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Methodology for Defining Multi-Axis Vibration Specifications

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Sandia National Laboratories

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In This Presentation

- Background
- Challenges to Specifying Multi-axis Tests
- Methodology for Defining Multi-axis Test Specifications

Why is Multi-axis Simulation Important?

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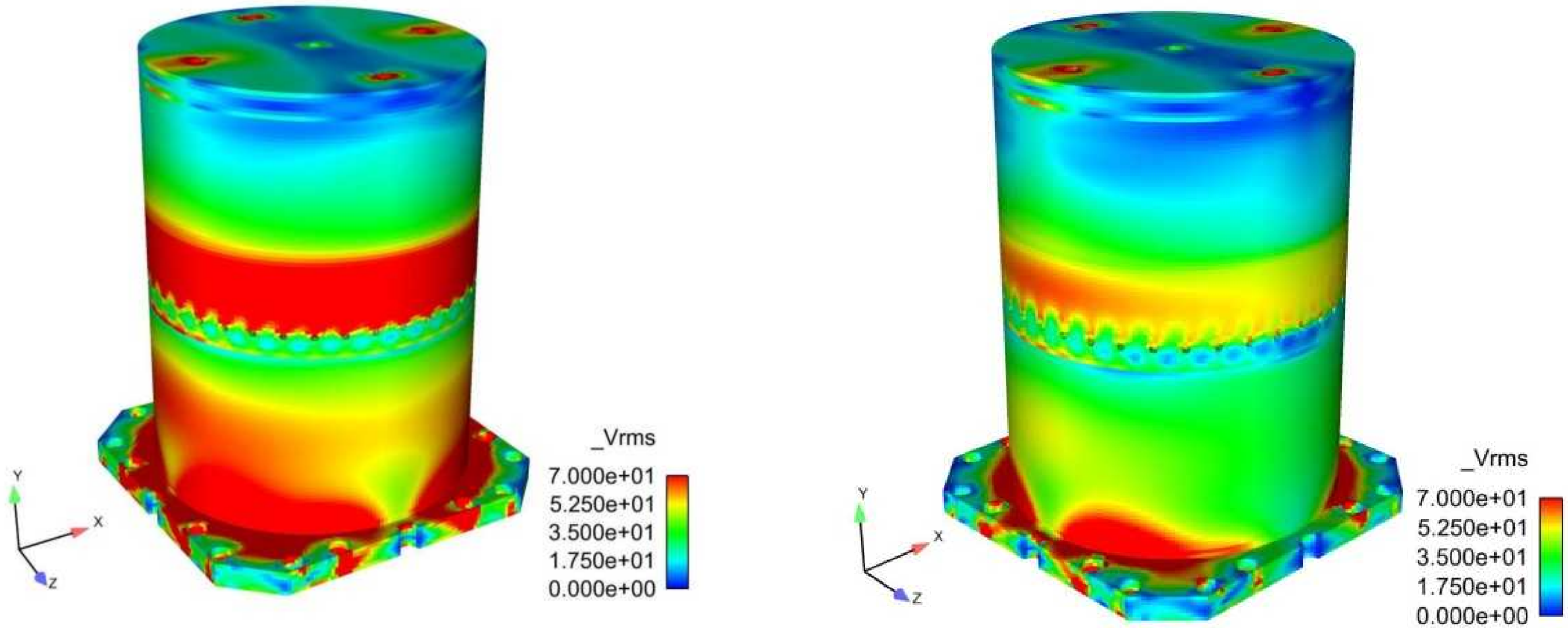
- Real (field) shock and vibration environments are multidemensional (6DOF)
- Single axis testing will not excite the modes of the system (or component) the same way they are excited in the real environment
  - Resulting stress states are not the same
  - Failure modes of system may be missed
    - The assumption that sequential testing in three axes is equivalent is not correct!
- Improved model validation experiments
  - Improved control of boundary conditions (multiple exciters)
    - 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)

Why is Multi-axis Simulation Important?



Left: RMS VonMises stress in the part due to 6-DoF input
Right: the RMS VonMises stress for pure 1-DoF input in x.

Benefits of 6DOF Testing

- Multi-axis testing excites all modes simultaneously with a more realistic stress loading (Berman, MB. “Inadequacies in Uniaxial Stress Screen Vibration Testing.” Journal of the IEST. Vol. 44, No. 4, Fall 2001:20-23)
- Test objects may pass uniaxial 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: 1014)
- 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” Experimental Techniques, November 2006)

How is Multi-axis Testing Accomplished?

	Tensor 900	Tensor 18kN
Sine Force Per Axis	200 lbf peak	4,800 lbf peak
Random Force Per Axis	135 lbf rms	3,600 lbf rms
Frequency Range	5-5000 Hz	5-2000 Hz
Velocity	60 ips	50 ips
Displacement	± 0.25 in. (Dynamic)	± 0.50 (Dynamic)
Moving Mass	9.0 lbs	430 lbs
Overall Mass	2,650 lbs	16,850 lbs
Sine Acceleration Bare Table	22-g peak	12-g peak
Random Acceleration Bare Table	15-grms	9-grms
Angular Rotation	± 5°	± 4°
Table Size	8 in.^{2}	30 in.^{2}

Tensor TE6-900

Tensor 18kN

U.S. Patent: 6 860 152
China Patent: ZL 03 809 374.X
Japan Patent: 4 217 210

www.teamcorporation.com

Show Movie

Challenges to Specifying Multi-axis Tests

$$\begin{pmatrix} \mathbf{S_{11}} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{12} & \mathbf{S_{22}} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{31} & S_{32} & \mathbf{S_{33}} & S_{34} & S_{35} & S_{36} \\ S_{41} & S_{42} & S_{43} & \mathbf{S_{44}} & S_{45} & S_{46} \\ S_{51} & S_{52} & S_{53} & S_{54} & \mathbf{S_{55}} & S_{56} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & \mathbf{S_{66}} \end{pmatrix}$$

Translations X Y, Z

Rotations R_{x}, R_{y}, R_{z}

To Fully define 6-DOF Test the 6X6 Spectral Density Matrix Must be known

- Will usually not be known from flight or test measurements
- Off diagonal terms are cross-spectral density terms (usually unknown)
- Can be calculated from high fidelity models
- Can also be determined from laboratory tests

The Specification Writing Challenge

- It is not clear how to write the specifications when there is a lack of sufficient data
- Method 1: specify the entire spectral density matrix, selecting the cross-spectra to
  - Minimize total drive energy to system
  - Match the PSD response for selected DOF's at selected response locations
  - Maximize response at selected locations for margin assessment
- Method 2: specify the diagonals of the density matrix
- Method 3: force all the cross-spectrum to zero

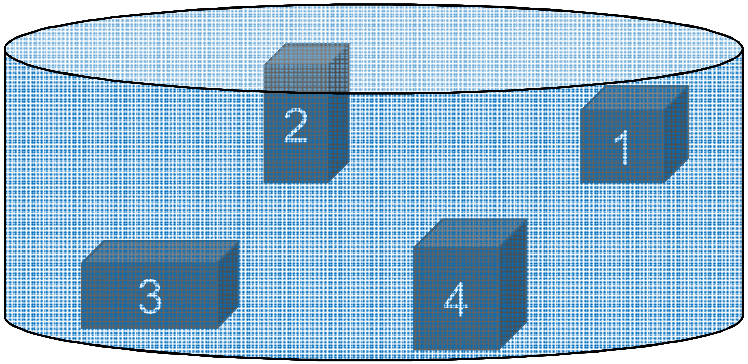
Comparison of Methods (1)

- Method 1: Specifying entire cross spectral matrix
  - Advantages:
    - Get test specifications that are based on structural response, so likely close to what would be seen in the field
    - Can minimize drive energy to make the tests easier for the shaker to run
    - Can get the most structural response for the least input
  - Disadvantages:
    - Have to have a high fidelity model or good multi-axis test data

Comparison of Methods (2)

- Method 2: Specifying only the diagonals of the matrix
  - Advantages:
    - It is easy, usually have most of that information
  - Disadvantages:
    - It doesn’t account for the structural response feeding the input
- Method 3: Force all the cross spectra to zero
  - Advantages:
    - It’s easy
  - Disadvantages:
    - Can make the drive requirements high, because you are forcing the system to do something it wouldn’t naturally do

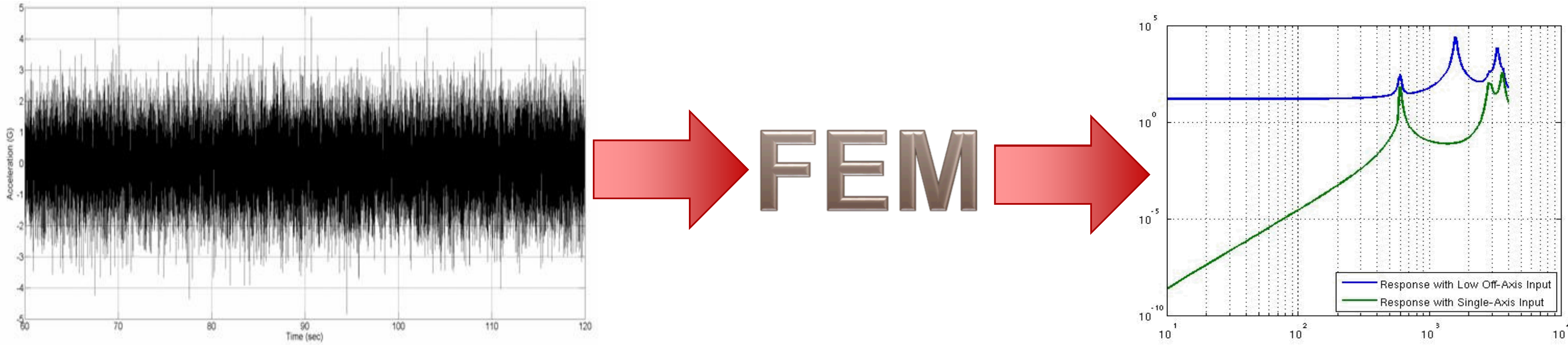
Defining the Problem



Part A

- Part A with some internal components that cannot be instrumented during flight tests
- From flight testing there is data from two locations on Part A
- From system level, uniaxial laboratory test, have three axes of data from all 4 internal components
- Have a high fidelity model of Part A
- Want to specify a multi-axis test for internal component 2

Determine Dynamic Response of Part

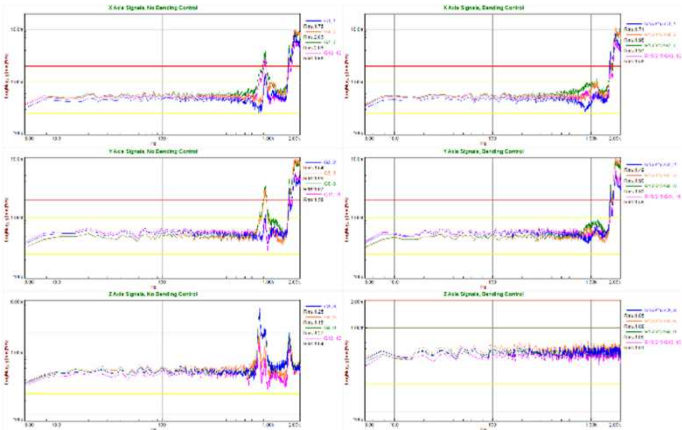


Alternate Method: Use a broadband random input into the part in the laboratory, and measure the responses, and use that output for the CSD matrix.

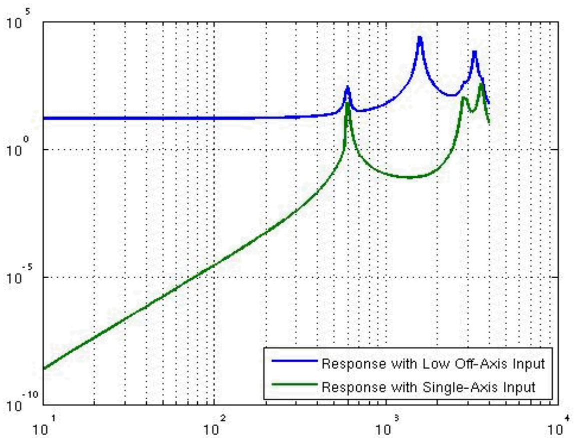
Advantage: using the actual part so there is no modeling uncertainty to influence the calculations.

Disadvantage: Requires multiple laboratory tests when dealing with trying to find CSDs for internal components.

Calculate the Spectral Density Matrix



PSDs from tests



Transfer Functions

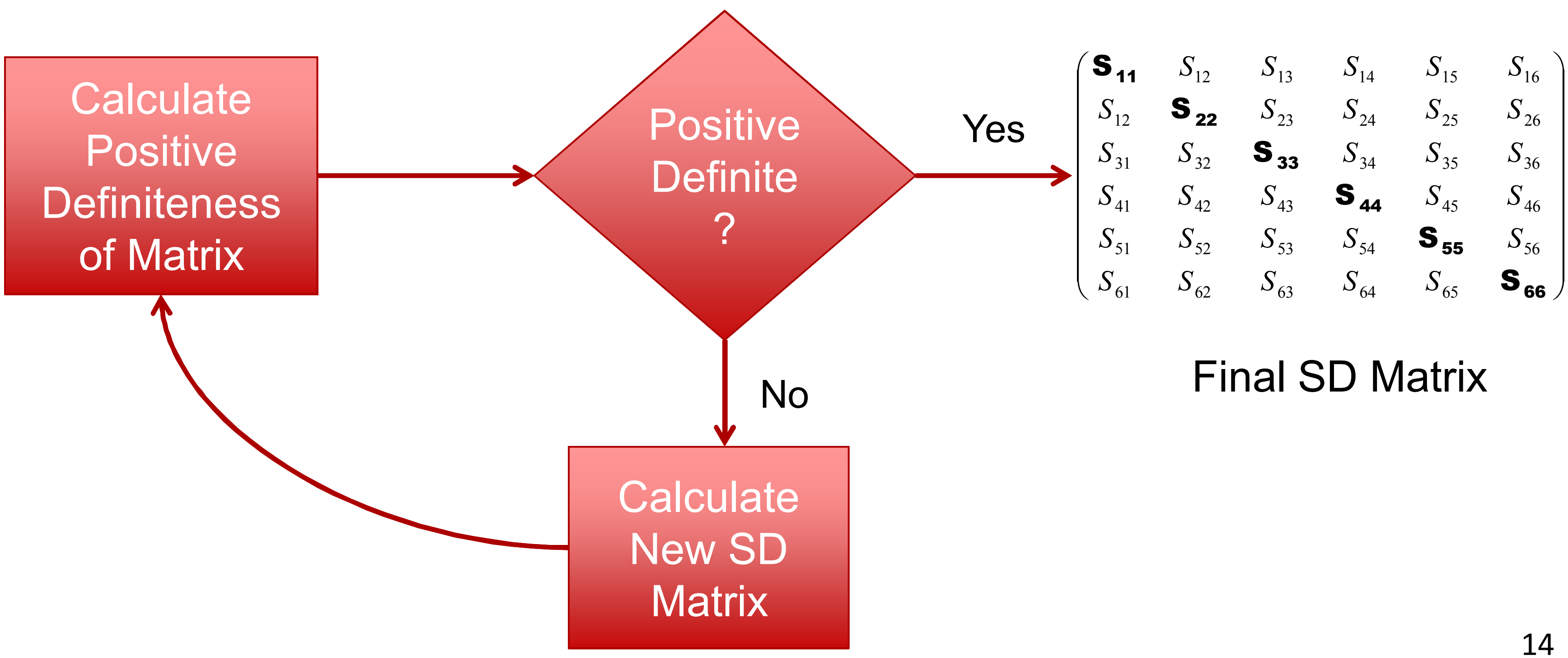
Smallwood's Algorithms

$$\begin{pmatrix} \mathbf{S_{11}} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{12} & \mathbf{S_{22}} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{31} & S_{32} & \mathbf{S_{33}} & S_{34} & S_{35} & S_{36} \\ S_{41} & S_{42} & S_{43} & \mathbf{S_{44}} & S_{45} & S_{46} \\ S_{51} & S_{52} & S_{53} & S_{54} & \mathbf{S_{55}} & S_{56} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & \mathbf{S_{66}} \end{pmatrix}$$

Spectral Density Matrix

Ensure Spectral Density Matrix is Positive Definite

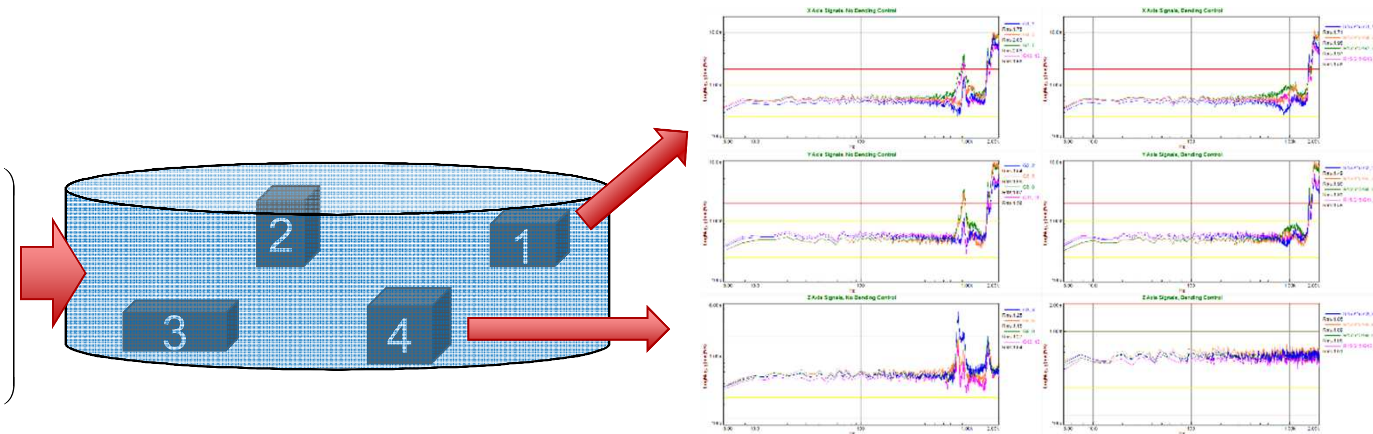
- Critical that the spectral density matrix is positive definite
- Do a calculation to determine if it is
- If it is not positive definite, vary the terms that are causing the spectral density matrix to not be positive definite until it is



Do Inverse Problem to Determine Inputs to Part

- Use the CSDs and do an inverse problem to back out the 6DoF inputs into Part A to match the responses for internal components 1-4.
- If it is not possible to match all the responses, do a least squares fit.

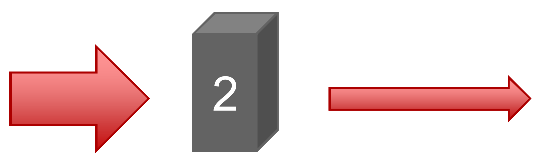
$$\begin{pmatrix} \mathbf{S_{11}} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{12} & \mathbf{S_{22}} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{31} & S_{32} & \mathbf{S_{33}} & S_{34} & S_{35} & S_{36} \\ S_{41} & S_{42} & S_{43} & \mathbf{S_{44}} & S_{45} & S_{46} \\ S_{51} & S_{52} & S_{53} & S_{54} & \mathbf{S_{55}} & S_{56} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & \mathbf{S_{66}} \end{pmatrix}$$

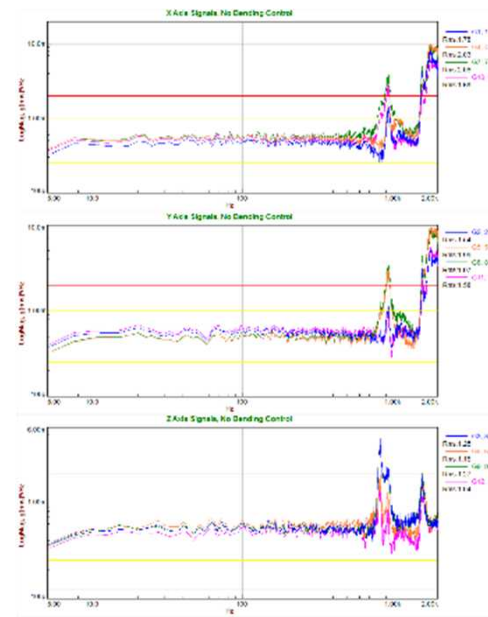


Determine 6DoF Inputs for Component 2

- Take response on points on Component 2 to determine 6DoF inputs for Component 2 to respond as it does in Part A.
- Do coordinate transformations as necessary to align inputs to that of the table.

$$\begin{pmatrix} \mathbf{S}_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{12} & \mathbf{S}_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{31} & S_{32} & \mathbf{S}_{33} & S_{34} & S_{35} & S_{36} \\ S_{41} & S_{42} & S_{43} & \mathbf{S}_{44} & S_{45} & S_{46} \\ S_{51} & S_{52} & S_{53} & S_{54} & \mathbf{S}_{55} & S_{56} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & \mathbf{S}_{66} \end{pmatrix}$$





Summary of Methodology

- Determine the transfer functions for dynamic response of the part
- Use the transfer functions to calculate a spectral density matrix to minimize drive energy
- Ensure that the spectral density matrix is positive definite, adjust the matrix if it is not
- Do an inverse problem to determine the input to the part that would yield the response in the spectral density matrix
- Use the input to calculate the response of the internal component of interest and the corresponding 6DoF inputs to the component to make the response occur

Conclusions

- Multi-axis testing has many benefits including the ability to get more realistic screening of parts and better data which will lead to more predictive models and better designs.
- It is challenging to define test specifications when no information about Cross Spectral Densities is known.
- Can use a combination of high fidelity models and known test data to determine reasonable Cross Spectral Densities for a multi-axis test.

Questions