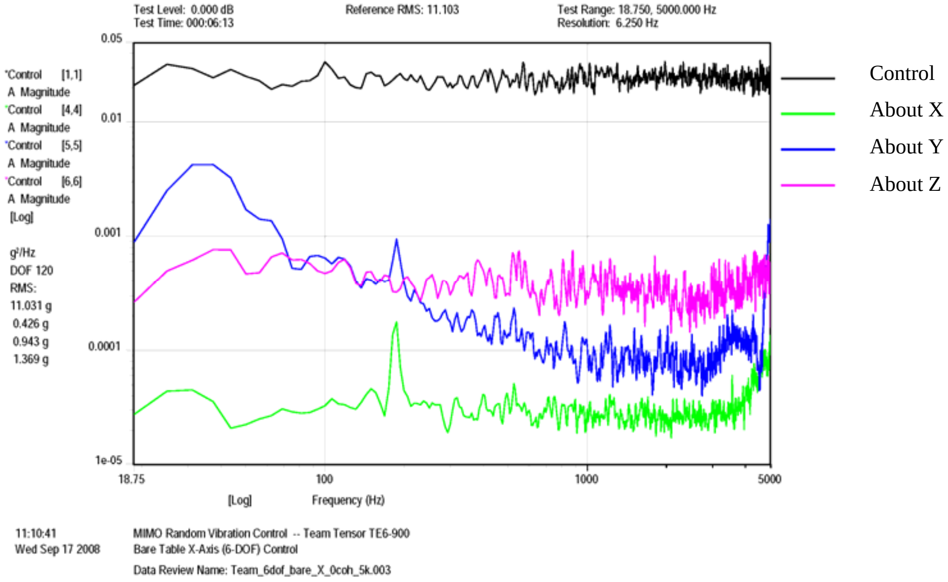


Figure 10 X-axis Test, Rotations About the X/Y/Z Axes

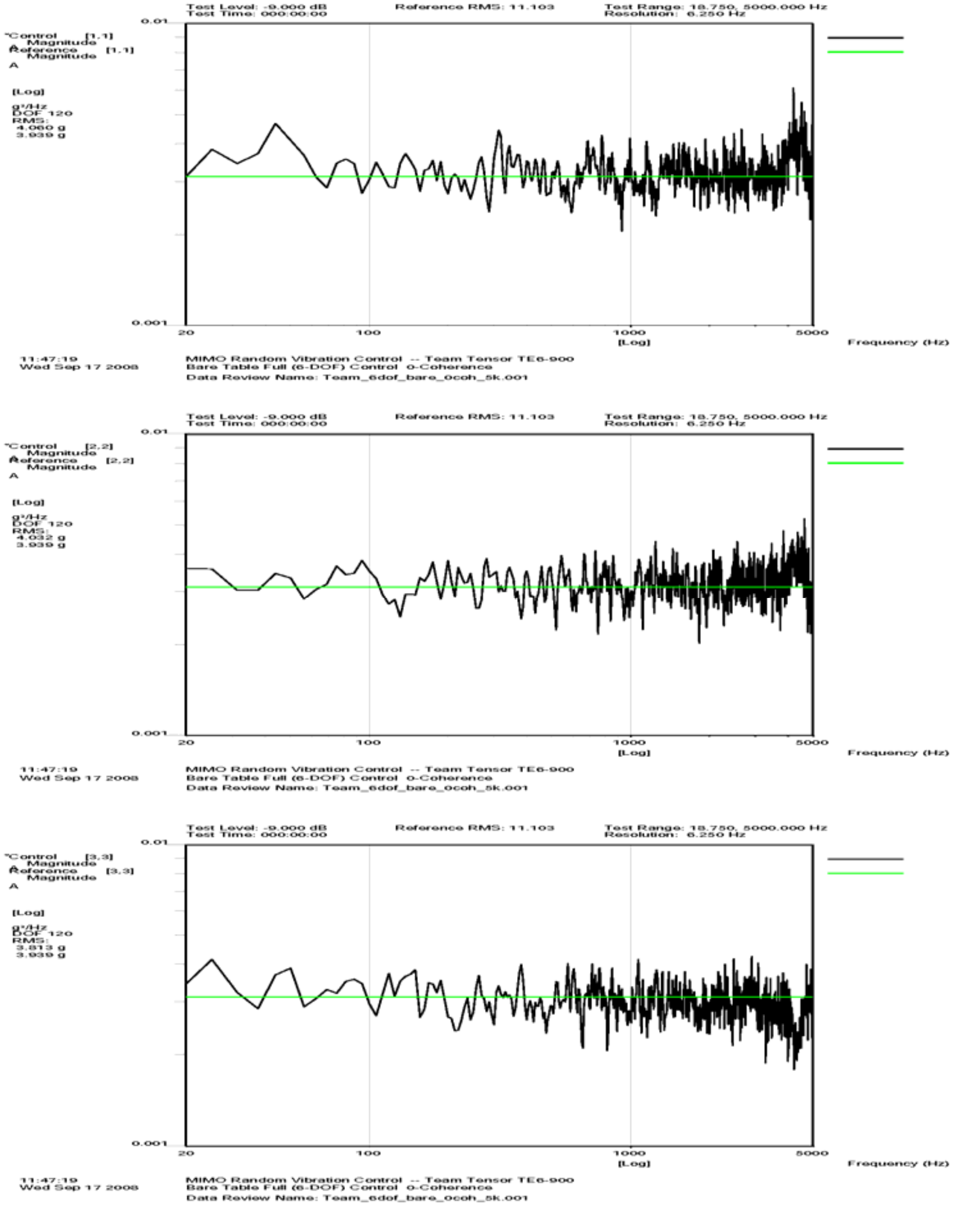


Figure 11 X/Y/Z Translations with Zero Coherence (6-DOF Input)

Other tests were run included: 1) Y-axis only, other degrees of freedom small, 2) Z-axis only, other degrees of freedom small, 3) Rotation about the X-axis only, 4) Rotation about the Y-axis only, 5) Rotation about the Z-axis only. All the test results were similar in the achieved control fidelity.

Noise Floor

The noise floor of the system was also measured under varying conditions (Figure 13). Everything looks pretty good until we turn the pumps on. We first thought that we were seeing pump noise, but because the frequencies are exact harmonics of 60 Hz we now suspect a ground loop somewhere in the system. We are actively searching for the source. In spite of the noise, the control was pretty good.

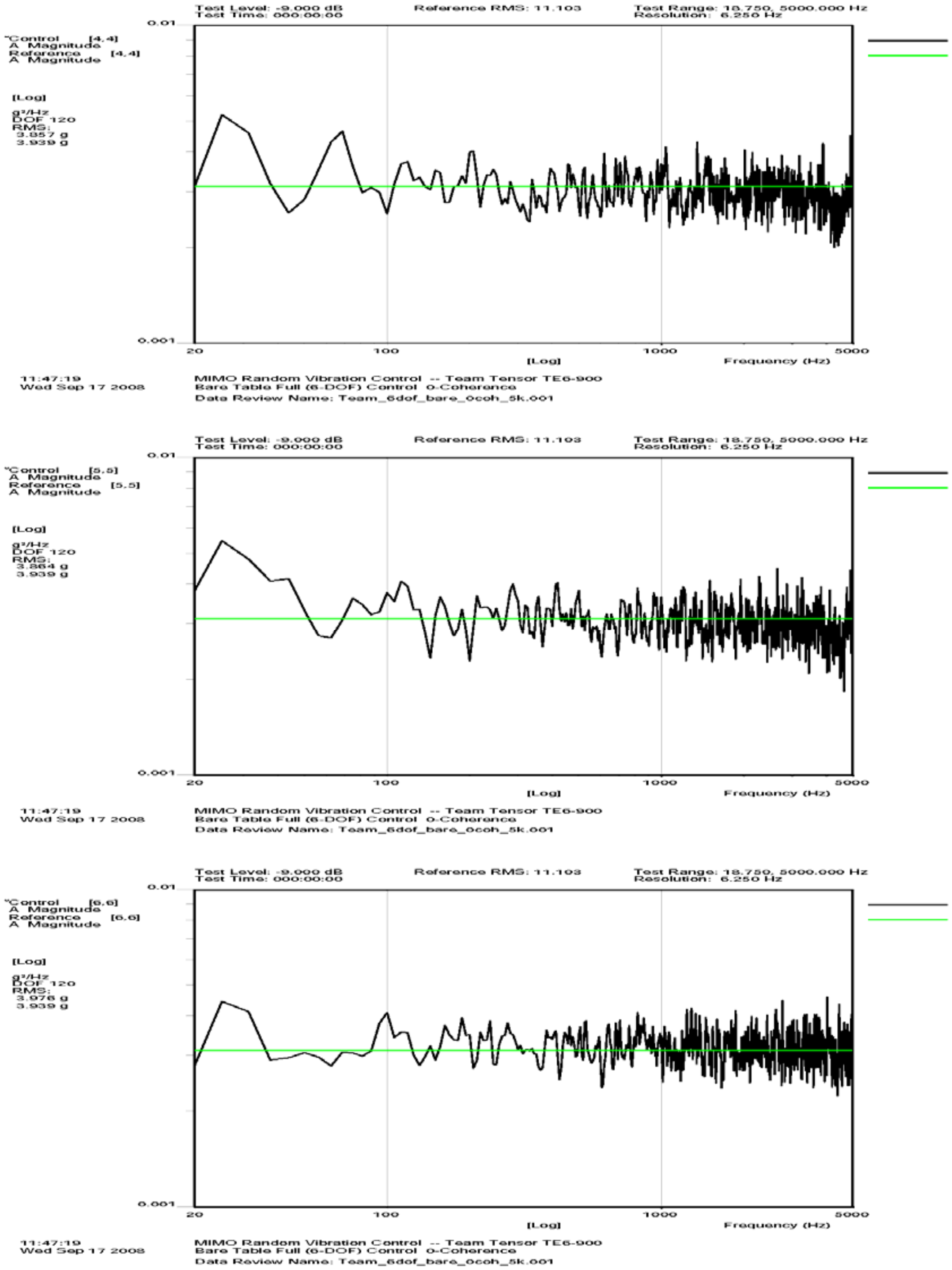
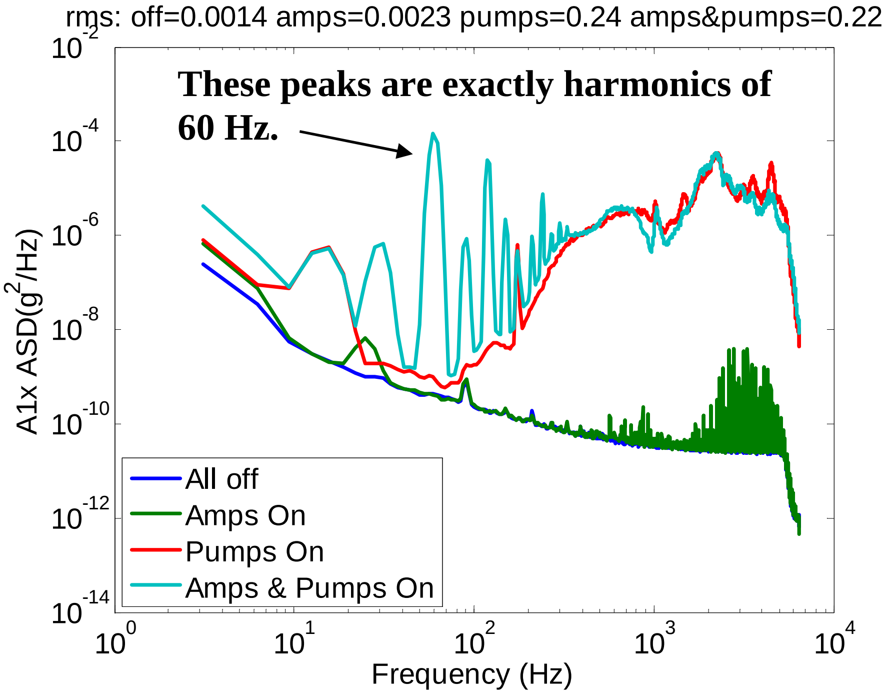


Figure 12 Rotations About the X/Y/Z Axes with Zero Coherence (6-DOF Input)



Every thing looks pretty good until we turn the pumps on.

We are actively searching for the source.

It suggests a ground loop somewhere.

In spite of the noise control was pretty good.

Figure 13 Noise Floor

WISH LIST FOR FUTURE SYSTEMS

System performance is critically determined by the setup parameters and the operators understanding of the system performance. Little things (like having an accelerometer inverted) can make a big difference. We found it useful to check each control accelerometer and each shaker before every test to make sure the system was operating as expected. The control system should be flexible enough to not require any re-patching between tests. This just increases the chances of an error. Any diagnostics that can be provided by either the shaker manufacturer or the supplier of the control system is greatly appreciated. It would be very useful to be able to monitor the voltage and current output to each shaker. We need to know the maximum allowable input voltage to the shaker amplifiers and be able to match this to the maximum output voltage of the control system. We are often running the system near its limits. We would like to be able to monitor the system impedance and its inverse (the system frequency response functions, FRF) as measured by the control system, and to be able to export these functions for external analysis. It is hard to gain insight from a 12x12 or a 6x6 matrix of FRF's. Separation of the hydraulics and amplifiers from the shaker might reduce the noise and make it easier to track down problems. Having the system in one box has its advantages from a packaging viewpoint, but it introduces some disadvantages like noise and system maintenance.

LESSONS LEARNED

Careful thought must be given to the design of the experiments. The correct setup is critical. You must understand the experiment you want and are performing. Intuition is difficult when you are dealing with multiple degrees of freedom.

CONCLUSIONS

The system has been run successfully to 5 kHz. This gives hope that future systems with more capability will have a useful bandwidth. The technology for controlling over specified systems has been demonstrated. The system has proved adequate for testing small components in multiple degrees of freedom at useful levels. The system has been used to characterize the dynamics of small components and to perform model validation experiments. We are continuing to evaluate the system for inputs other than stationary random.