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Comparison of Multi-Axis and Single Axis Testing on Plate Structures

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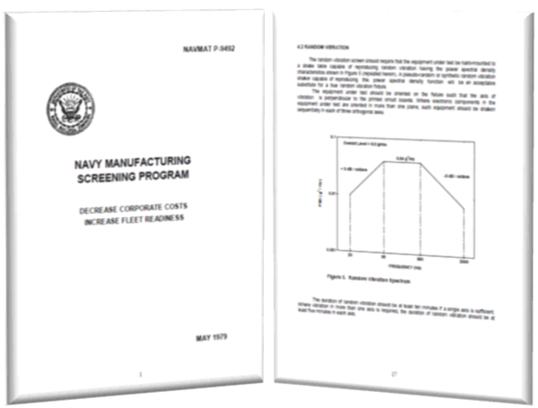
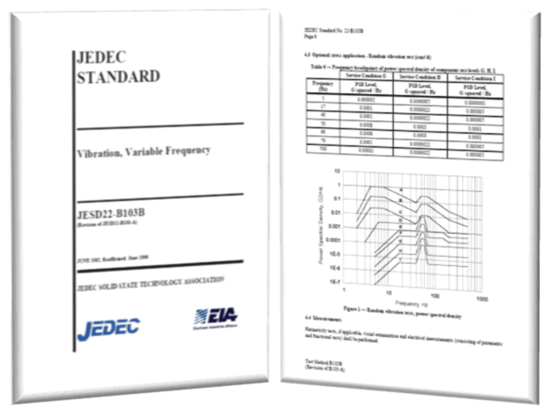
Outline

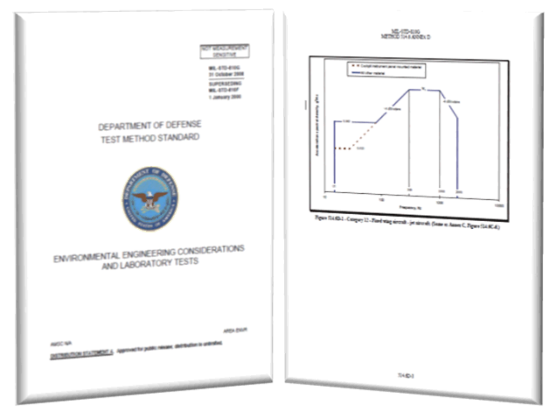
- Motivations & Objective
- Equipment
- Test Article
- Sensor Selection & Configuration
- Test Sequence
  - Axes
  - Levels
  - Coherence and Phase
- Overview of Test Results
  - Energy Levels
  - Peak Accelerations
  - Modal Contributions

Motivations

- Sequential single axis testing 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

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- 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
    - How are fatigue life estimates influenced by stimulation from more than one axis?
    - Can results from a single axis test be used to predict multi-axis results for a given part structure?
    - What's the effect of multi-axis inputs on a test article's modal response?
  - The effect of coherence and/or phase relationships on the energy levels experienced by a part during biaxial or triaxial vibration testing
  - The benefit of single axis testing conducted on equipment capable of mitigating off-axis (and rotational) vibration

Test Equipment

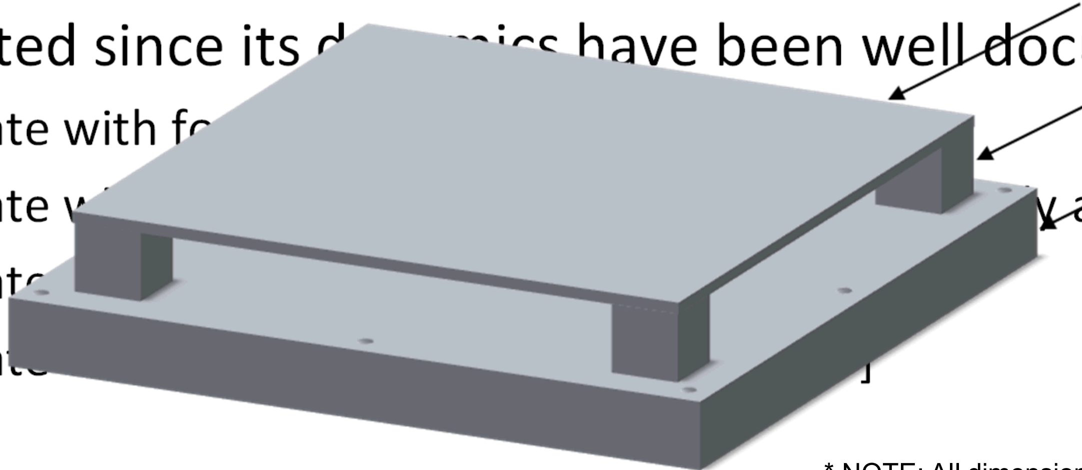
- Shaker System: Team Corporation Tensor™ 900
  - Simultaneous or sequential excitation of X, Y, and/or Z axes
  - Complete control of rotations around all axes

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 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… have been well doc…
  - Plate with fo…
  - Plate w… …y at]
  - Plat…
  - Pla…]

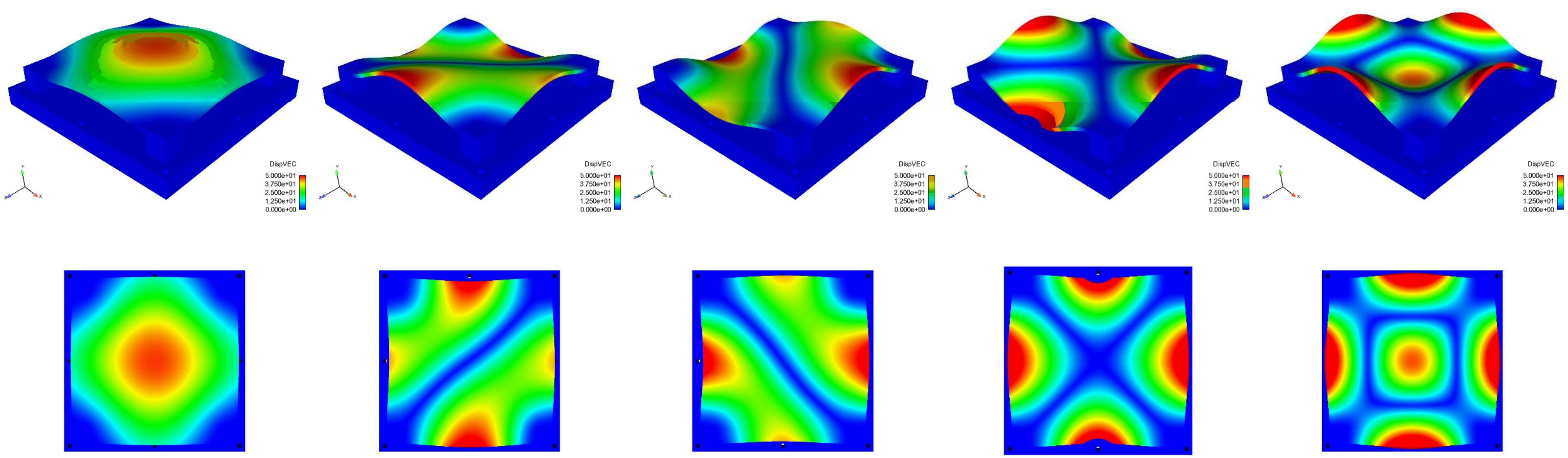


* NOTE: All dimensions in inches

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



Sensor Selection & Configuration

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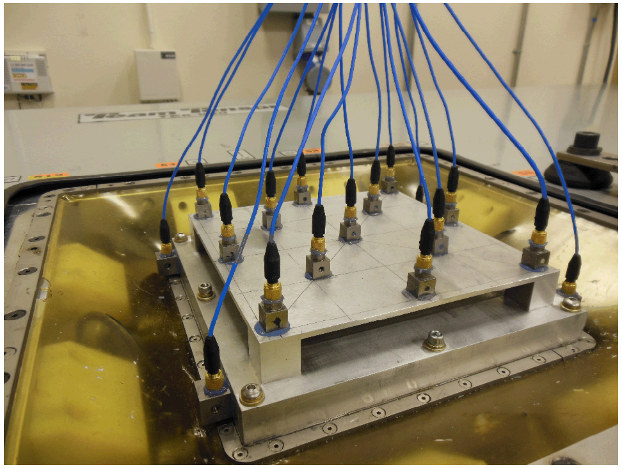
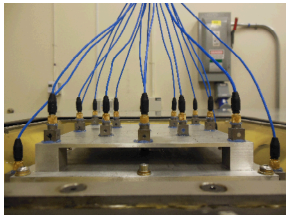
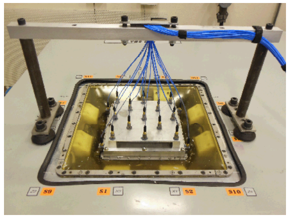
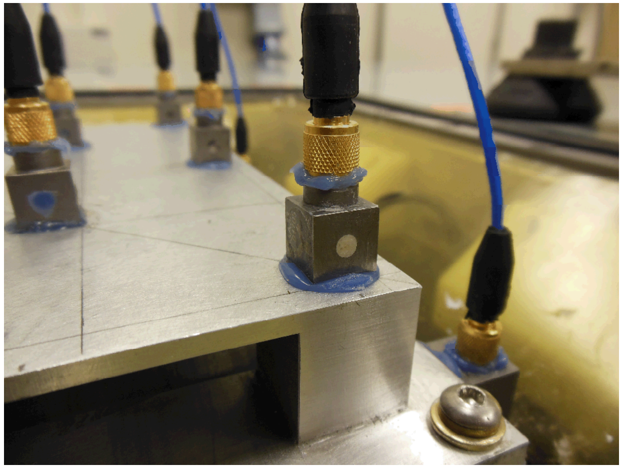
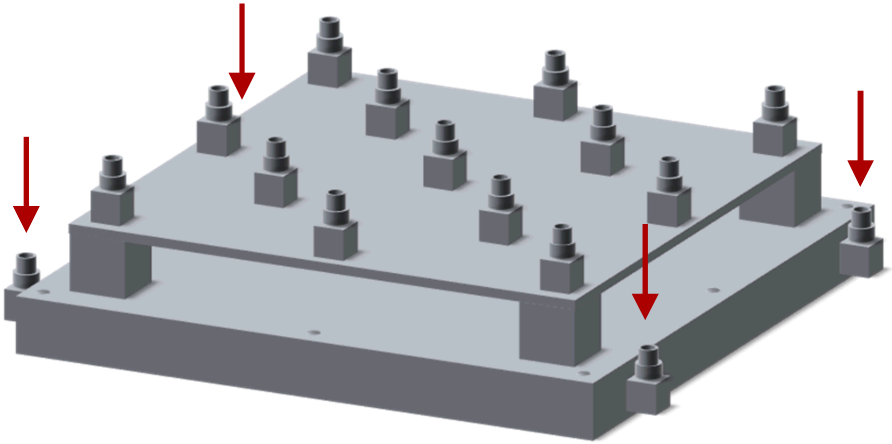
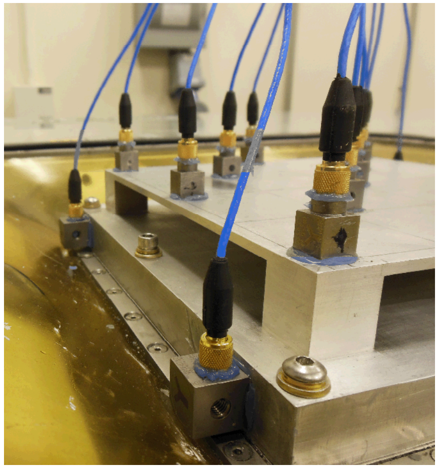
- Control Accelerometers
  - PCB 356A15
    - Triaxial ICP Accelerometer
    - Nominal Sensitivity: 100 mV/g
    - Weight: 0.37 oz
- Response Accelerometers
  - PCB 356A33
    - Triaxial ICP Accelerometer
    - Nominal Sensitivity: 10 mV/g
    - Weight: 0.19 oz

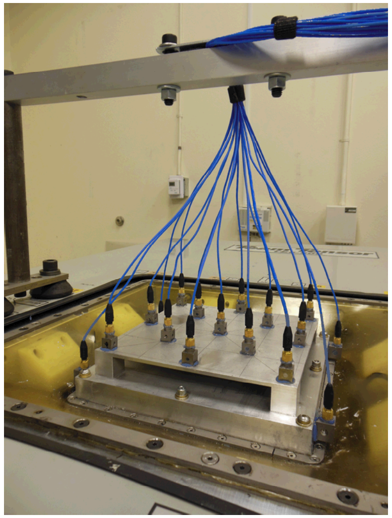





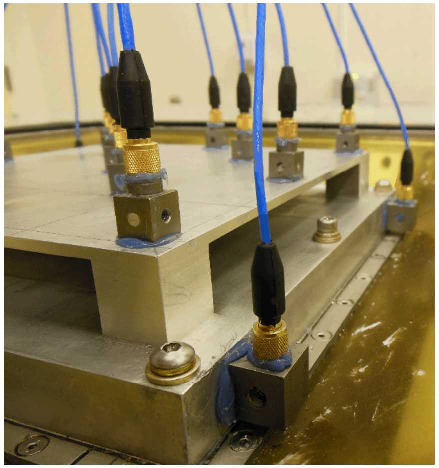
Sensor Selection & Configuration

- Control Sensor Placement
  - Symmetric about both lateral axes on base
  - Allows calculation of all base translational and rotational degrees of freedom









Sensor Selection & Configuration

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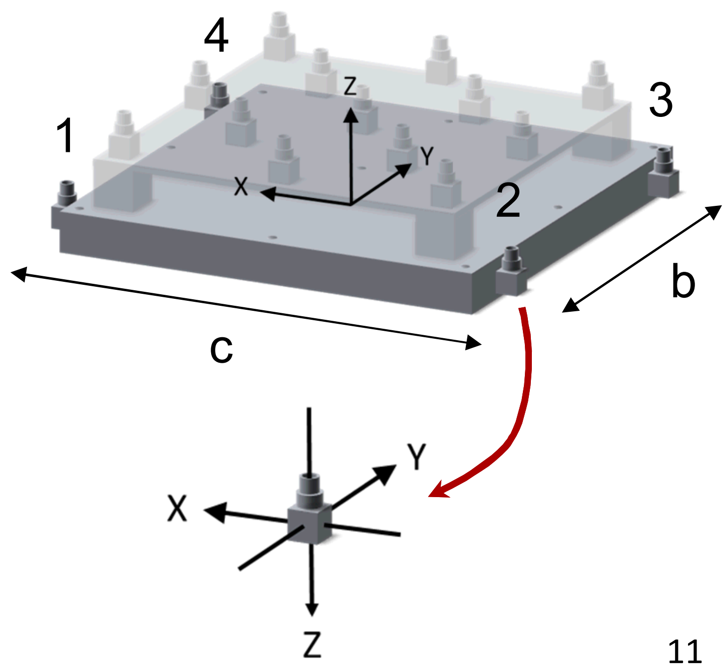
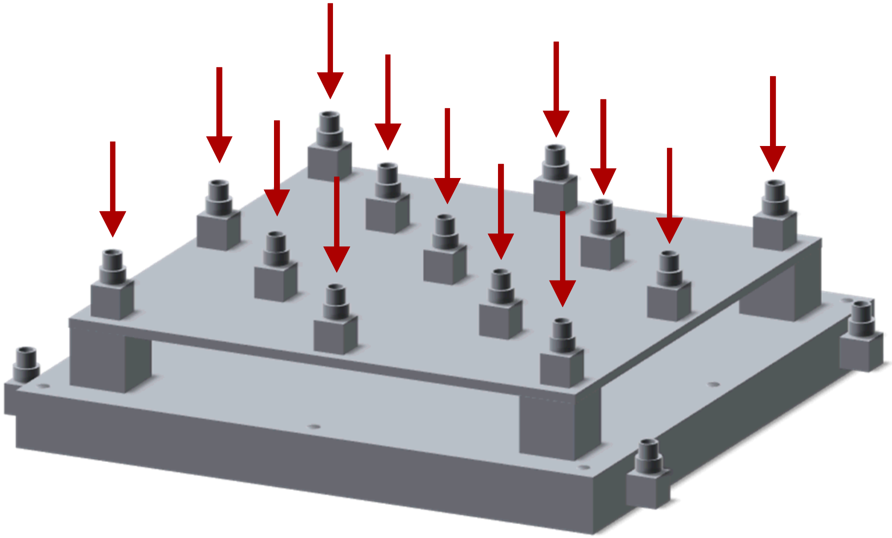
- Control Transformation
  - Given the acceleration from triaxial control accelerometers
    - a_{x_i} , a_{y_i} , and a_{z_i}
  - Calculate the base input translational and rotational acceleration [14]
    - $\vec{A} = H\vec{a}$

$$\underbrace{\begin{bmatrix} A_X \\ A_Y \\ A_Z \\ A_\Psi \\ A_\Theta \\ A_\Phi \end{bmatrix}}_{\vec{A}} = \underbrace{\begin{bmatrix} \frac{1}{4} & 0 & 0 & \frac{1}{4} & 0 & 0 & \frac{1}{4} & 0 & 0 & \frac{1}{4} & 0 & 0 \\ 0 & \frac{1}{4} & 0 & 0 & \frac{1}{4} & 0 & 0 & \frac{1}{4} & 0 & 0 & \frac{1}{4} & 0 \\ 0 & 0 & -\frac{1}{4} & 0 & 0 & -\frac{1}{4} & 0 & 0 & -\frac{1}{4} & 0 & 0 & -\frac{1}{4} \\ 0 & 0 & -\frac{g_0}{2b} & 0 & 0 & \frac{g_0}{2b} & 0 & 0 & \frac{g_0}{2b} & 0 & 0 & -\frac{g_0}{2b} \\ 0 & 0 & -\frac{g_0}{2c} & 0 & 0 & -\frac{g_0}{2c} & 0 & 0 & \frac{g_0}{2c} & 0 & 0 & \frac{g_0}{2c} \\ -\frac{g_0}{4b} & -\frac{g_0}{4c} & 0 & \frac{g_0}{4b} & -\frac{g_0}{4c} & 0 & \frac{g_0}{4b} & \frac{g_0}{4c} & 0 & -\frac{g_0}{4b} & \frac{g_0}{4c} & 0 \end{bmatrix}}_{H} \underbrace{\begin{bmatrix} a_{x_1} \\ a_{y_1} \\ a_{z_1} \\ a_{x_2} \\ a_{y_2} \\ a_{z_2} \\ a_{x_3} \\ a_{y_3} \\ a_{z_3} \\ a_{x_4} \\ a_{y_4} \\ a_{z_4} \end{bmatrix}}_{\vec{a}}$$

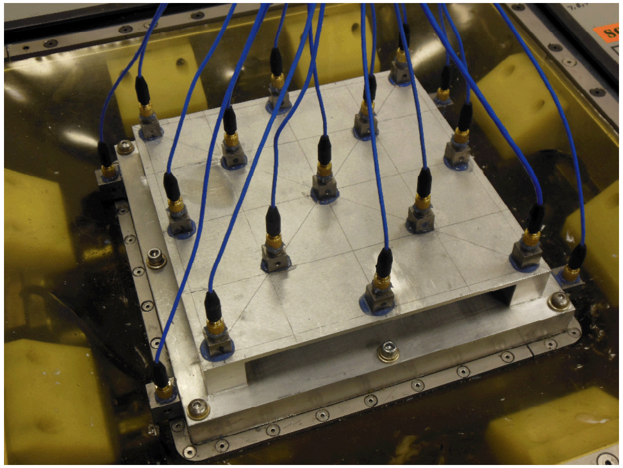


Sensor Selection & Configuration

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

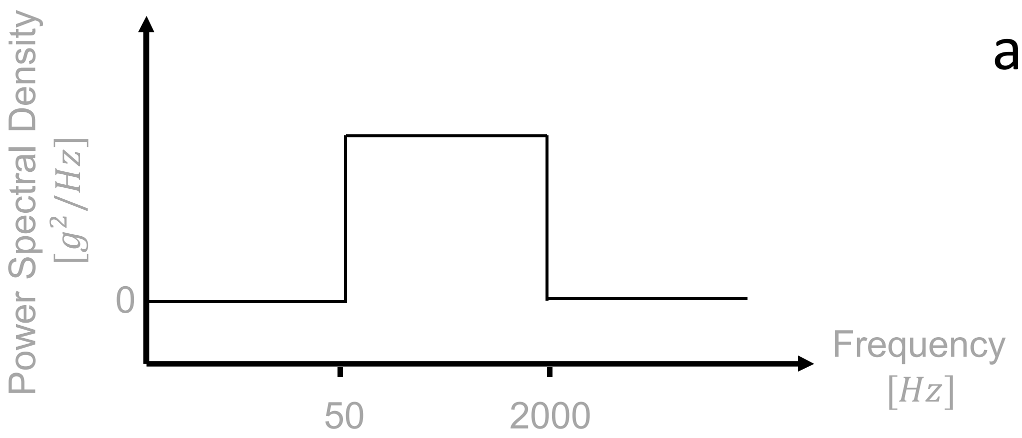


- The high number of accelerometers caused a mass loading affect on the top plate
- Their positions were selected to mitigate mode shape distortion
- FEA data confirms that modes are preserved although all frequencies were shifted lower



Test Sequence

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



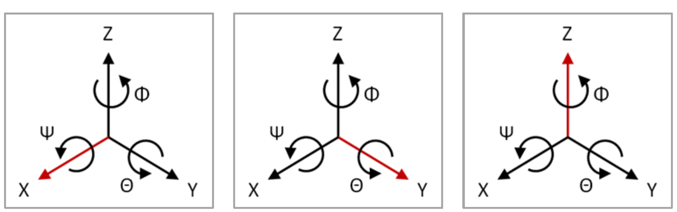
- Band-limited white noise (50Hz – 2kHz)
- Causes simultaneous excitation of all frequencies within range
- All frequency dependence in stimulated responses can be attributed to plate dynamics

Test Sequence

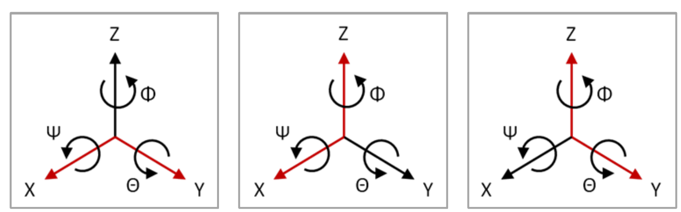
- Control Signal
- ➢ Axes
- Input Level
- Cross-Axis Coherence & Phase

- 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

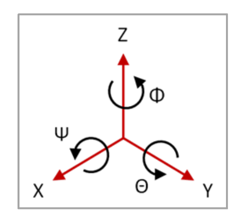
Uniaxial



Biaxial



Triaxial

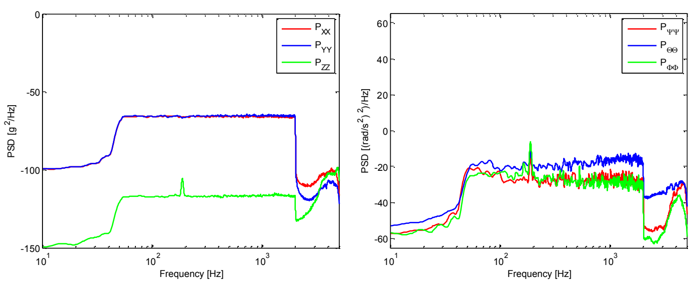


Test Sequence

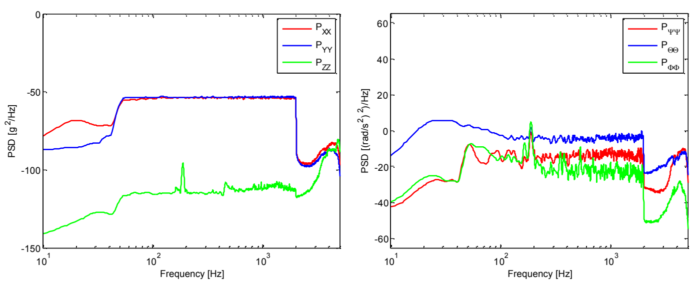
- Control Signal
- Axes
- ➢ Input Level
- Cross-Axis Coherence & Phase

- 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



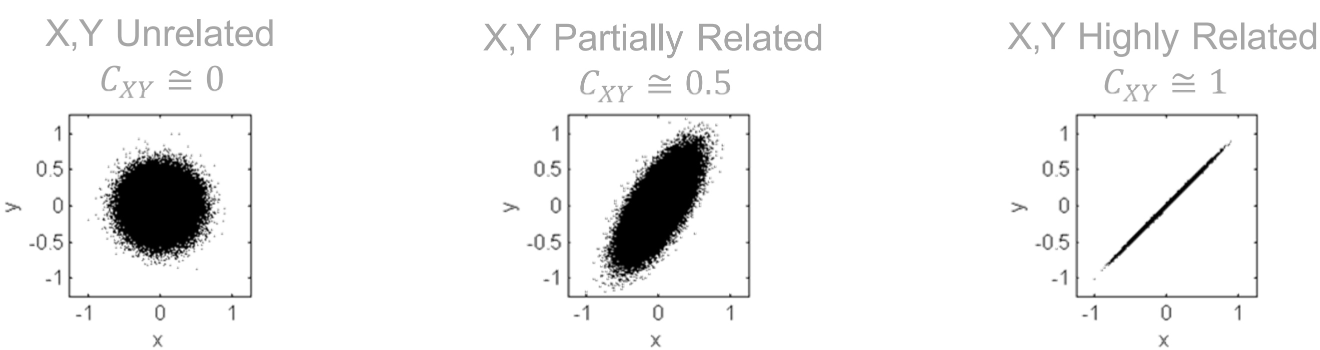
X & Y Translation Controlled (@ 2g)
Z Translation & All Rotations Minimized



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



Response Energy

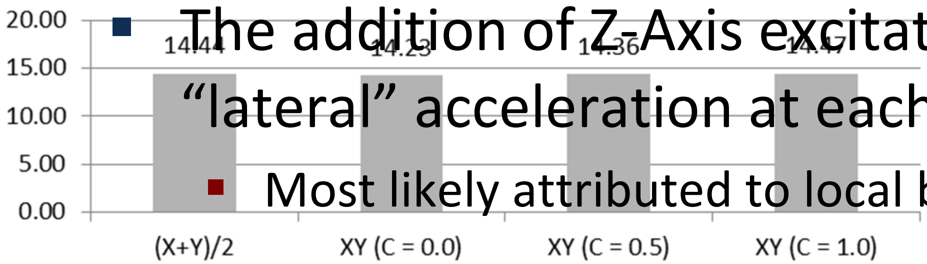
- $e = e_x + e_y + e_z$
  - Where, $e_n = \frac{1}{L}\sum_{j=1}^{L} v_n[j]^2 \;\{\forall n = x, y, z\}$
- The energy of the *i* th response accelerometer ($e_{R_n[i]}$) was normalized by the energy of the control input (e_C)
  - $e'_{\mathrm{R_n[i]}} = \mathrm{e}_{R_n[i]}/e_C$
  - This accounts for the known input energy level differences between single and multi-axis test cases
- Then, the total normalized energy of the response accelerometers is given by
  - $E'_n = \sum_{i=1}^{N} e'_{\mathrm{R_n[i]}} \;\{N = 13\;(total\ number\ of\ response\ accels)\}$

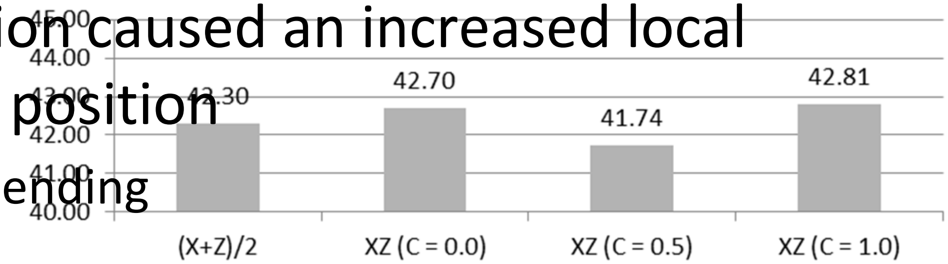
Response Energy

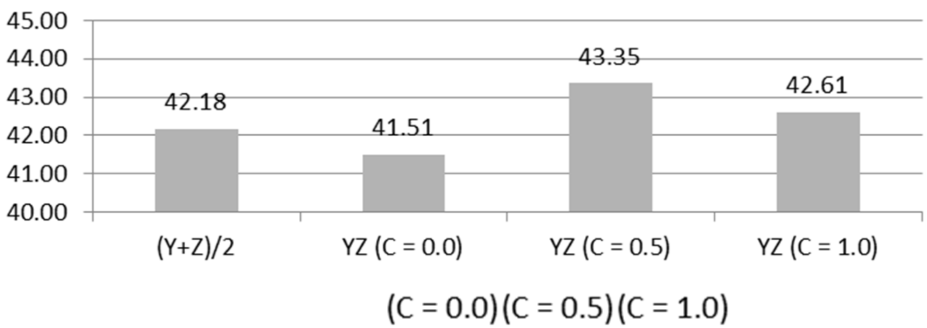
- Total normalized energy levels are comparable between multi-ax
- Total no approxi applicable single ax

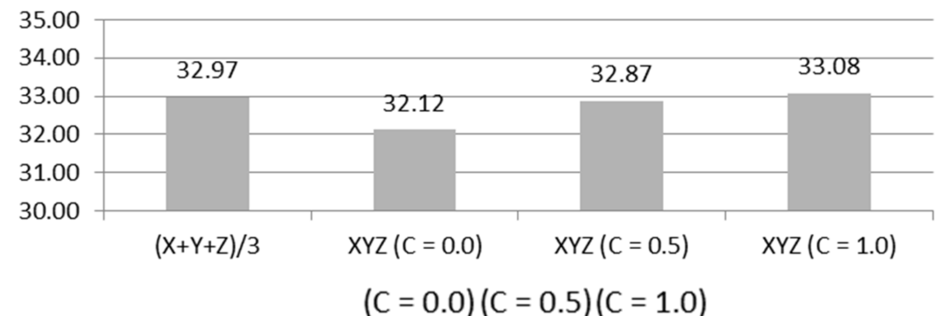
This estimate was bounded by the maximum and minimum energy levels for multi-axis tests
∴
It can’t serve as either a reliable upper or lower bound for anticipated multi-axis energy levels

- The addition of Z-Axis excitation caused an increased local “lateral” acceleration at each position
  - Most likely attributed to local bending

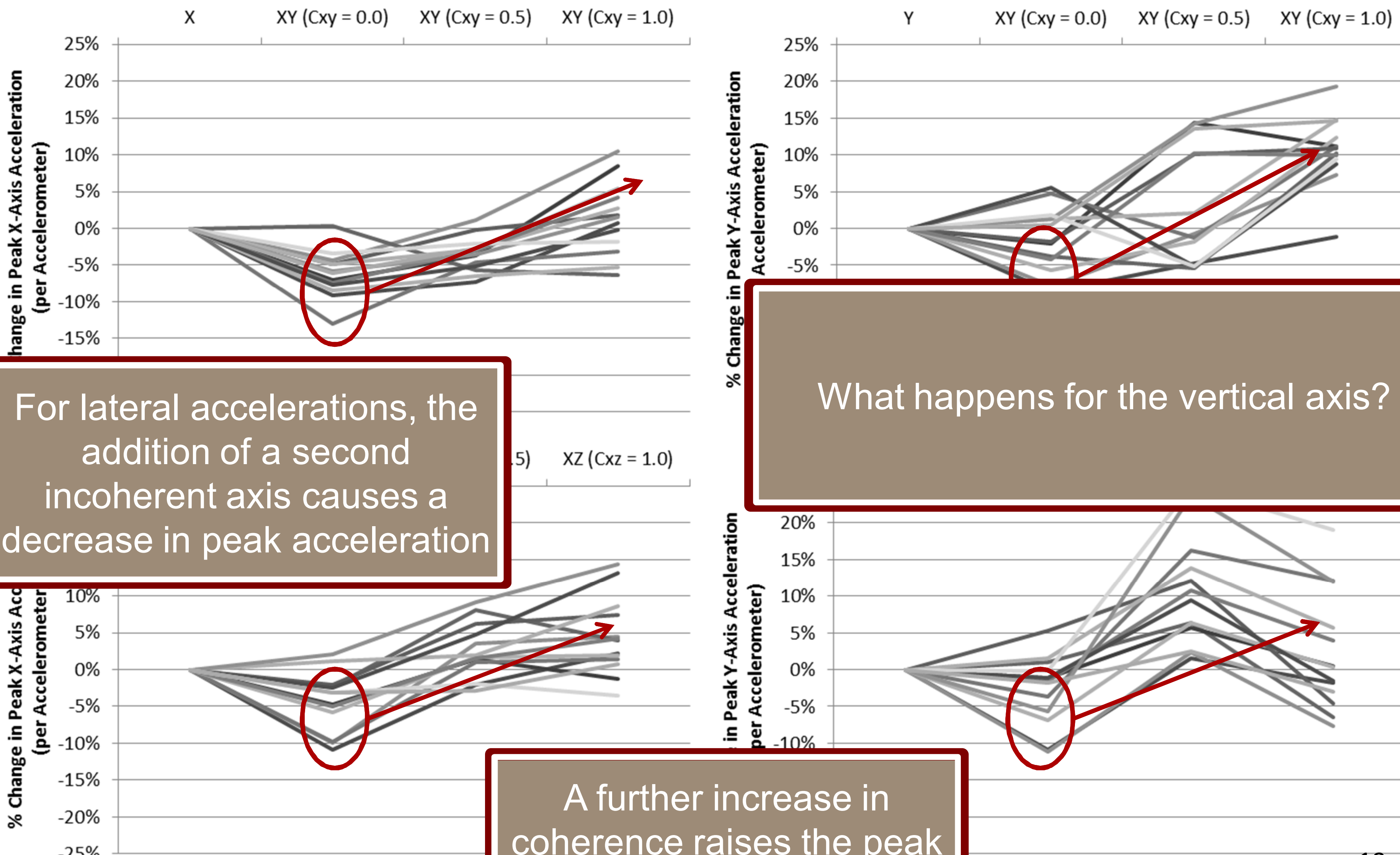








Peak Acceleration

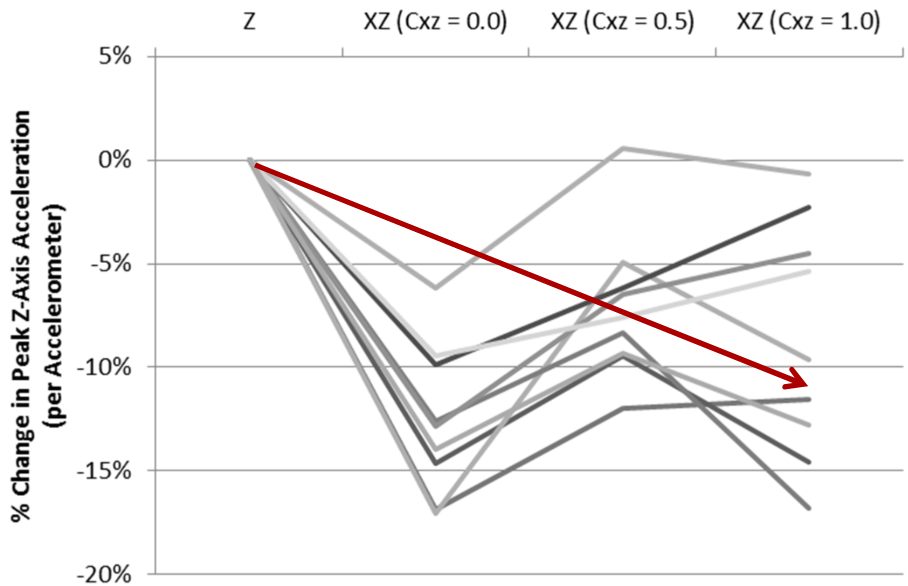


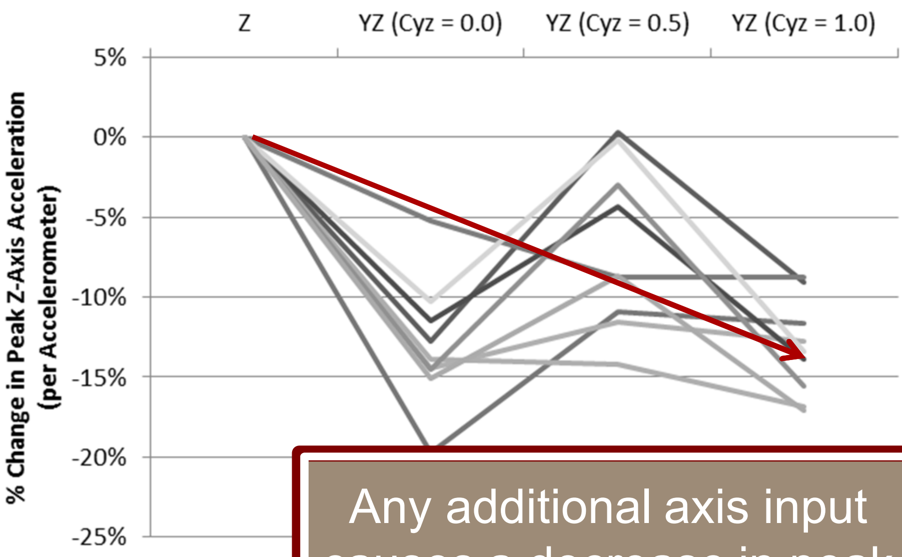
For lateral accelerations, the addition of a second incoherent axis causes a decrease in peak acceleration

What happens for the vertical axis?

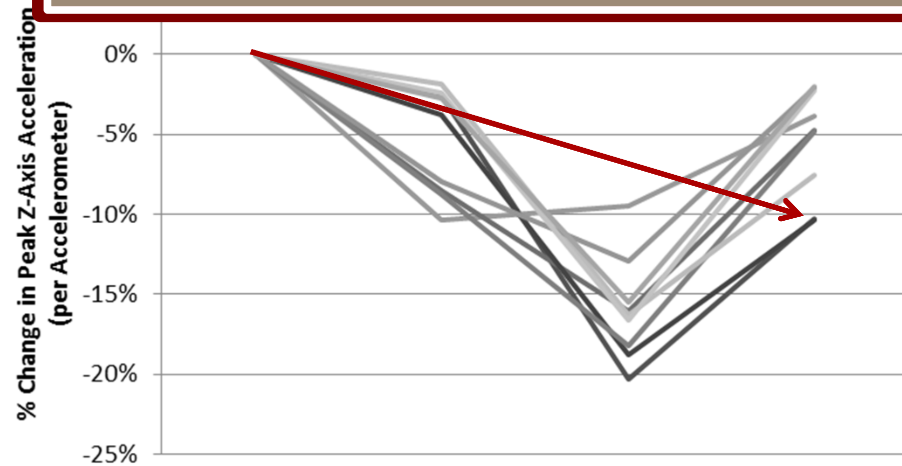
A further increase in coherence raises the peak levels

Peak Acceleration





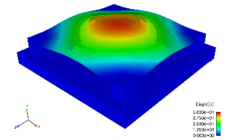
What happens for the vertical axis?

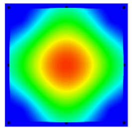


Any additional axis input causes a decrease in peak acceleration levels

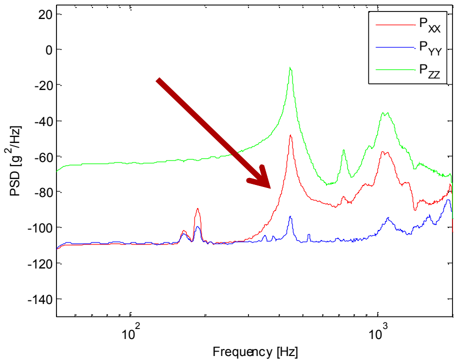
Modal Response

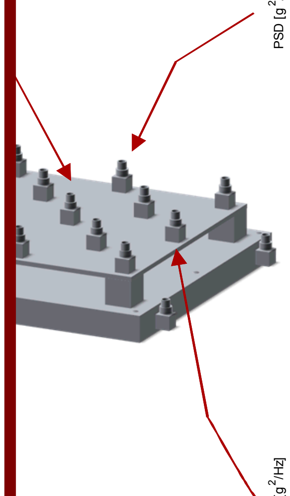
- Responses for each test dominated by first mode shape



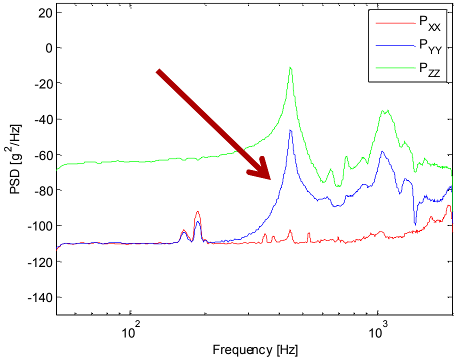


X Edge Accelerometer

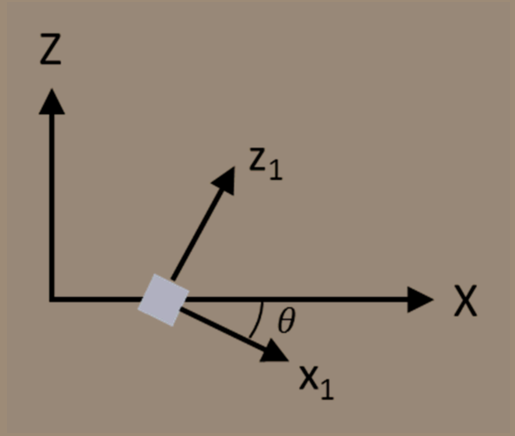




Y Edge Accelerometer

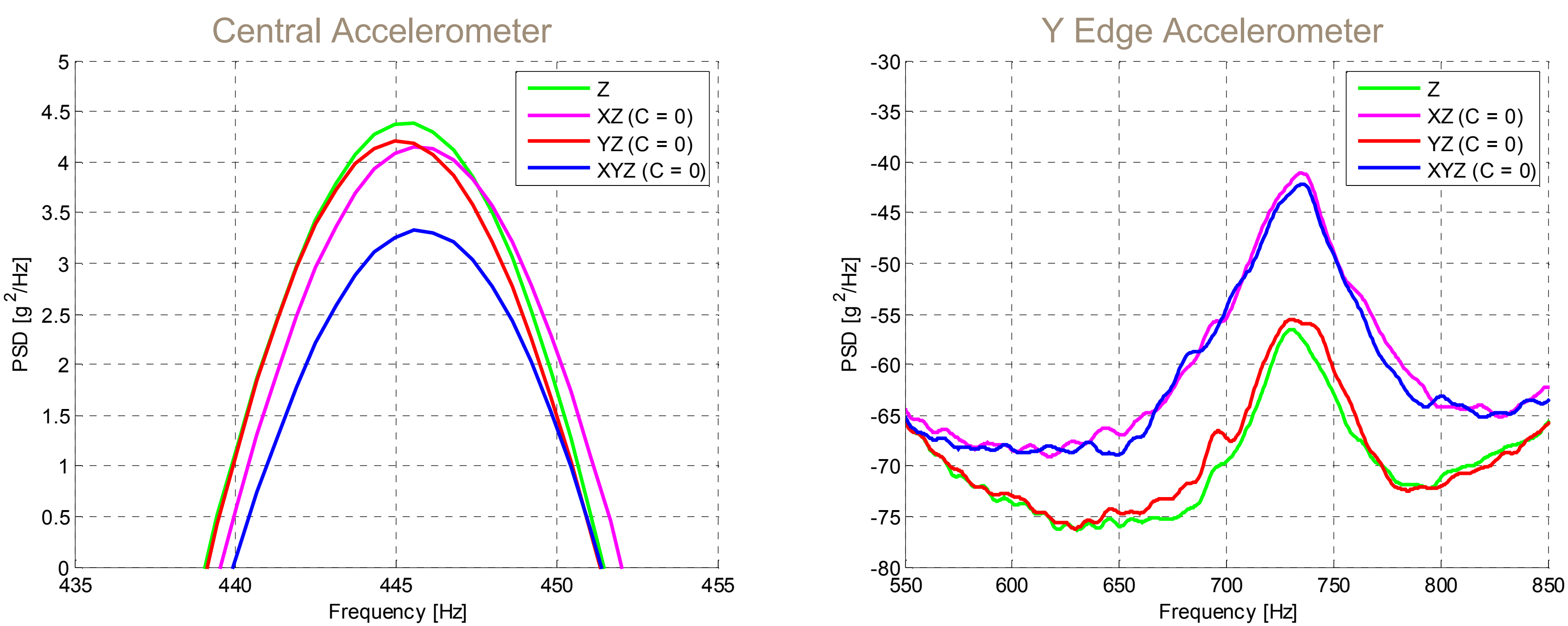


For edge accelerometers, the observed lateral response is due to plate bending. For a bent plate, a portion of the global z-axis acceleration appears locally as a x or y-axis acceleration



Modal Response

- Dominant frequencies remain constant, but modal contribution changes depending on excitation level of additional axes



Conclusions

- For a plate structure, uniaxial testing in line with the dominant axis results in worst case testing
- For conservative fatigue or life-cycle testing, peak response axis must be known a-priori
- Even for simple structures, modal contribution is altered by multi-axis testing
  - Corresponding stress state will never be captured by single axis tests
- On uniaxial shakers, presence of off axis stimuli due to internal coupling may distort results
  - True single axis testing can only be performed on multi-axis shaker
  - Control of off axis contributions can enable improved model validation
- Combined single axis response data cannot accurately be used to predict or bound multi-axis scenarios

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Thank you for your attention!

QUESTIONS?