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Responses of Structures to SDoF vs MDoF Vibration Testing

IMAC XXXV

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Outline

- Motivations & Objective
- Test Equipment
- Test Article and Instrumentation
- Visual Comparison
- Comparison Metrix
- Observations
- Conclusions

Motivations

- Sequential single axis testing has been firmly established as the preferred test method for environmental vibration characterization and analysis
- Recent developments in electrodynamic shaker capabilities have enabled reliable and controllable simultaneous multi-axis testing
- Growing body of evidence indicates shortcomings in conventional single axis testing.
- Multi-axis testing is shown to produce loading conditions that more closely simulate real world environments.

Motivations

- Traditional multi-axis testing conducted by developing a control scheme based on rigid body acceleration at the base of a component.
- Limitations of instrumentation during field tests, it is rare to be able to directly derive 6DoF inputs at the component or sub-system level.
- Coherence and phase between axes is not adequately quantified.

Objective

- Use directly measured field data to drive a multi-axis vibration test
- Benchmark the performance of other methods for deriving a 6DoF test inputs from field data with limited instrumentation
- Compare the results of tests conducted with input signals derived from only response channels which would have been available during a standard field test to those conducted with the true input signals directly measured

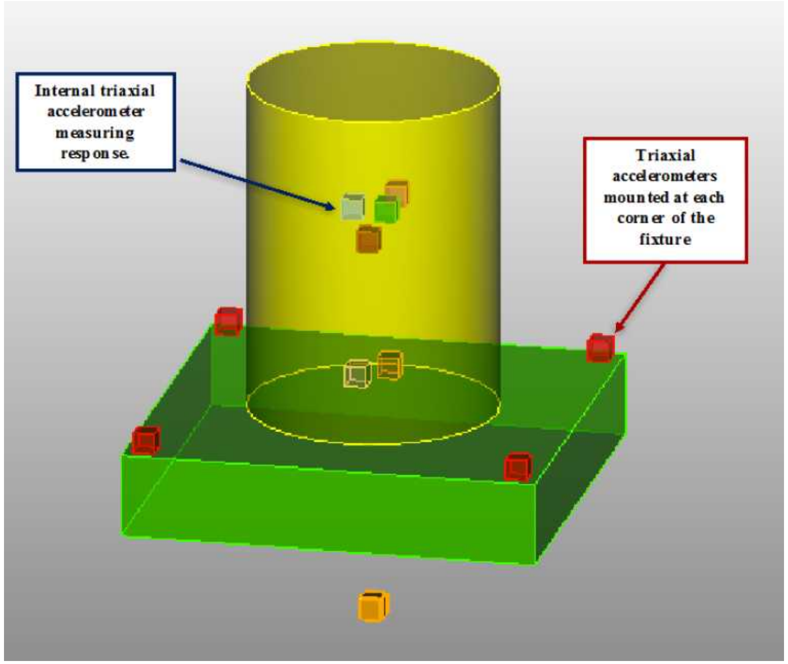
Test Equipment

- Shaker System: Team Corporation Tensor™ 18kN
  - Simultaneous or sequential excitation of X, Y, and/or Z axes
  - Complete control of rotations around all axes

Specifications	
Table First Frequency	4,000 Hz
Test Frequency Range	10 - 4,000 Hz
Max Displacement	1.0 in
Max Acceleration (w/max payload)	10 g

- Controller Software: Data Physics Control and Analysis System
  - Multi-Input and Multi-Output Control
  - Input and Output Transformation for 6DOF Control
- Data Acquisition: National Instruments™ LabVIEW and NI Data Acquisition Modules

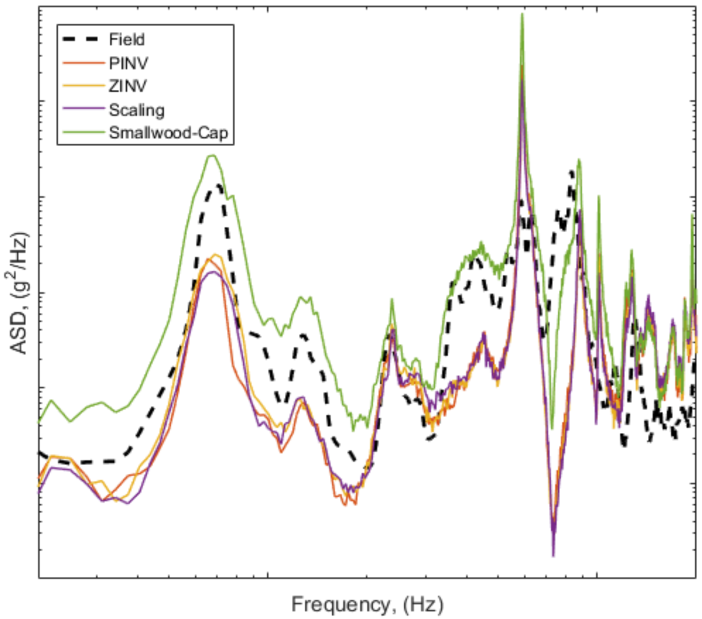
Test Article and Instrumentation



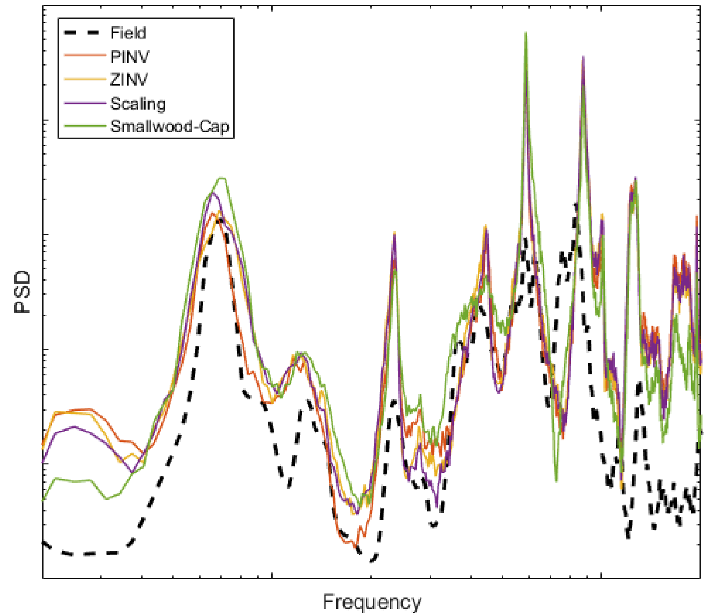
- Test article equipped with array of triaxial accelerometers for control
- Control accelerometers positioned symmetrically about both lateral axes
- Additional Accelerometers internally to the system

Visual Comparison

3DoF Inputs



6DoF Inputs



Which response best matches the field test?

Comparison of Responses

- Features of interest
  - Shape of the PSD curve – gives information about the frequency content of the response
  - Over all energy in the response
- Challenges in comparison
  - Small differences in natural frequencies between field and test units could show up as shifts in the PSD
  - Small shifts of peaks in the PSD could lead to low correlation coefficient, even if the shapes are very similar
- Converting the data from all the frequency lines to sixth octave spacing smooths out the shifts in frequency due to unit to unit variability

Metrics Comparing Energy Levels

- Mean in the RMS
  - $\boldsymbol{error_{rms} = 20\log\left(\frac{rms_{test}}{rms_{flight}}\right)}$
  - $\boldsymbol{normalized_{rms} = 1 - \frac{TotalRmsError}{MaxRmsError}}$
  - $\boldsymbol{metric_{rms} = \frac{normalized_{rms}}{\max(normalized_{rms})}}$
- Mean dB Error
  - $\boldsymbol{error_{dB} = \frac{1}{N}\sum_{f_{min}}^{f_{max}} 10\left(\log\left(\frac{test(f)}{flight(f)}\right)\right)}$
  - $\boldsymbol{normalized_{dB} = 1 - \frac{TotaldBError}{MaxdBError}}$
  - $\boldsymbol{metric_{dB} = \frac{normalized_{dB}}{\max(normalized_{dB})}}$

Metrics Comparing PSD Shapes

- Correlation Coefficient
  - Correlation coefficient (corr) is calculated using the corrcoef function in Matlab
  - $\boldsymbol{normalized_{corr} = 0.5(corr + 1)}$
  - $\boldsymbol{metric_{corr} = \frac{normalized_{corr}}{\max(normalized_{corr})}}$
- Cross Correlation Coefficient
  - Cross correlation coefficient (xcorr) is calculated using the xcorr function in Matlab
  - $\boldsymbol{normalized_{xcorr} = 0.5(xcorr + 1)}$
  - $\boldsymbol{metric_{xcorr} = \frac{normalized_{xcorr}}{\max(normalized_{xcorr})}}$

Comparison Metrics

Method	No Cross Products		Coherence Only		Coherence & Phase	
	Metric	Rank	Metric	Rank	Metric	Rank
6th Octave 3DoF	2.710	14	++	++	++	++
6th Octave 6DoF	1.935	25	++	++	++	++
PINV 3DoF	3.139	8	2.938	12	3.253	5
PINV 6DoF	2.707	15	2.457	17	2.187	23
ZINV 3DoF	3.140	7	2.934	13	3.324	4
ZINV 6DoF	2.411	19	2.278	21	2.444	18
Scaling 3DoF	3.032	9	2.681	16	3.025	10
Scaling 6DoF	2.220	22	2.323	20	2.034	24
Smallwood-Cap 3DOF	3.152	6	3.723	2	3.763	1
Smallwood-Cap 6DOF	**	**	3.005	11	3.372	3

** No data available
++ Not Specified

Observations

- Using the full 6DoF inputs as measured in the field yielded responses least like those in the field
  - Boundary conditions in the field and the laboratory are different
  - Unit tested in laboratory is different than the one in the field test
  - Inverse methods could account for those differences, allowing for the laboratory response to be closer for the inverse methods than the field data
- 3DoF tests matched field data better than their 6DoF counterparts
- Smallwood-Cap 3DoF method gave the best match to the field test data no matter how the cross spectra were defined
- In general, including the coherence and phase in the cross spectra yielded closer matches with the field data

Conclusions

- Recent field tests at Sandia National Laboratories had sufficient instrumentation to derive the full 6DoF inputs using a variety of methods.
- With the exception of the Smallwood-Cap method, the 3DoF input produced a response that was lower than field data
- The 6DoF inputs produced a response that matched well at low frequencies, but was too high at higher frequencies
- The inverse methods seem to remove some of the effects of the different boundary condition and unit to unit variability
- It is difficult to use a visual inspection of the data to draw any conclusions about which methods performed best

Conclusions (con't)

- Multiple metrics are needed to capture comparisons between energy and shape of the PSDs
- The 3DoF tests matched the 6DoF tests better than their 6DoF counterparts
- The Smallwood-Cap 3DoF method gave the best match to the field test data, no matter how the cross spectra were defined
- In general, including both the coherence and phase improved the response of the system

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Thank you for your attention!

QUESTIONS?