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Evaluation of a Six-DOF Electrodynamic Shaker System

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

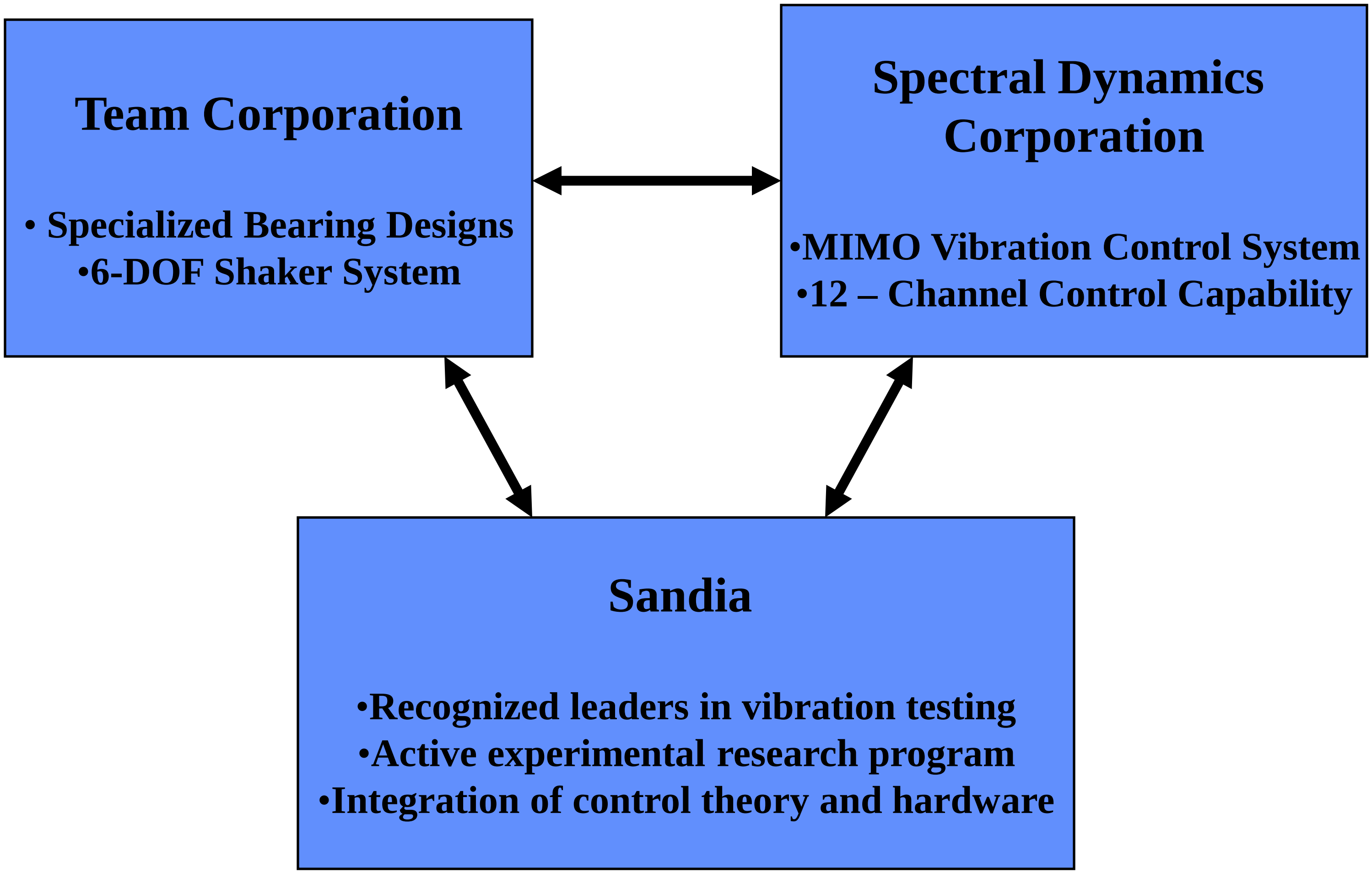
Why is it important?

- Real shock and vibration environments are multidimensional (6 degrees-of-freedom)
  - 3 translations and 3 rotations

- Single axis testing will not excite the modes of the system (or component) the same way they are excited in the real environment
  - Resulting stress states are not the same
  - Failure modes of system may be missed
    - The assumption that sequential testing in three axes is equivalent is not correct!

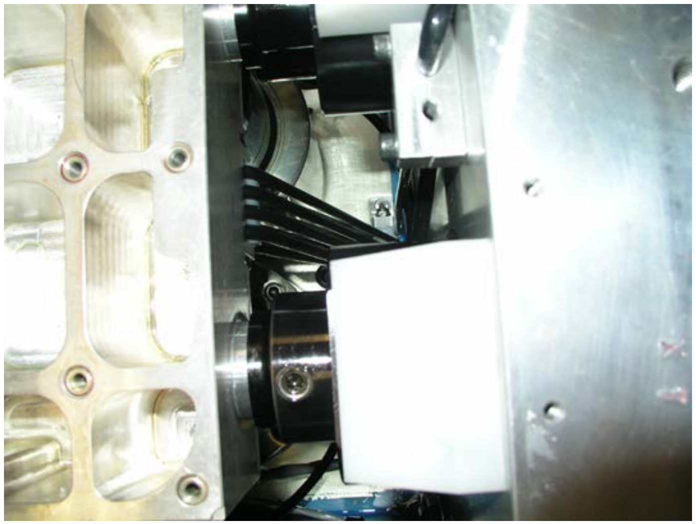
- Improved model validation experiments
  - Improved control of boundary conditions (multiple exciters)
    - Forces and moments available to tailor boundary conditions
      - Approach idealized boundary conditions used in models such as fixed-free
    - Single axis shaker tests are not really single axis
  - Selectively provide single or coupled loadings to structure
    - Full definition of input including rotations
      - Ignored in the past

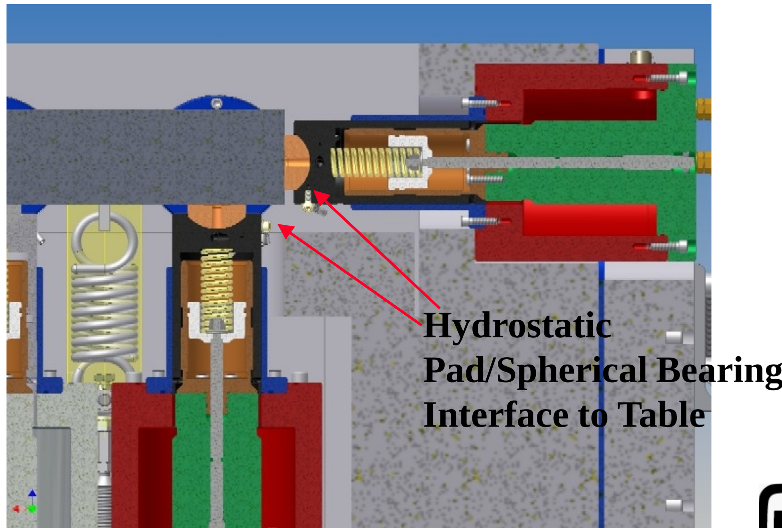
Collaboration for Theory, Hardware, Environmental Specification and Control



Team Tensor TE6-900
6-DOF Shaker System

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





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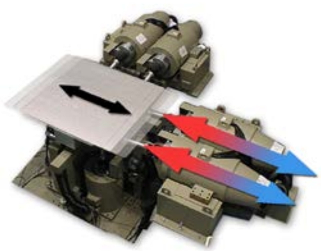
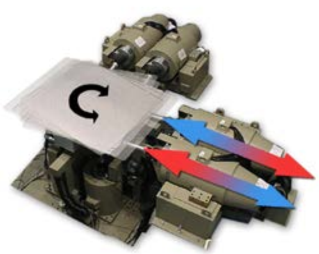
6- DOF System with Top Cover Removed

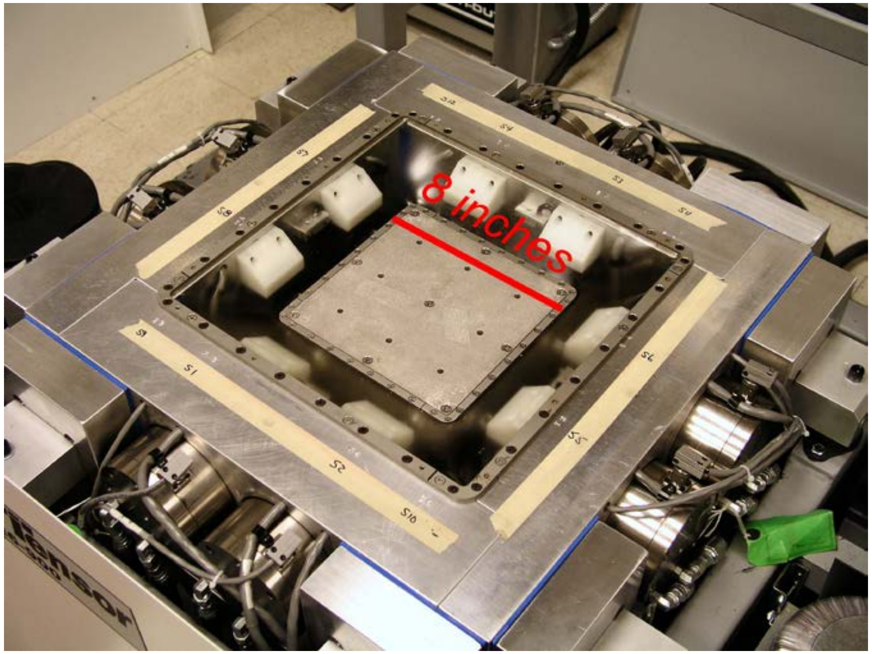
Utilizes 12 Independent Electrodynamic Exciters with Hydraulic Bearing Assemblies:

- **4 - Vertical Shakers**
- **8 - Horizontal Shakers (4 per axis)**





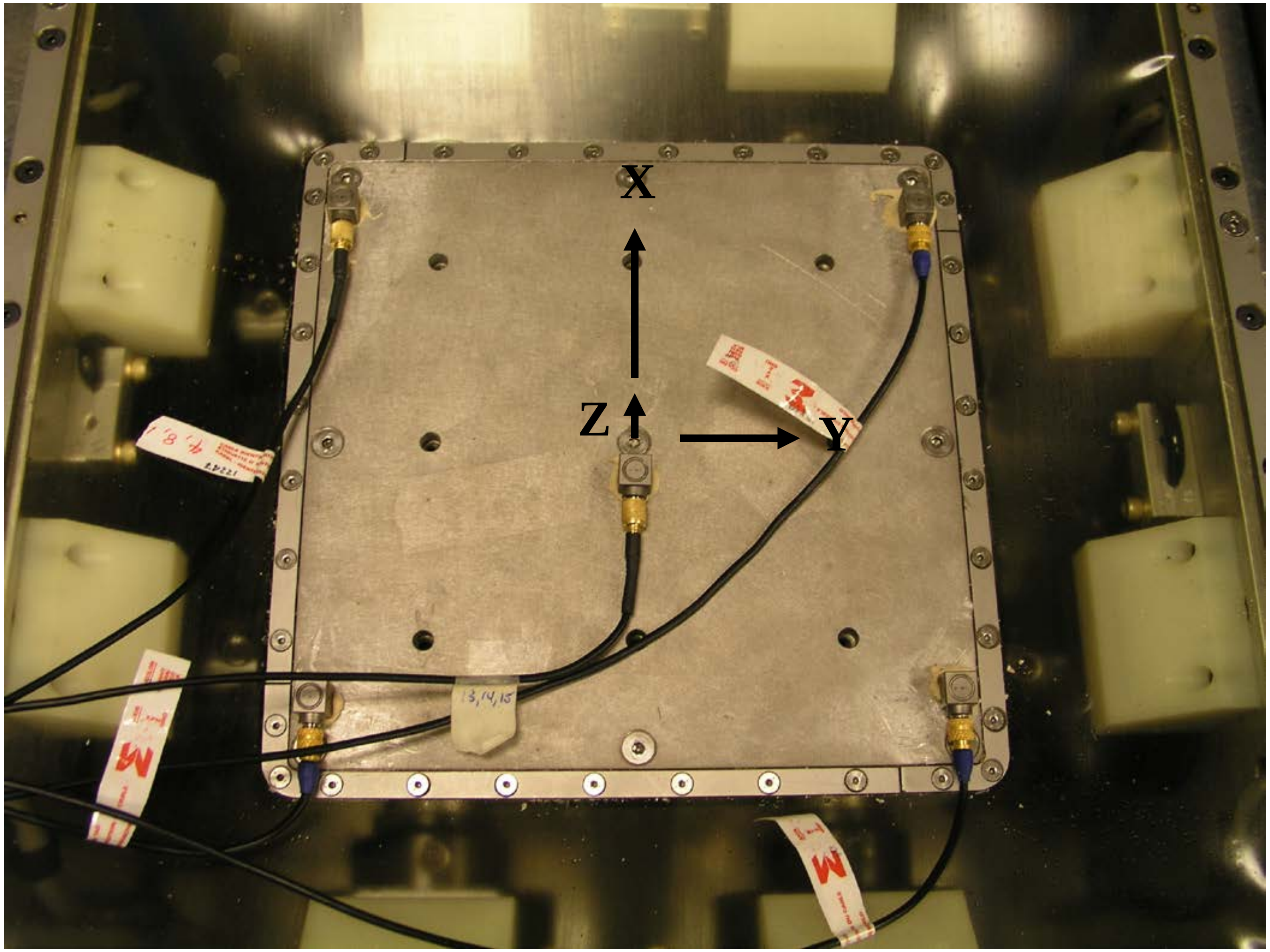
Selecting phase relationships between exciters will generate translations and/or rotations



12-actuators/6-DOF's

- **Provides Over-determined system**
- **Versatility to specify control methods tailored to test objectives**

Location of control accelerometers



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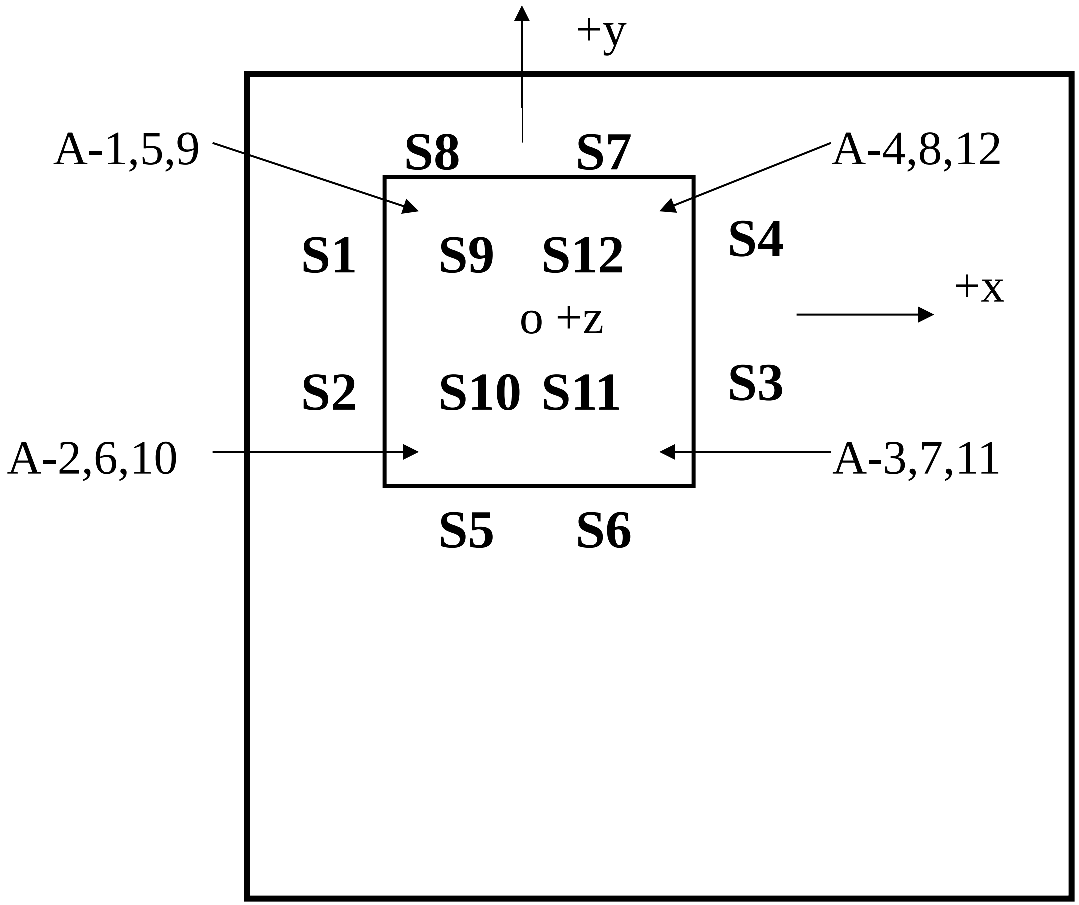
Accelerometer and Shaker Numbering Convention



Input/output transformation matrices were used to convert 12 accelerometers and 12 shakers to a 6x6 rigid body control matrix

Accel to mode

1/4	1/4	1/4	1/4	0	0	0	0	0	0	0	0
0	0	0	0	1/4	1/4	1/4	1/4	0	0	0	0
0	0	0	0	0	0	0	0	1/4	1/4	1/4	1/4
0	0	0	0	0	0	0	0	1/4	-1/4	-1/4	1/4
0	0	0	0	0	0	0	0	1/4	1/4	-1/4	1/4
-1/8	1/8	1/8	-1/8	-1/8	-1/8	1/8	1/8	0	0	0	0

Input/output transformation matrices were used to convert 12 accelerometers and 12 shakers to a 6x6 rigid body control matrix

Output transformation matrix (Mode to Shaker)$^{-1}$

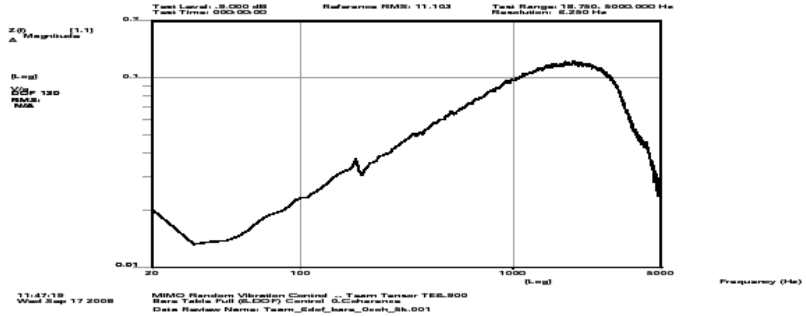
1/4	1/4	-1/4	-1/4	0	0	0	0	0	0	0	0
0	0	0	0	1/4	1/4	-1/4	-1/4	0	0	0	0
0	0	0	0	0	0	0	0	1/4	1/4	1/4	1/4
0	0	0	0	0	0	0	0	1/4	1/4	-1/4	-1/4
0	0	0	0	0	0	0	0	1/4	1/4	-1/4	1/4
-1/8	1/8	-1/8	1/8	-1/8	1/8	-1/8	1/8	0	0	0	0

Typical impedance function

0.2v/g

x-translation

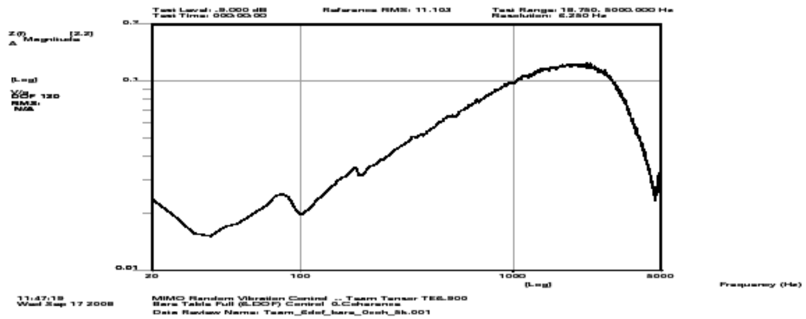
0.01v/g



0.2v/g

y-translation

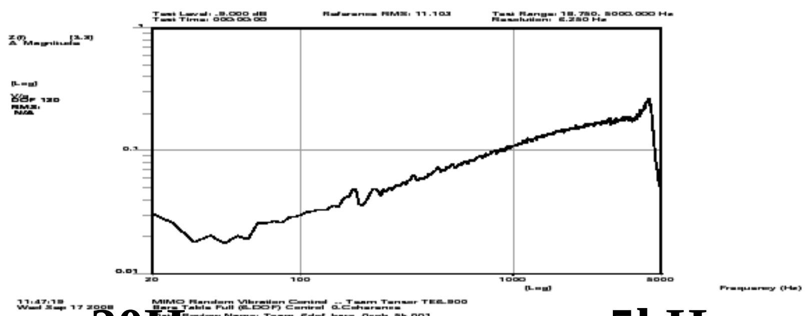
0.01v/g



1 v/g

z-translation

0.01v/g



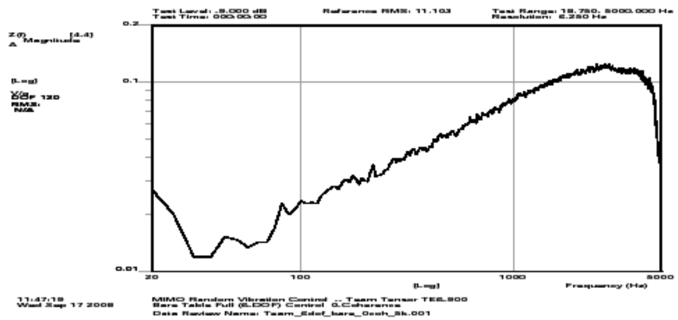
20Hz **5kHz**

Rotation impedance functions

0.2v/g

rotation about x

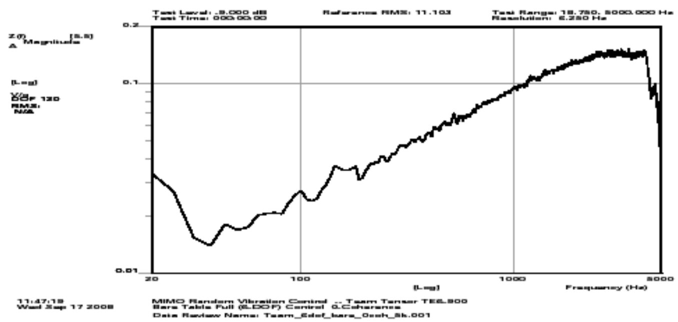
0.01v/g



0.2v/g

rotation about y

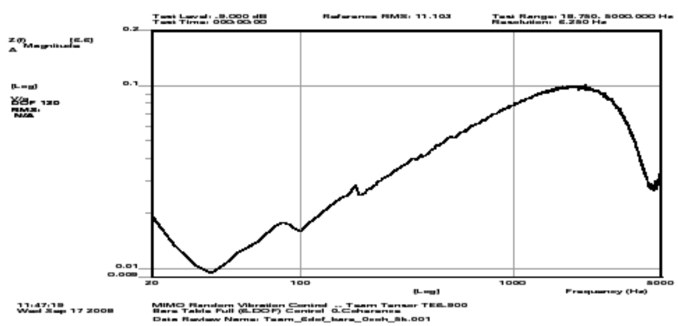
0.01v/g



0.2 v/g

rotation about z

0.01v/g



20Hz 5kHz

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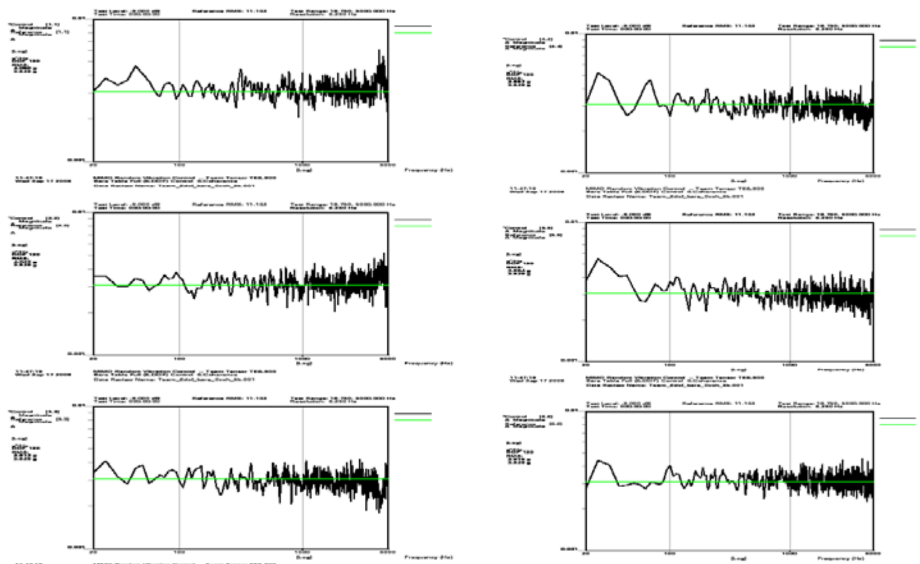
Results

- **Successful Demonstration of full 6-Dof closed loop random vibration test**
  - **Independent power spectrums controlled for three translations and three rotations**
  - **First time 12 shakers have been simultaneously controlled to 5000 Hz**
  - **4grms**

Translations

Rotations



All vertical scales g^2/Hz **0.01** **0.001**

All frequency axes **20** **5000Hz**

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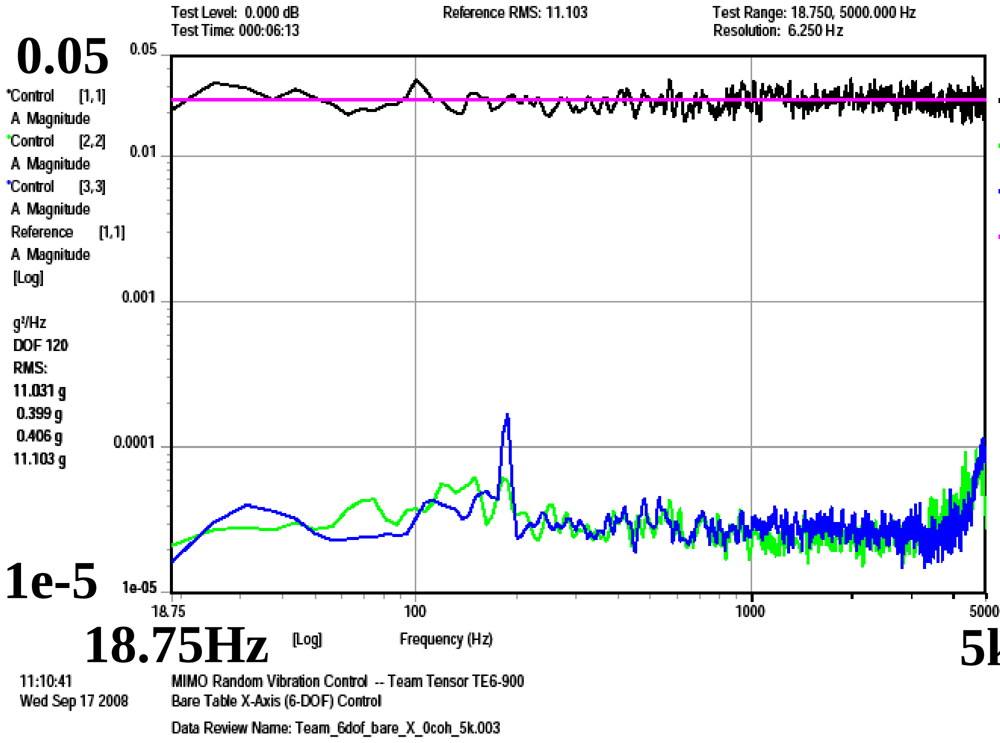
X-axis test with other degrees of freedom restrained



0.05

g^2/Hz

1e-5

18.75Hz

5kHz

x-translation

y-translation

z-translation

reference

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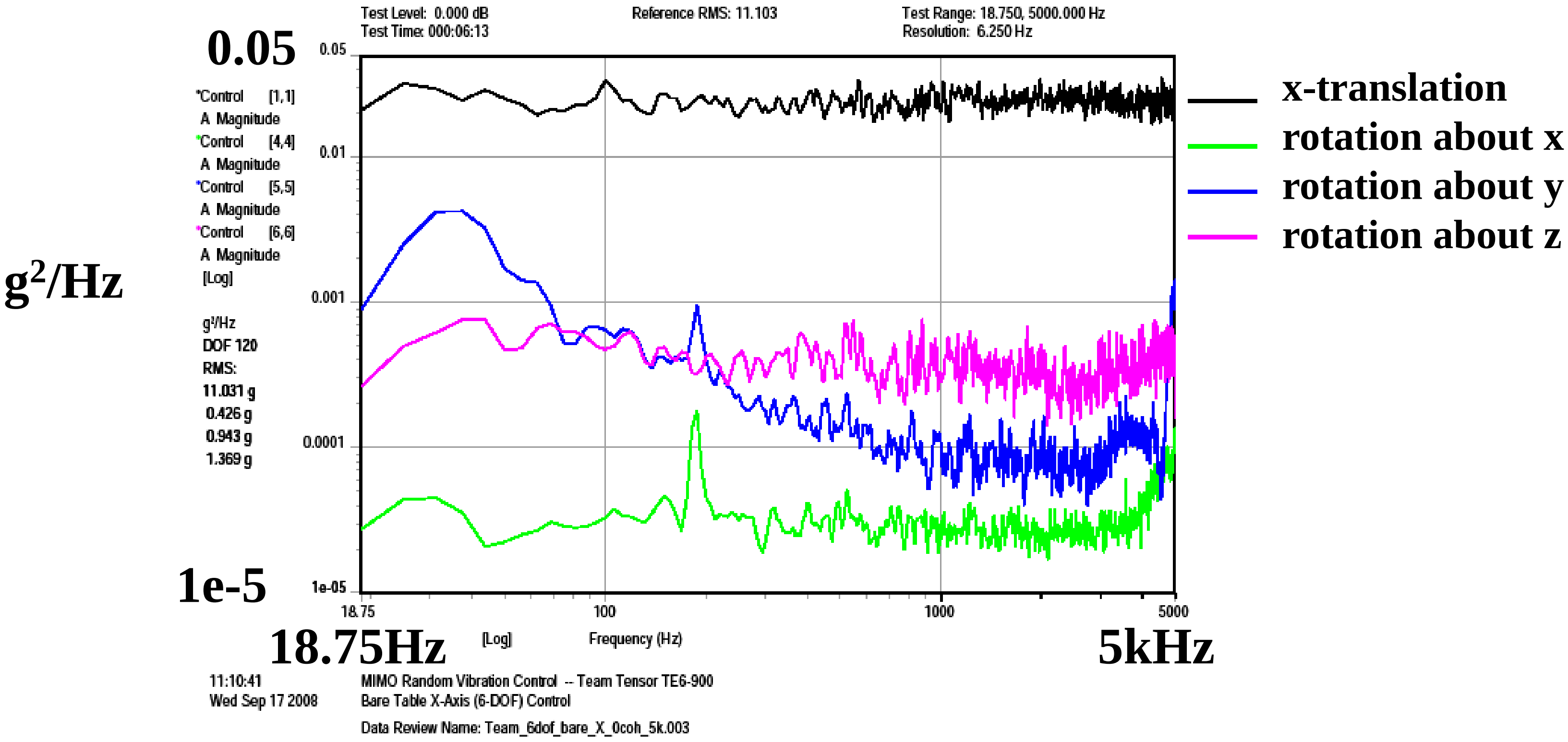
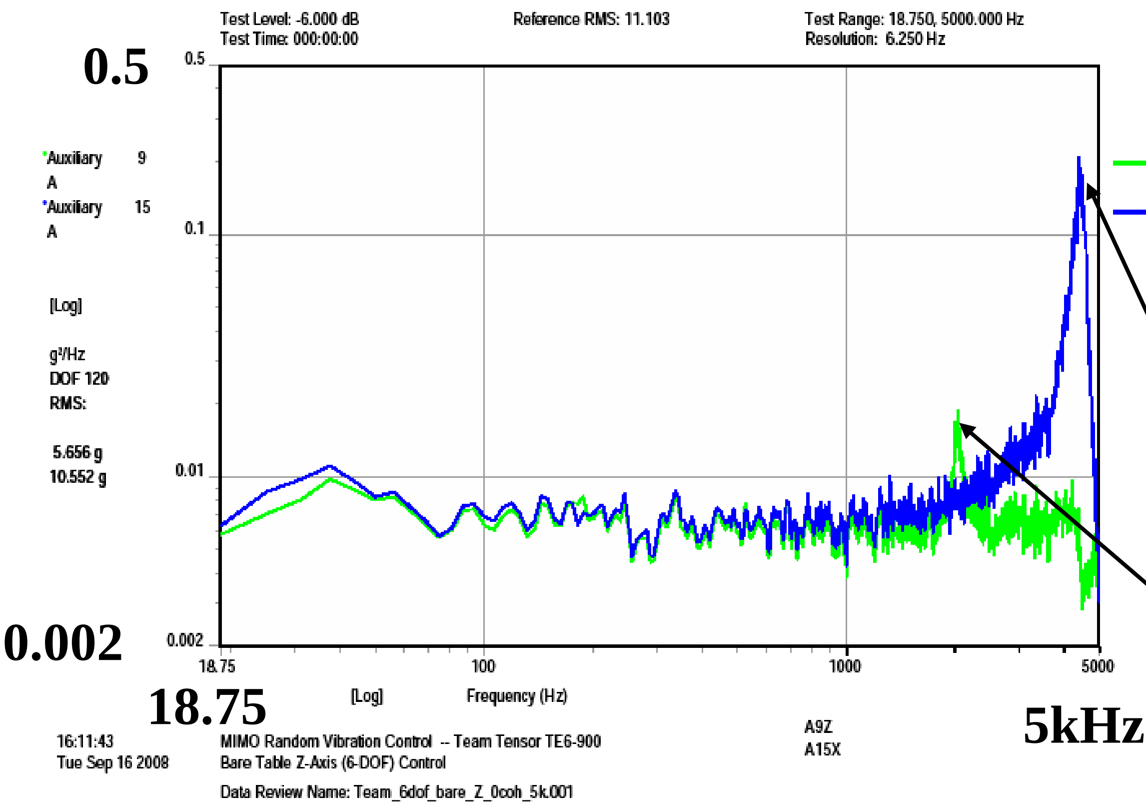
X-axis test with other degrees of freedom restrained



We have identified two table modes below 5kHz



one z-axis control accel.

z-axis accel. at center of table

We have a plate diaphragm mode at 4381Hz

We have a table torsion mode at 2031Hz. Note center accel. does not respond

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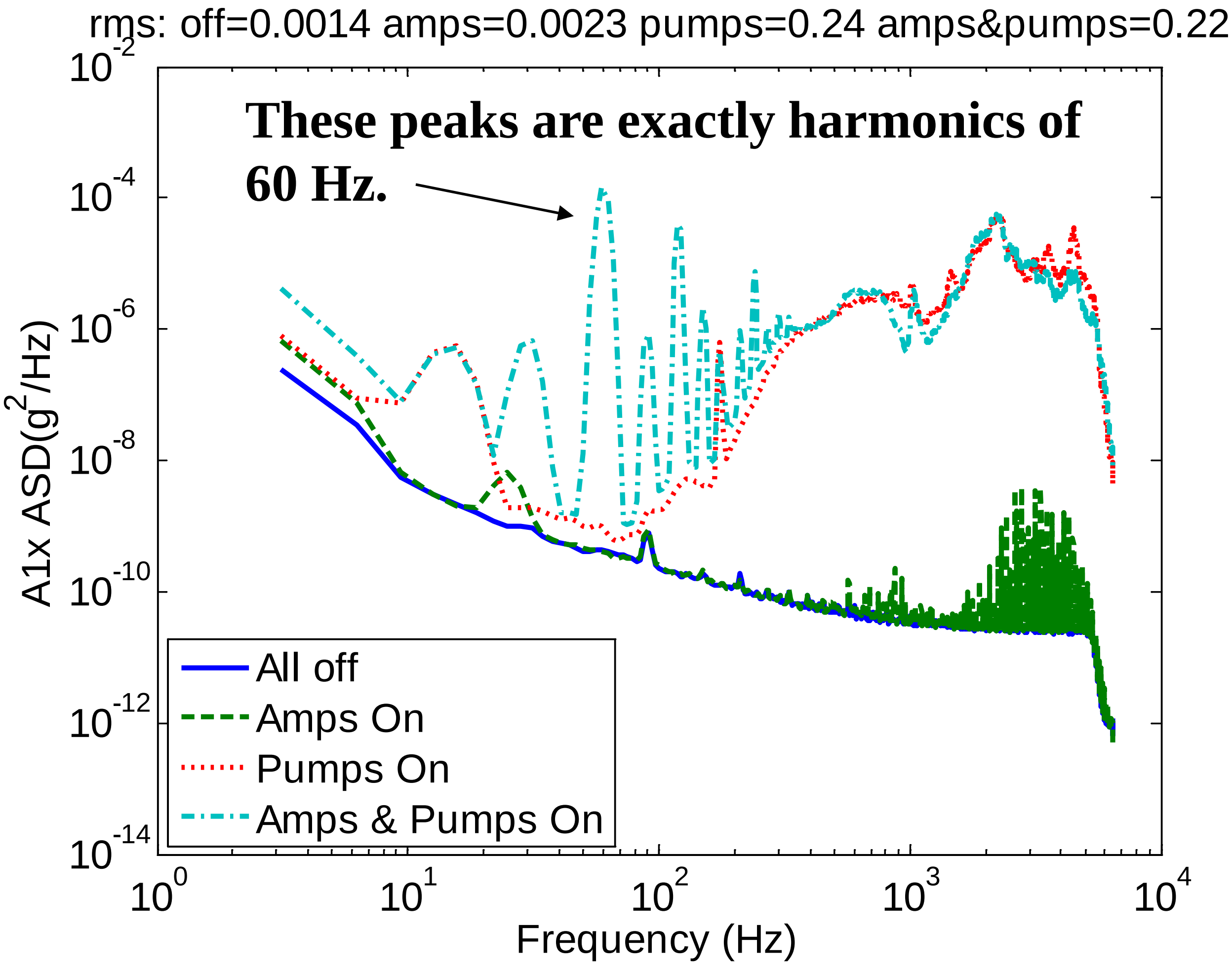
Noise Floor Measurement



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.

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Desired Shaker Design Improvements

- Output current and voltage signals available
  - Very difficult to access system capability without these measurements
  - Assist in optimizing the control strategy
- Master gain control on each amplifier
  - Balance the control system drive outputs
- Separate hydraulic power supply from shaker cabinet
  - Reduce system noise
- Improved access to all electrical connectors to allow better trouble-shooting
- Interlock to prevent field current when pumps are off
- Improved technique for establishing cord tensions to achieve desired preload/position

- BIGGER SYSTEM (Same Cost---- Fat Chance!)

Desired Control System Improvements

- Improved diagnostic tools to verify system integrity
  - State of health checks
    - Comparison of impedance functions from previous tests
    - Ability to view FRF's (Inverse of Impedance) directly---More intuitive
    - Other
  - Export FRF's and Impedance for offline computations
- Ability to specify any set of accelerometers as controls (not necessarily starting with channel one)
  - Re-patching channels increases chances for error
- Improved description of error messages

Lessons Learned

- Correct Setup is Critical
  - Inoperative accelerometer or shaker is deadly
  - Accelerometers
    - Sensitivities, polarity, location
- Careful thought must be given to design of the experiment
  - Selection and definition of control strategy can greatly affect the results

Summary

- Team 6-Dof system is installed and operational
- System performance evaluated
  - All six degrees of freedom have been achieved
  - 5 kHz closed loop random vibration control has been demonstrated for all three translations and three rotations
- 6-Dof system shows great promise for the future

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Publications Regarding Benefits of Realistic Multi-axis Environments

- **Multi-axis testing excites all modes simultaneously with a more realistic stress loading** (Berman, M.B. "Inadequacies in Uniaxial Stress Screen Vibration Testing*." Journal of the IEST*. Vol. 44, No. 4, Fall 2001: 20-23)
- **Test objects may pass uni-axial testing but fail under operating conditions** (Freeman, M.T. "3-axis Vibration Test System Simulates Real World" *Test Engineering and Management.* Dec/Jan 1990-91: 10-14)
- **Rate of fatigue damage is increased by a factor of two with three axis excitation** (Himelblau, H. and M.J. Hine. "Effects of Triaxial and Uniaxial Random Excitation on the Vibration Response and Fatigue Damage of Typical Spacecraft Hardware". *Proceedings of the 66th Shock and Vibration Symposium.* Arlington, VA: SAVIAC 1995)
- **Durability of objects vary when exposed to sequential vs. simultaneous excitation** (French, M. *"Comparison of Simultaneous and Sequential Single Axis Durability":* To be published in *Experimental Techniques*, November 2006)