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Responses of Structures to SDoF vs MDoF Vibration Testing

IMAC XXXIV

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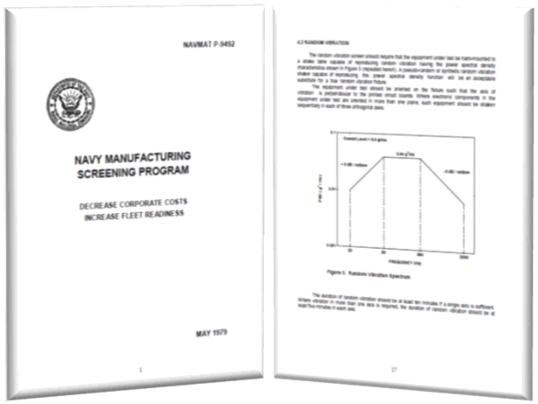
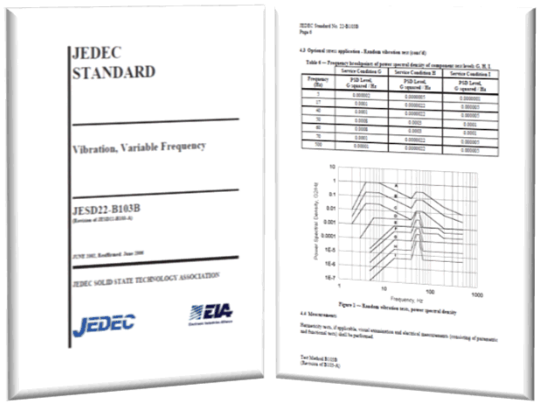
Outline

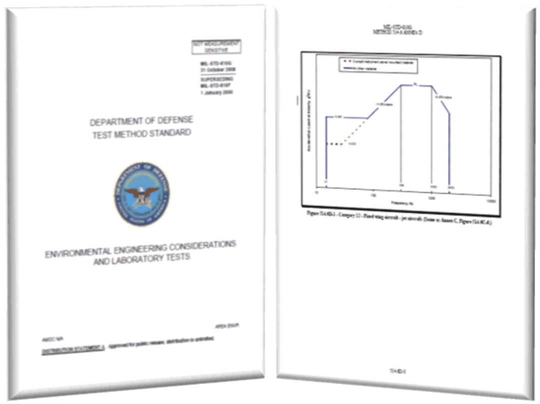
- Motivations & Objective
- Equipment
- Test Article
- Sensor Selection & Configuration
- Test Sequence
  - Axes
  - Levels
  - Coherence and Phase
- Overview of Test Results
  - Energy Levels
  - Peak Accelerations
  - Modal Contributions

Motivations

- <u>Sequential single axis testing</u> has been firmly established as the preferred test method for environmental vibration characterization and analysis
  - MIL STD 810G: U.S. Department of Defense Environmental Test Standard
  - NAVMAT P-9492: U.S. Navy Manufacturing Screening Test Standards
  - JESD22-B103B: JEDEC Environmental Test Standards for Microelectronics







Motivations

- Unfortunately, vibrations in real world environments are 3-dimensional and these vibrations can result in different failure modes and component lifecycles [1-5]
- Recent developments in electrodynamic shaker capabilities have enabled reliable and controllable simultaneous multi-axis testing [6,7]
- Multi-axis control makes possible true single axis testing by allowing control of off axis and rotational vibrations that may be present in uniaxial shakers [8]
- Model validation and system identification via single axis test results cannot account for off axis affects [9]

Objective

- Through a collaboration of experimental and modeling work conducted on a given test article investigate:
  - The relationship between single axis and multi-axis vibration testing
    - What is the difference in response when off-axis energy is controlled vs when it is not?
    - What is the influence of the boundary conditions of the different types of tests on the response?
    - What's the effect of multi-axis inputs on a test article's modal response?
  - How much off-axis energy is input for the different test methods?
  - The benefit of single axis testing conducted on equipment capable of mitigating off-axis (and rotational) vibration

Test Equipment – Multi-axis

- Shaker System: Team Corporation Tensor™ 900
  - Simultaneous or sequential excitation of X, Y, and/or Z axes
  - Complete control of rotations around all axes

Specifications	
Table First Frequency	5,000 Hz
Test Frequency Range	10 - 5,000 Hz
Max Payload	9 lbs
Max Displacement	0.5 in
Max Acceleration (w/max payload)	10 g

- Controller Software: Spectral Dynamics JAGUAR Shaker Control and Analysis System
  - Multi-Input and Multi-Output Control
  - Input and Output Transformation for 6DOF Control
- Data Acquisition: National Instruments™ LabVIEW and NI PXIe-4496 Data Acquisition Modules

Test Equipment – Single Axis

- Shaker System: Unholtz-Dickie T2000
  - Sequential excitation of X, Y, and Z axes
  - To test different axes an adapter cube is required

Specifications	
Test Frequency Range	10 – 3,000 Hz
Max Displacement	1.0 in
Force Rating - Random	107 kN-rms
Force Rating - Sine	111 kN-peak

- Controller Software: Spectral Dynamics JAGUAR Shaker Control and Analysis System
- Data Acquisition: National Instruments™ LabVIEW and NI PXIe-4496 Data Acquisition Modules

Test Article

- A column supported square aluminum 6061 plate
  - Base, columns, and top plate made of a continuous piece of material
  - Both homogenous and isotropic
  - Eliminates added dynamics due to support boundaries
- Evenly spaced mounting holes
  - Eight (8) circumferential and one (1) central
  - Uniform bolt tension applied to each
- Selected since its d... amics have been well do...
  - Plate with f...
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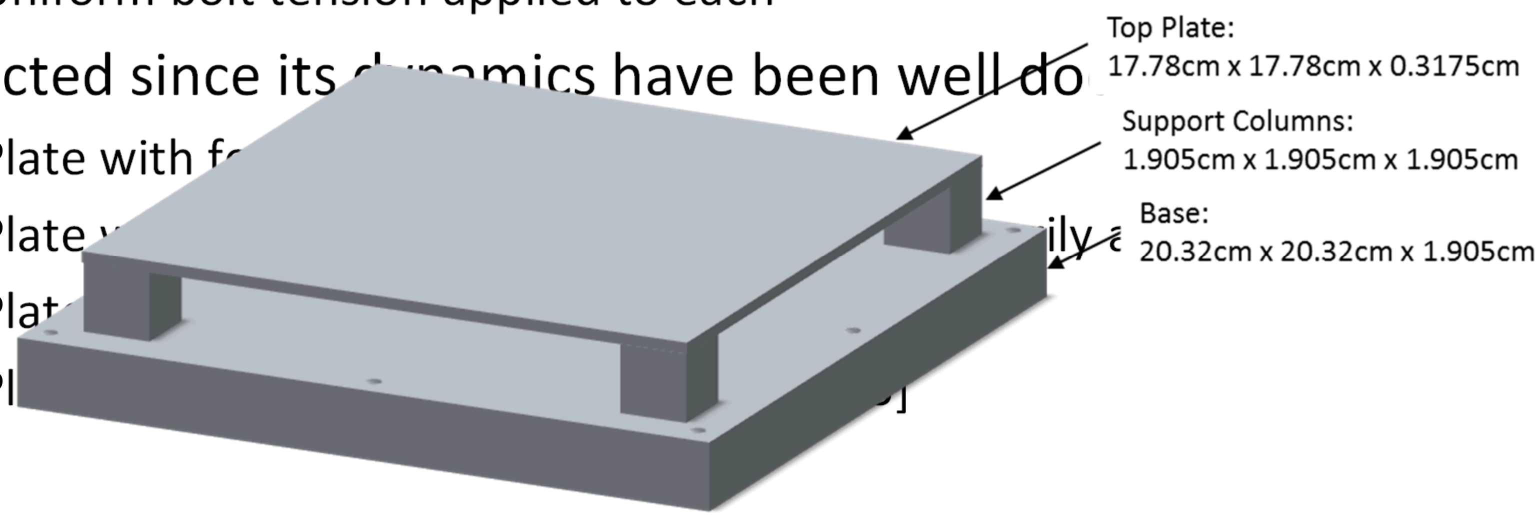
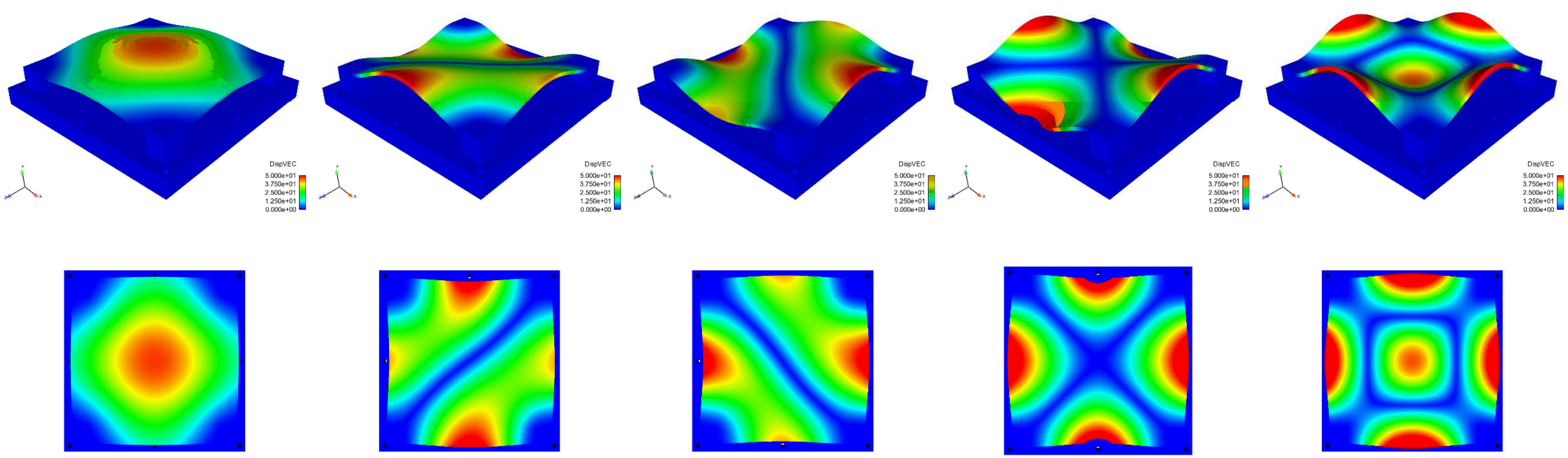


Test Article

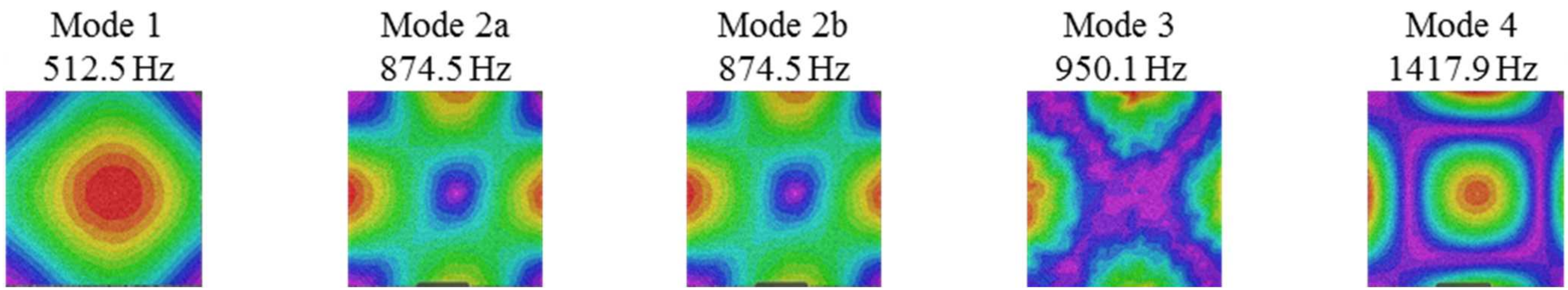
- Finite Element Model
  - Used to predict dominant mode shapes and frequency components
  - Confirms that support columns are not dynamically active in frequency range of interest
- Primary Mode Shapes Identified

506 Hz 856 Hz 856 Hz 936 Hz 1407 Hz



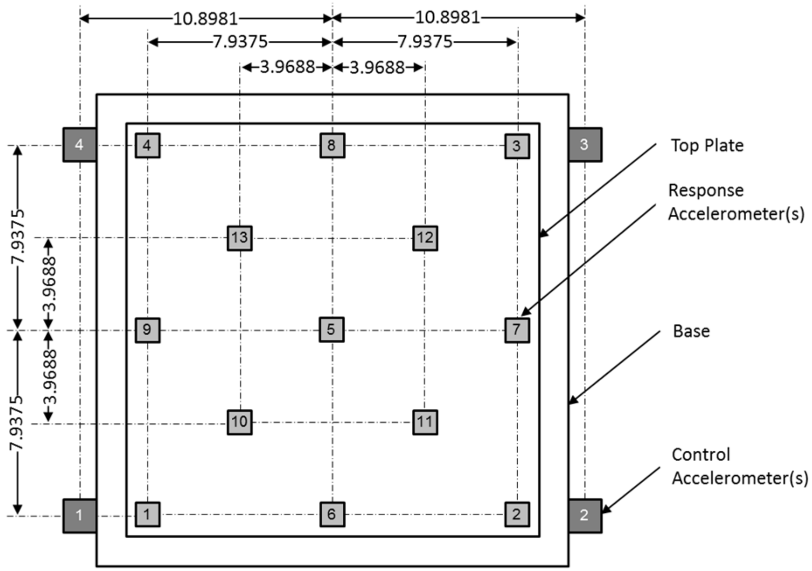
Experimental Test Article Mode Shapes

- Digitial Image Correlation used to extract and verify mode shapes
- The mode shapes and their frequencies agree with those predicted by the model

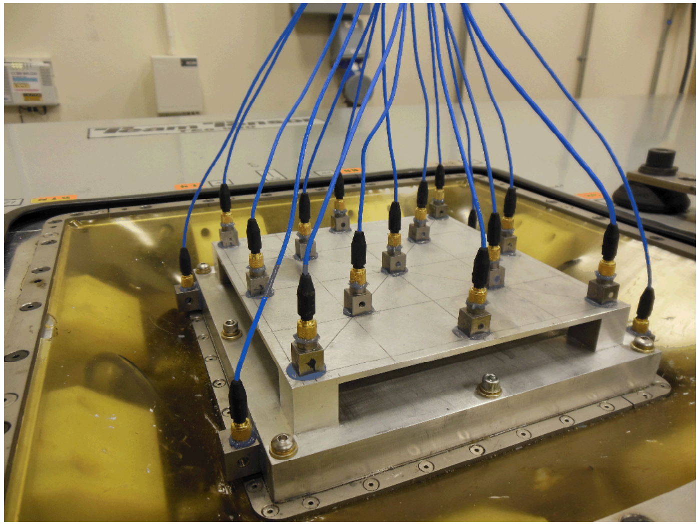


Sensor Configuration – Multi-axis

- Control Accelerometers,
  - PCB 356A15
    - Triaxial ICP Accelerometer
    - Nominal Sensitivity: 100 mV/g
    - Weight: 0.37 oz
- Response Accelerometers
  - PCB 356A33
    - Triaxial ICP Accelerometer
    - Nominal Sensitivity: 10 mV/g

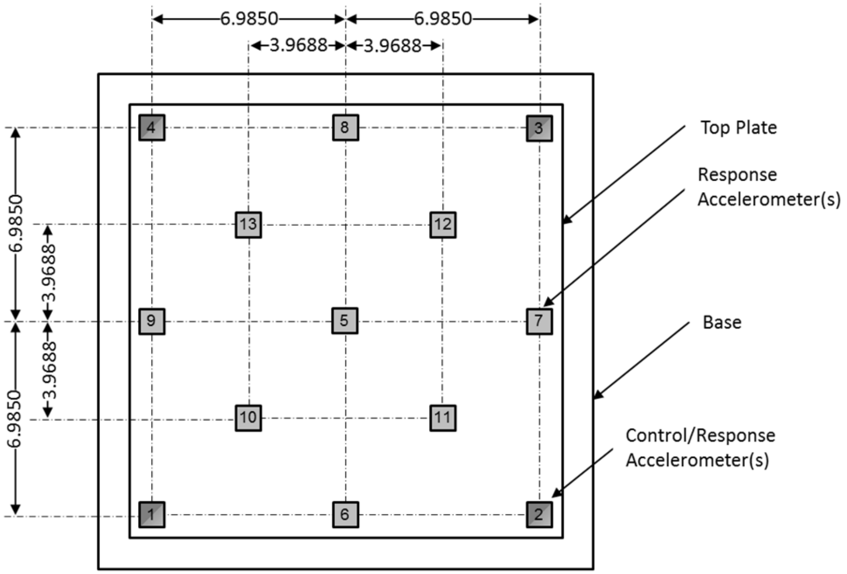


*All dimensions are in centimeters



Sensor Configuration – Single Axis

- Control Accelerometers,
  - PCB 356A33
    - Triaxial ICP Accelerometer
    - Nominal Sensitivity: 10 mV/g
- Response Accelerometers
  - PCB 356A33
    - Triaxial ICP Accelerometer
    - Nominal Sensitivity: 10 mV/g



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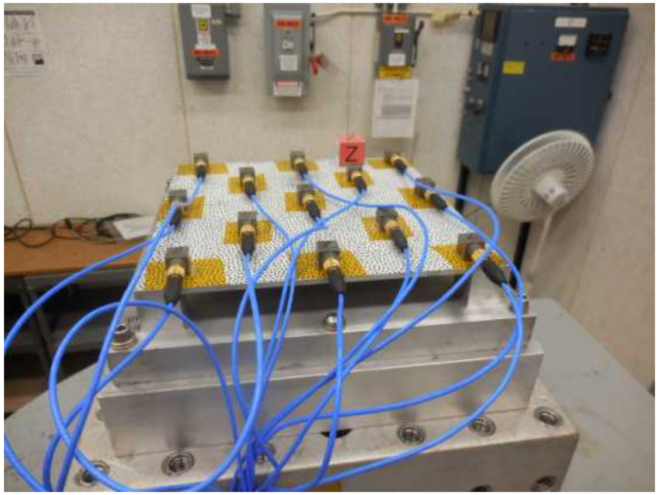
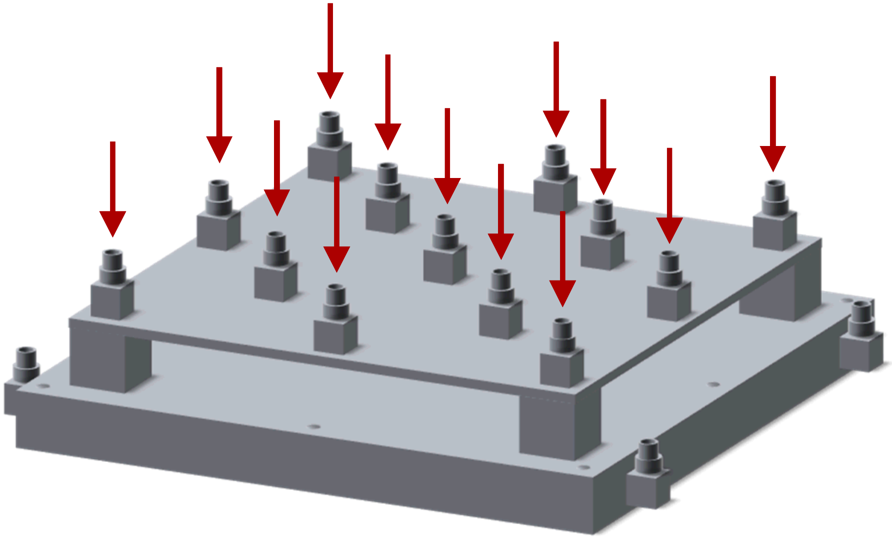
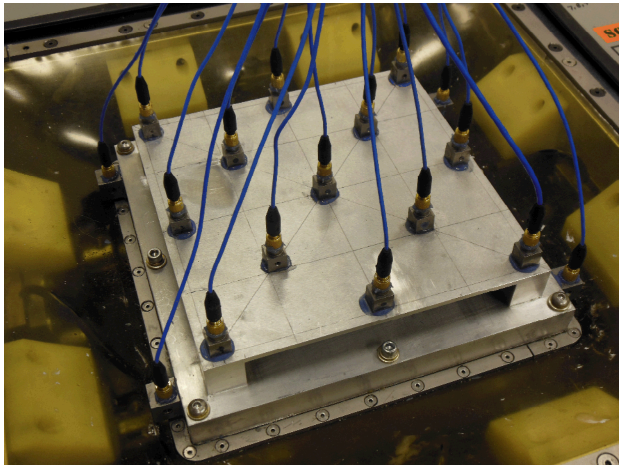


Sensor Selection & Configuration

- Reference Sensor Placement:
  - Center of plate
  - Each corner
  - Mid-span of each side
  - Along each diagonal placed evenly between the center and corner accelerometers

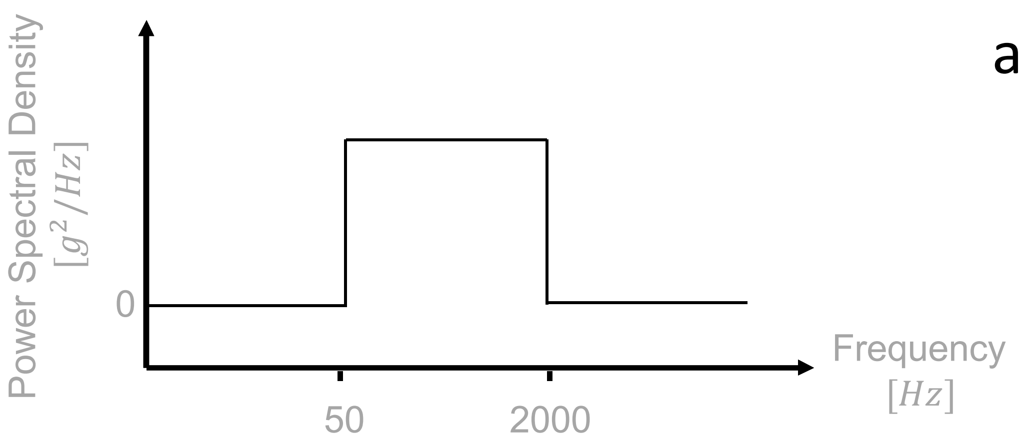


- The high number of accelerometers caused a mass loading affect on the top plate
- Their positions were selected to mitigate mode shape distortion
- FEA data confirms that modes are preserved although all frequencies were shifted lower



Test Sequence

- Control Signal
- Axes
- Input Level
- Cross-Axis Coherence & Phase



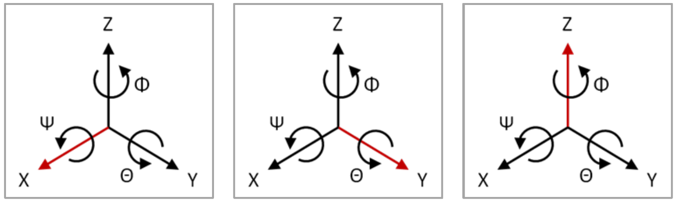
- Band-limited white noise (20Hz – 2kHz)
- Causes simultaneous excitation of all frequencies within range
- All frequency dependence in stimulated responses can be attributed to plate dynamics

Test Sequence

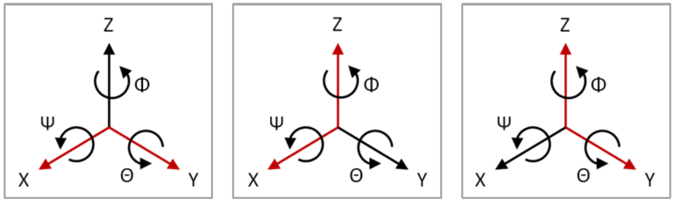
- Control Signal
- ➢ Axes
- Input Level
- Cross-Axis Coherence & Phase

- Single and Multi-Axis
  - Uniaxial: One translational axis at a time (X, Y, Z)
  - Biaxial: Two translational axes at a time (XY,XZ,YZ)
  - Triaxial: All three axes simultaneously (XYZ)
- All axes always controlled, but not all to full test levels

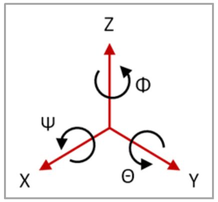
Uniaxial



Biaxial



Triaxial

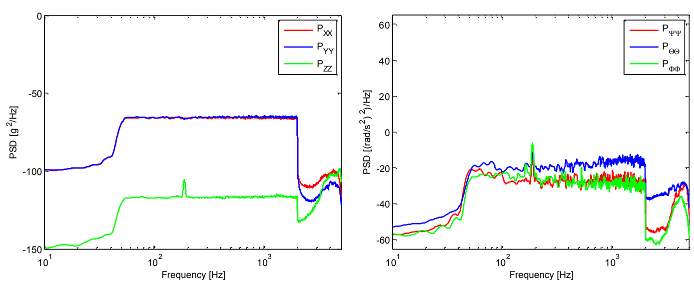


Test Sequence

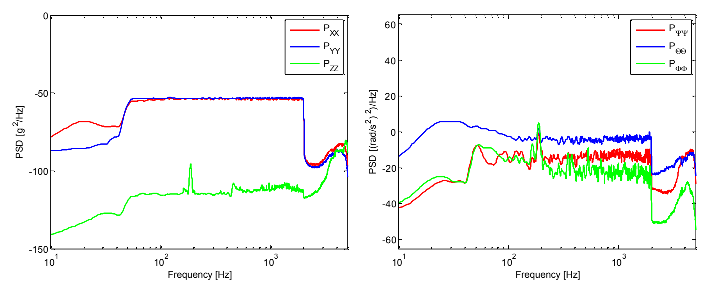
- Control Signal
- Axes
- ➢ Input Level
- Cross-Axis Coherence & Phase

- Input Acceleration Levels: low ($1g_{rms}$) & high ($2g_{rms}$)
- Same acceleration level for all applicable axes
- All other DOFs controlled to low level

X & Y Translation Controlled (@ 1g)
Z Translation & All Rotations Minimized



X & Y Translation Controlled (@ 2g)
Z Translation & All Rotations Minimized

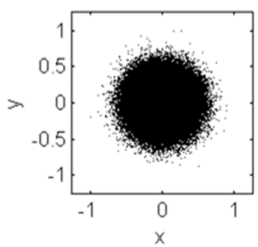


Test Sequence

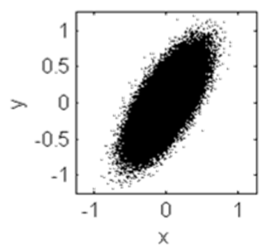
- Control Signal
- Axes
- Input Level
- ➢ Cross-Axis Coherence & Phase

- Zero phase between all axes
- Coherence is measure of relationship between two signals
- Levels: low (~0), medium (0.50), and high (~1)
  - Coherence with and between all other DOFs set at zero

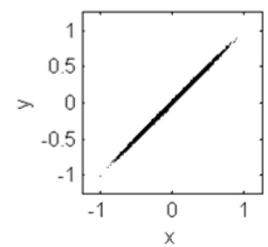
X,Y Unrelated
$C_{XY} \cong 0$



X,Y Partially Related
$C_{XY} \cong 0.5$



X,Y Highly Related
$C_{XY} \cong 1$



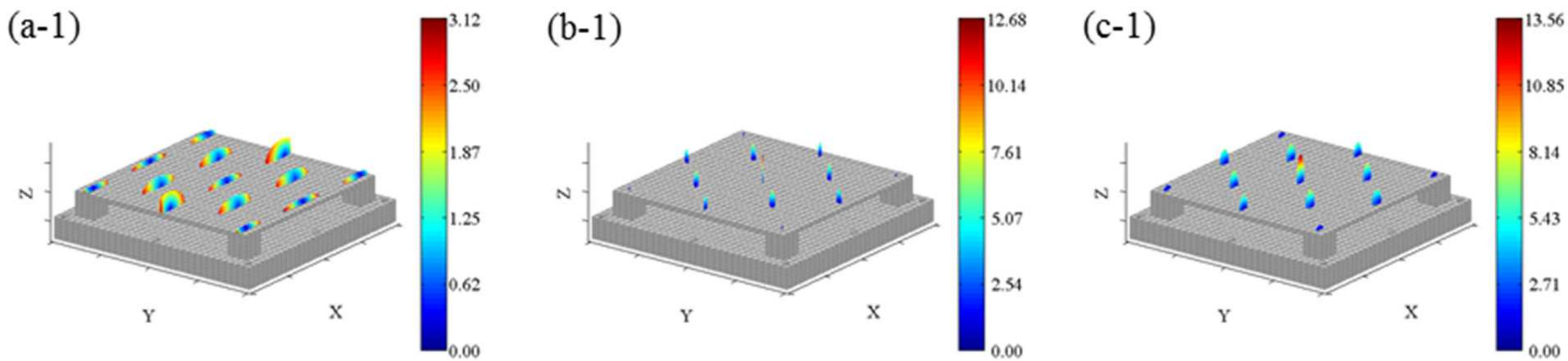
Off Axis Acceleration Levels

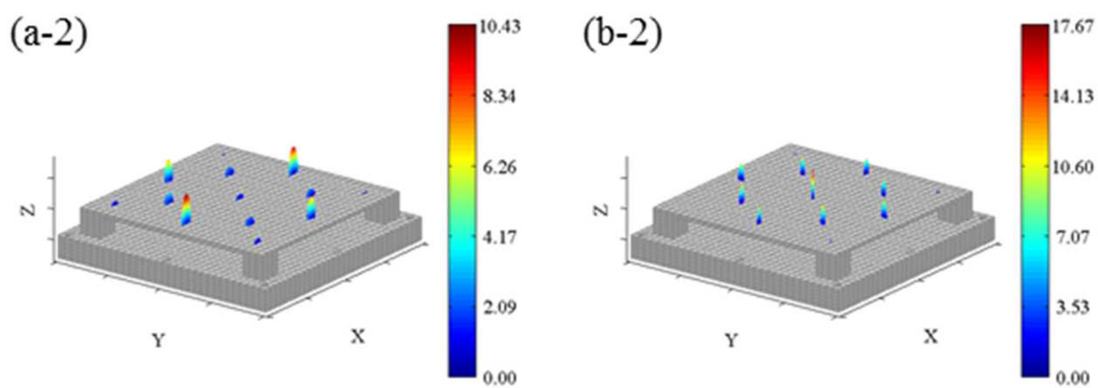
System	Test	Level	Acceleration		
			Transverse X (g)	Longitudinal Y (g)	VerticalZ (g)
1D	X	1g	-	*	*
		2g	-	7.01%	36.54%
	Z	1g	6.95%	9.10%	-
		2g	6.35%	8.44%	-
6D	X	1g	-	6.17%	11.64%
		2g	-	3.24%	13.24%
	Y	1g	6.03%	-	8.18%
		2g	3.13%	-	5.78%
	Z	1g	6.08%	6.46%	-
		2g	3.29%	3.38%	-

*Data Not Available

RMS Accelerometer Responses

X Excitation | Z Excitation | X&Z Excitation

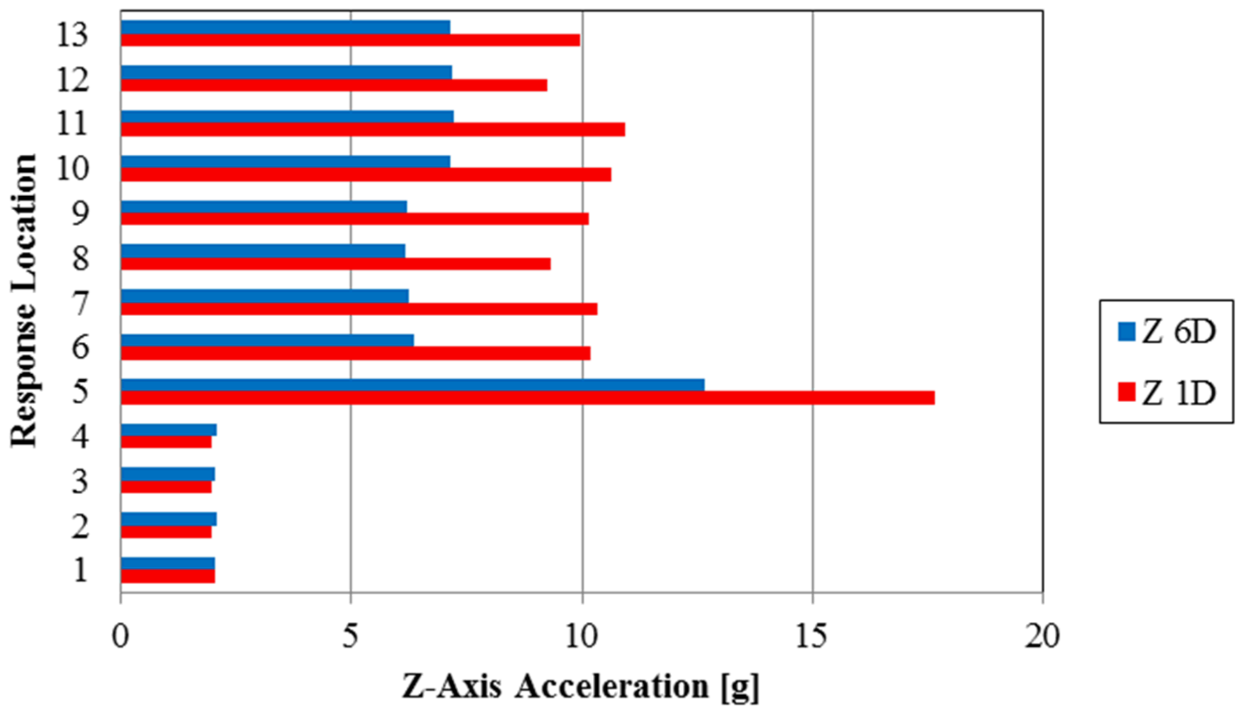




- Response of structure agrees well with expected response for multi-axis shaker (1)
- When conducting test on single axis shaker, uncontrolled off axis energy results dominated by Z axis.

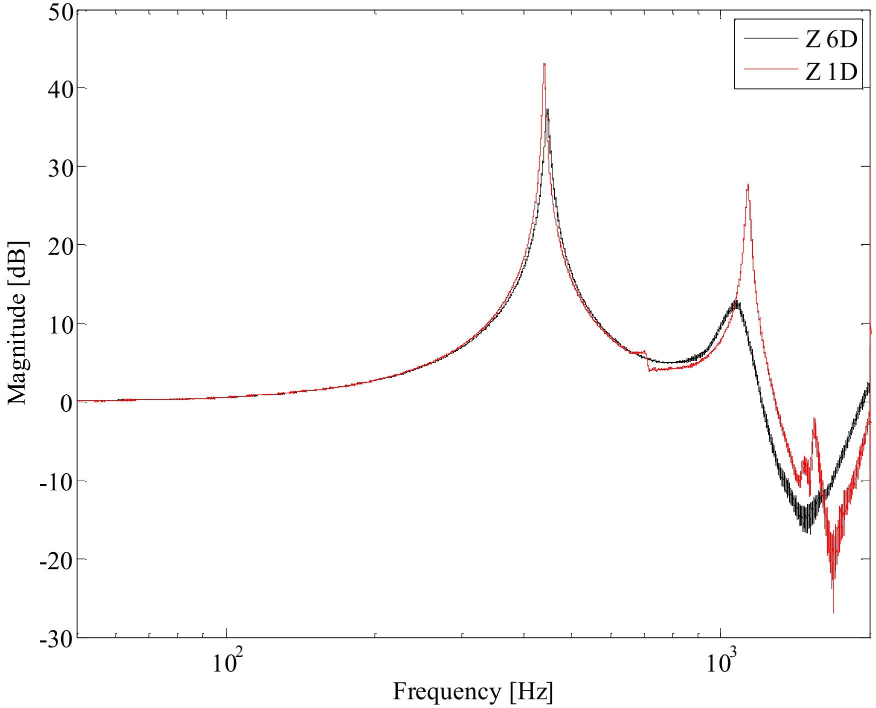
RMS Accelerometer Responses (2)

- Controlled the vertical acceleration to the same level on both shakers, the RMS levels of the plate response on the systems differed substantially.



Response at the Center of the Plate

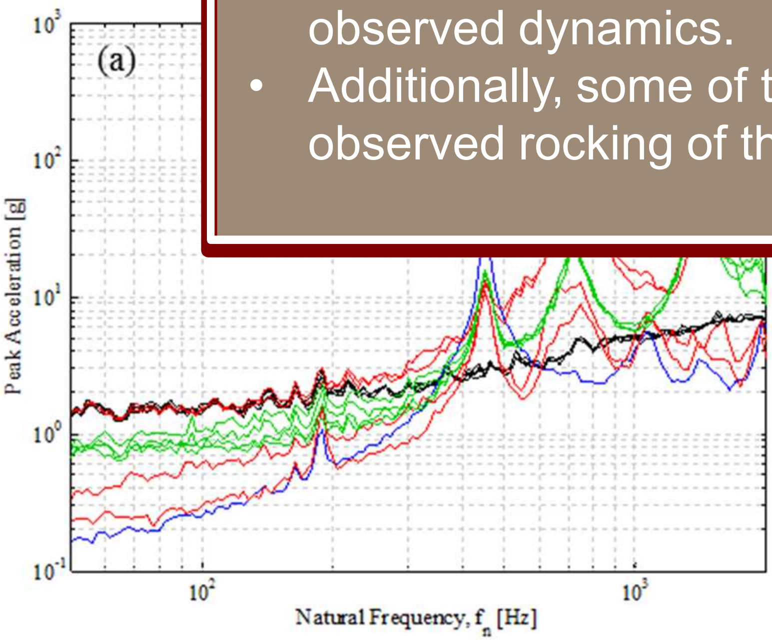
- Response influenced by two critical modes.
  - On multi-axis shaker, they are at 446Hz and 1073Hz
  - On uniaxial shaker, they are at 440Hz and 1137Hz
  - Larger response occurs at both resonances on uniaxial shaker system.

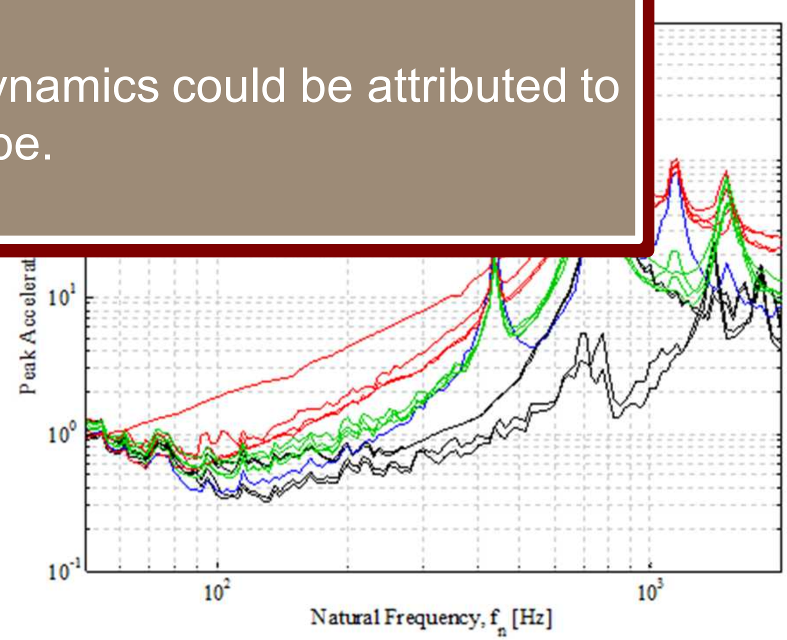


Shock Response Spectra (SRS)

- SRS graphically portrays the peak acceleration that would be experienced by a series of single degree of freedom system with
- The c … s at frequ

> - Additional modal contributions on uniaxial test likely due to boundary conditions created by the cube.
> - Out of axis deformation of cube could contribute to observed dynamics.
> - Additionally, some of the dynamics could be attributed to observed rocking of the cube.





Conclusions

- Single axis testing on uniaxial shaker results in larger peak energy levels than those conducted on multi-axial shakers
  - Comparing results to multiaxial tests, it is not due contributions of off-axis translational excitation
  - Tests were not conducted with added rotations, which may have contributed to this effect.
- Any test with a z-axis stimuli would be dominated by a response in the z-axis, even the x-axis test on the uniaxial shaker.
- The peak acceleration levels found by the SRS demonstrated that the primary modes were invariant to the addition of lateral excitation.
- The lateral response had additional modes due to the dynamics of the mounting cube,
- For model validation, the uncontrolled effects of the testing system must be well documented.

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Thank you for your attention!

QUESTIONS?