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Exceptional service in the national interest

Sandia National Laboratories

Multi-axis Testing at Sandia National Laboratories

Laura Jacobs

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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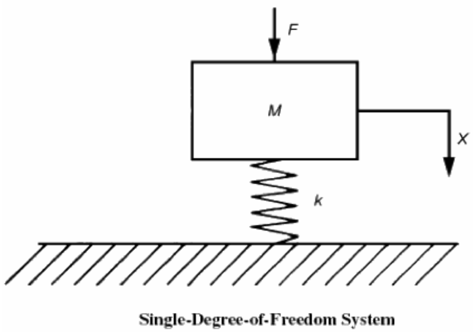
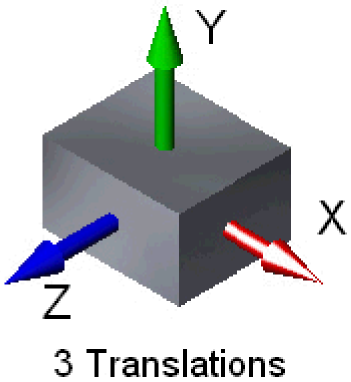
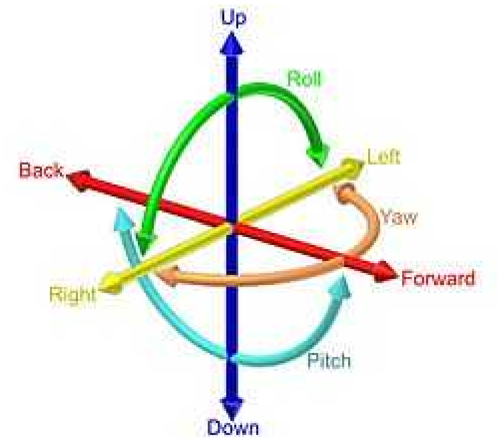
What is Multi-axis Testing



SDOF
http://nmgolfscience.tripod.com/heavy_hit2.htm



3DOF
http://www.capinc.com/2011/04/06/life-long-mates



6DOF
from http://en.wikipedia.org/wiki/Six_degrees_of_freedom

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

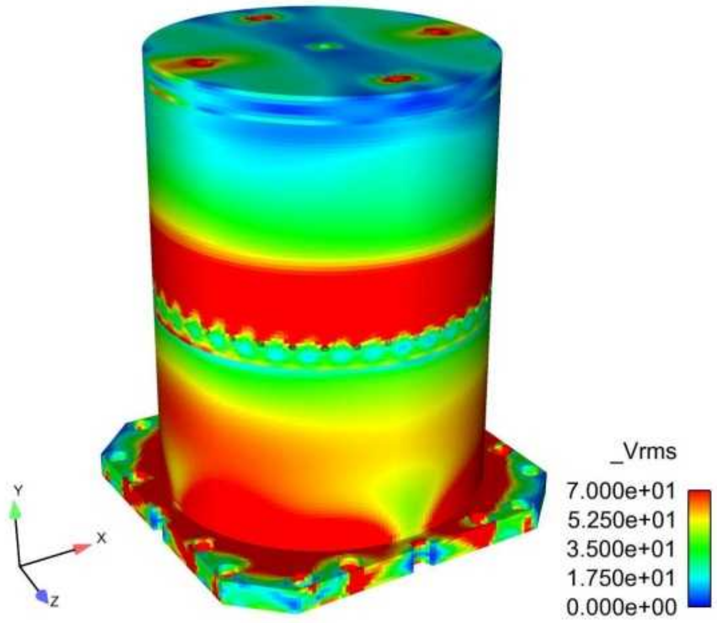
U.S. Patent: 6 860 152
China Patent: ZL 03 809 374.X
Japan Patent: 4 217 210

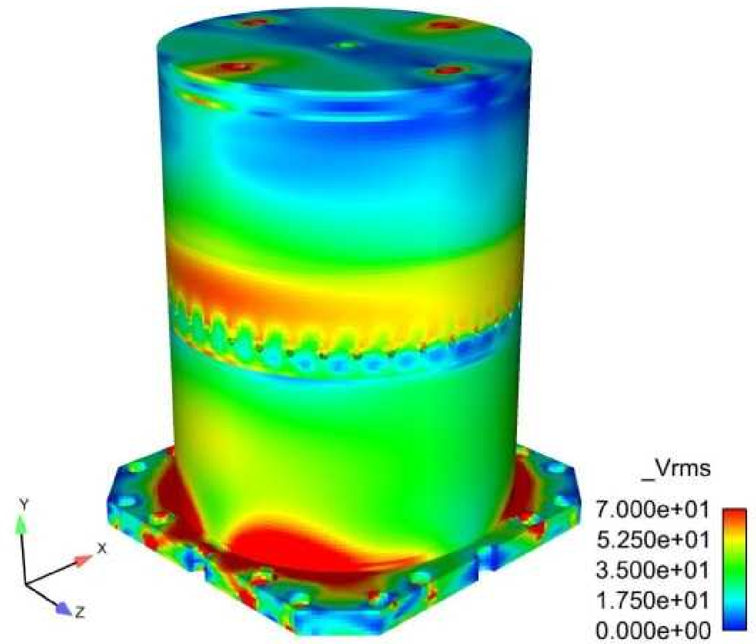
www.teamcorporation.com

Why is Multi-axis Testing Important?

- 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)

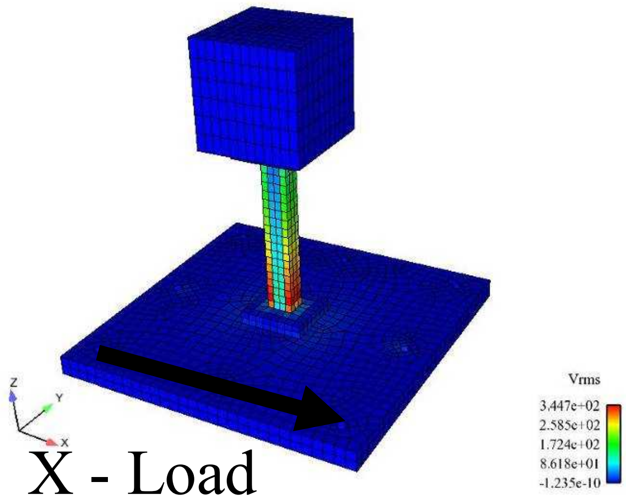
Why is Multi-axis Testing Important?

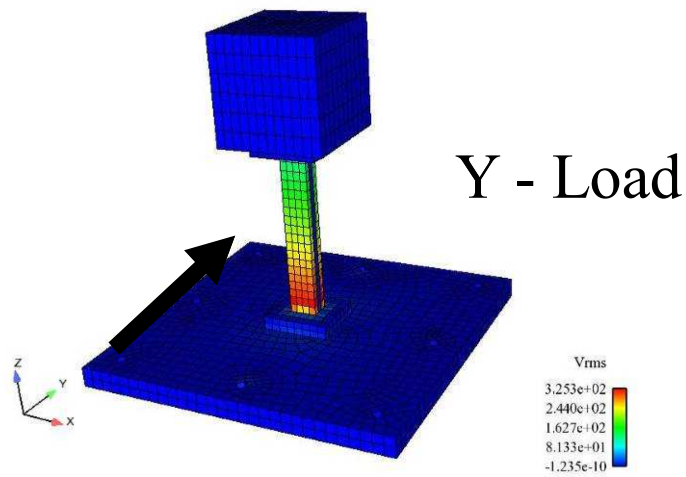


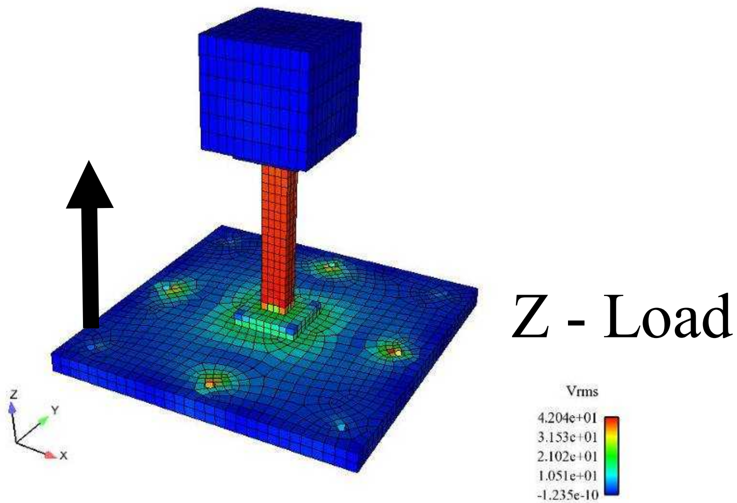


Right: RMS VonMises stress in the part due to 6-DoF input
Left: the RMS VonMises stress for pure 1-DoF input in x.

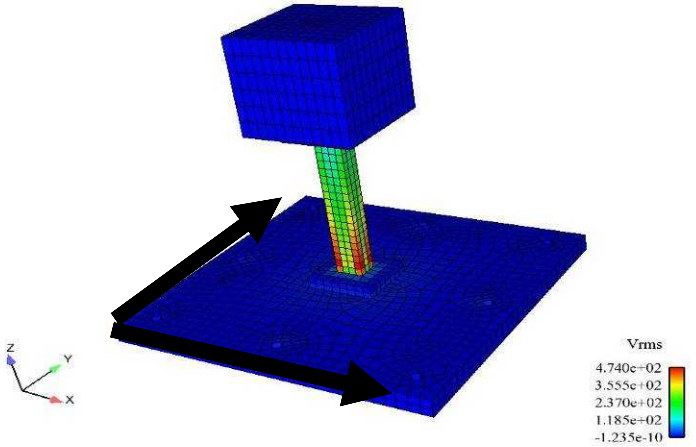
Single Axis Loads



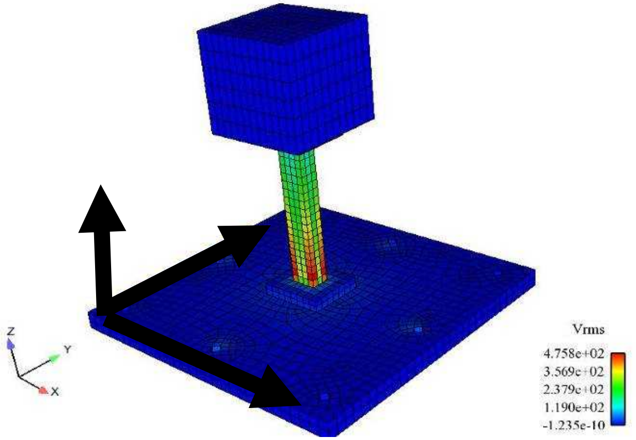




Combined Axis Inputs



XY - Inputs



XYZ - Inputs

Input Loading	Max VM [psi]
X - Input	345
Y - Input	325
Z - Input	42
XY - Input	474
XYZ - Input	476

The magnitude <u>and</u> location of the maximum stress are different for multi-axis inputs

- Different failure mode
- Different fatigue life

Why is 6DOF Testing Important?

- Only ¼ of the structural stiffness matrix contains terms with no rotation
- That means we are failing to validate ¾ of the response of the structure!

$$
\begin{bmatrix} N^i \\ V_2^i \\ V_3^i \\ T^i \\ M_2^i \\ M_3^i \\ \hline N^j \\ V_2^j \\ V_3^j \\ T^j \\ M_2^j \\ M_3^j \end{bmatrix}
=
\left[\begin{array}{cccccc|cccccc}
\frac{EA}{L} & 0 & 0 & 0 & 0 & 0 & -\frac{EA}{L} & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{12EI_3}{L^3} & 0 & 0 & 0 & \frac{6EI_3}{L^2} & 0 & -\frac{12EI_3}{L^3} & 0 & 0 & 0 & \frac{6EI_3}{L^2} \\
0 & 0 & \frac{12EI_2}{L^3} & 0 & -\frac{6EI_2}{L^2} & 0 & 0 & 0 & -\frac{12EI_2}{L^3} & 0 & -\frac{6EI_2}{L^2} & 0 \\
0 & 0 & 0 & \frac{GJ}{L} & 0 & 0 & 0 & 0 & 0 & -\frac{GJ}{L} & 0 & 0 \\
0 & 0 & -\frac{6EI_2}{L^2} & 0 & \frac{4EI_2}{L} & 0 & 0 & 0 & \frac{6EI_2}{L^2} & 0 & \frac{2EI_2}{L} & 0 \\
0 & \frac{6EI_3}{L^2} & 0 & 0 & 0 & \frac{4EI_3}{L} & 0 & -\frac{6EI_3}{L^2} & 0 & 0 & 0 & \frac{2EI_3}{L} \\
\hline
-\frac{EA}{L} & 0 & 0 & 0 & 0 & 0 & \frac{EA}{L} & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{12EI_3}{L^3} & 0 & 0 & 0 & -\frac{6EI_3}{L^2} & 0 & \frac{12EI_3}{L^3} & 0 & 0 & 0 & -\frac{6EI_3}{L^2} \\
0 & 0 & -\frac{12EI_2}{L^3} & 0 & \frac{6EI_2}{L^2} & 0 & 0 & 0 & \frac{12EI_2}{L^3} & 0 & \frac{6EI_2}{L^2} & 0 \\
0 & 0 & 0 & -\frac{GJ}{L} & 0 & 0 & 0 & 0 & 0 & \frac{GJ}{L} & 0 & 0 \\
0 & 0 & -\frac{6EI_2}{L^2} & 0 & \frac{2EI_2}{L} & 0 & 0 & 0 & \frac{6EI_2}{L^2} & 0 & \frac{4EI_2}{L} & 0 \\
0 & \frac{6EI_3}{L^2} & 0 & 0 & 0 & \frac{2EI_3}{L} & 0 & -\frac{6EI_3}{L^2} & 0 & 0 & 0 & \frac{4EI_3}{L}
\end{array}\right]
\begin{bmatrix} u_1^i \\ u_2^i \\ u_3^i \\ \theta_1^i \\ \theta_2^i \\ \theta_3^i \\ \hline u_1^j \\ u_2^j \\ u_3^j \\ \theta_1^j \\ \theta_2^j \\ \theta_3^j \end{bmatrix}
$$

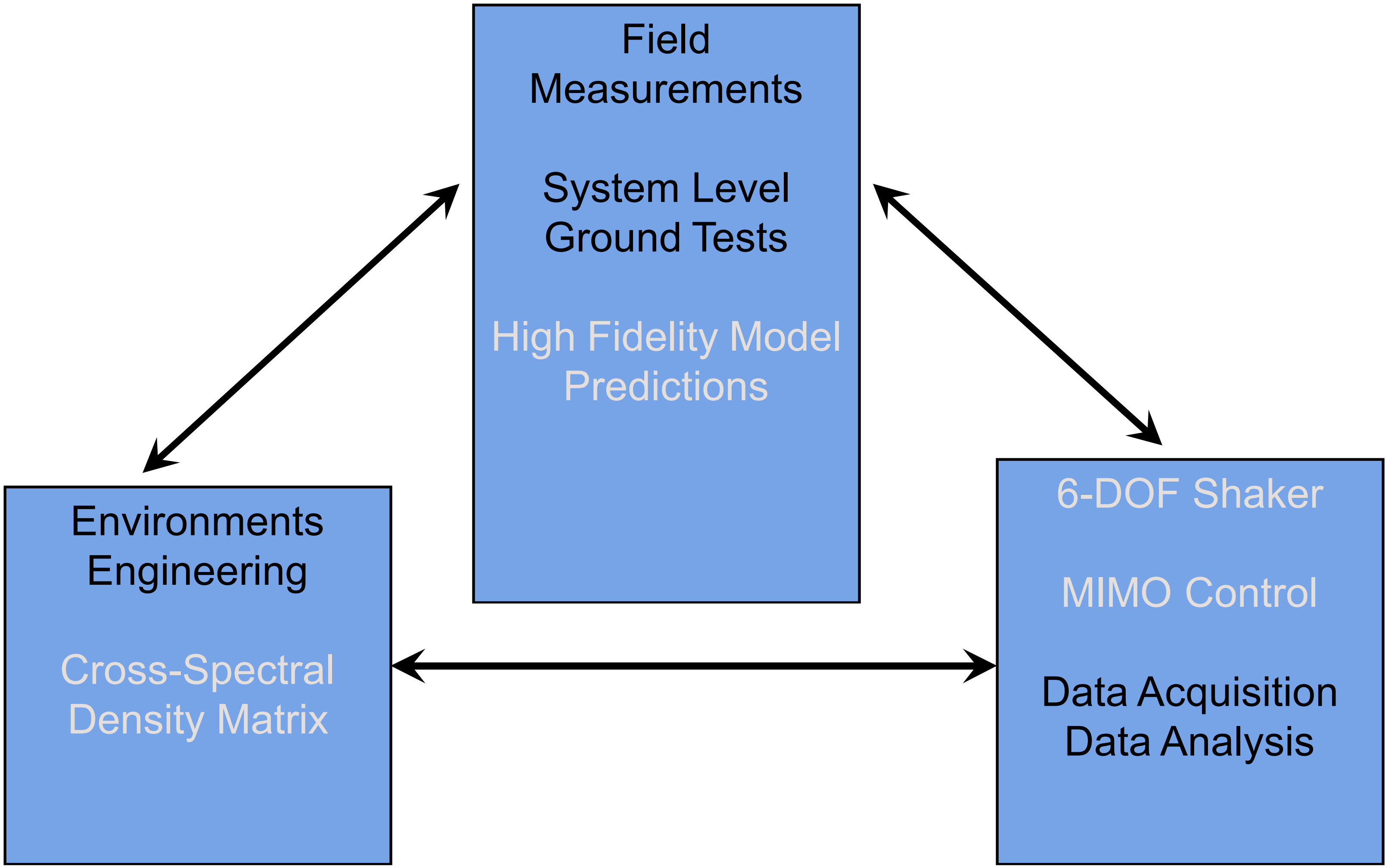
Benefits of 6DOF Testing

- 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)

Benefits of 6DOF Testing

- Laboratory simulations are used to assess the adequacy of the design of mechanical and aerospace systems. The better the simulation, the better the assessment
- 6DOF testing allows for the evaluation and validation of a greater portion of the response
- Single axis testing has been thought to be conservative due to increased test times, however, that is not the case
- Less time handling hazardous test articles
- Decreased time to test
- Get more complete data for model validation

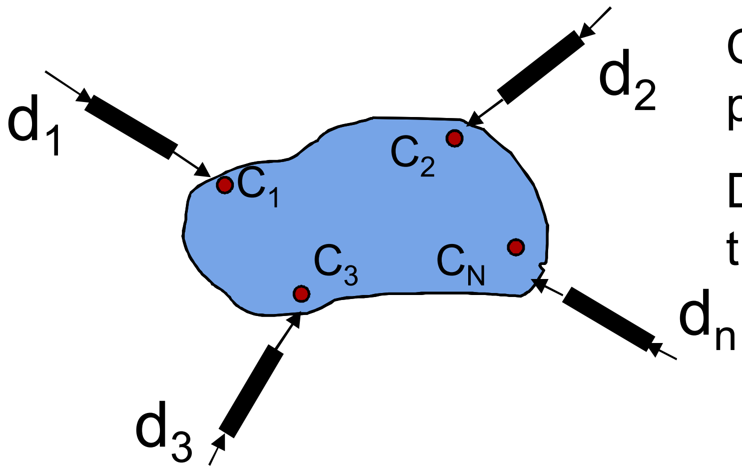
Multi-axis (6-Dof) Test Steps



Multi-axis Simulation Challenges

- The full specification of all 6DOF will not be available from field data
  - May drive instrumentation and data analysis of future ground and flight test measurements
- Methods for control
- Effects of part to part variability on specifications and control
- Effects of machine to machine variability on specifications and control

The Control Scheme Challenge



Create drive signals d_i to the actuators that produce desired responses at control points c_j

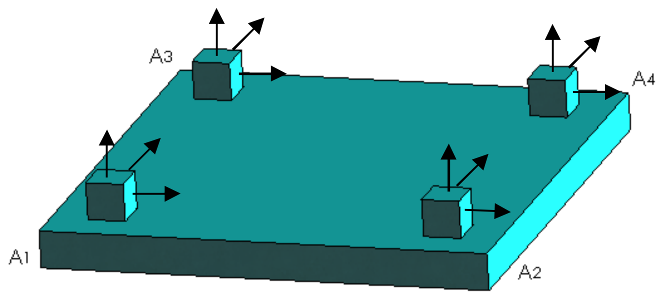
Desired responses c_j are completely specified by the cross spectral density matrix, S_{ij}

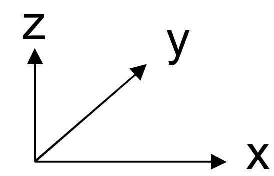
$$\begin{pmatrix} H_{11}(f) & H_{12}(f) & . & . & H_{1n}(f) \\ H_{21}(f) & H_{22}(f) & . & . & . \\ . & . & H_{33}(f) & . & . \\ . & . & . & . & . \\ H_{n1}(f) & . & . & . & H_{nn}(f) \end{pmatrix}$$

$$\begin{pmatrix} S_{11}(f) & S_{12}(f) & . & . & S_{1n}(f) \\ S_{21}(f) & S_{22}(f) & . & . & . \\ . & . & S_{33}(f) & . & . \\ . & . & . & . & . \\ S_{n1}(f) & . & . & . & S_{nn}(f) \end{pmatrix}$$

System Transfer Function Matrix H_{ij} describes how inputs are coupled— Must be inverted at every frequency line

Control Degrees of Freedom w/ Input Transformation Can Include Elastic Modes or Other Measures of Response





Translations

$$X = \tfrac{1}{4}\left(A_{1x} + A_{2x} + A_{3x} + A_{4x}\right)$$

$$Y = \tfrac{1}{4}\left(A_{1y} + A_{2y} + A_{3y} + A_{4y}\right)$$

$$Z = \tfrac{1}{4}\left(A_{1z} + A_{2z} + A_{3z} + A_{4z}\right)$$

Rotations

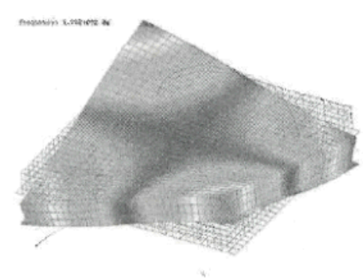
$$R_x = \tfrac{1}{4}\left(-A_{1z} - A_{2z} + A_{3z} + A_{4z}\right)\tfrac{g}{r}$$

$$R_y = \tfrac{1}{4}\left(A_{1z} - A_{2z} + A_{3z} - A_{4z}\right)\tfrac{g}{r}$$

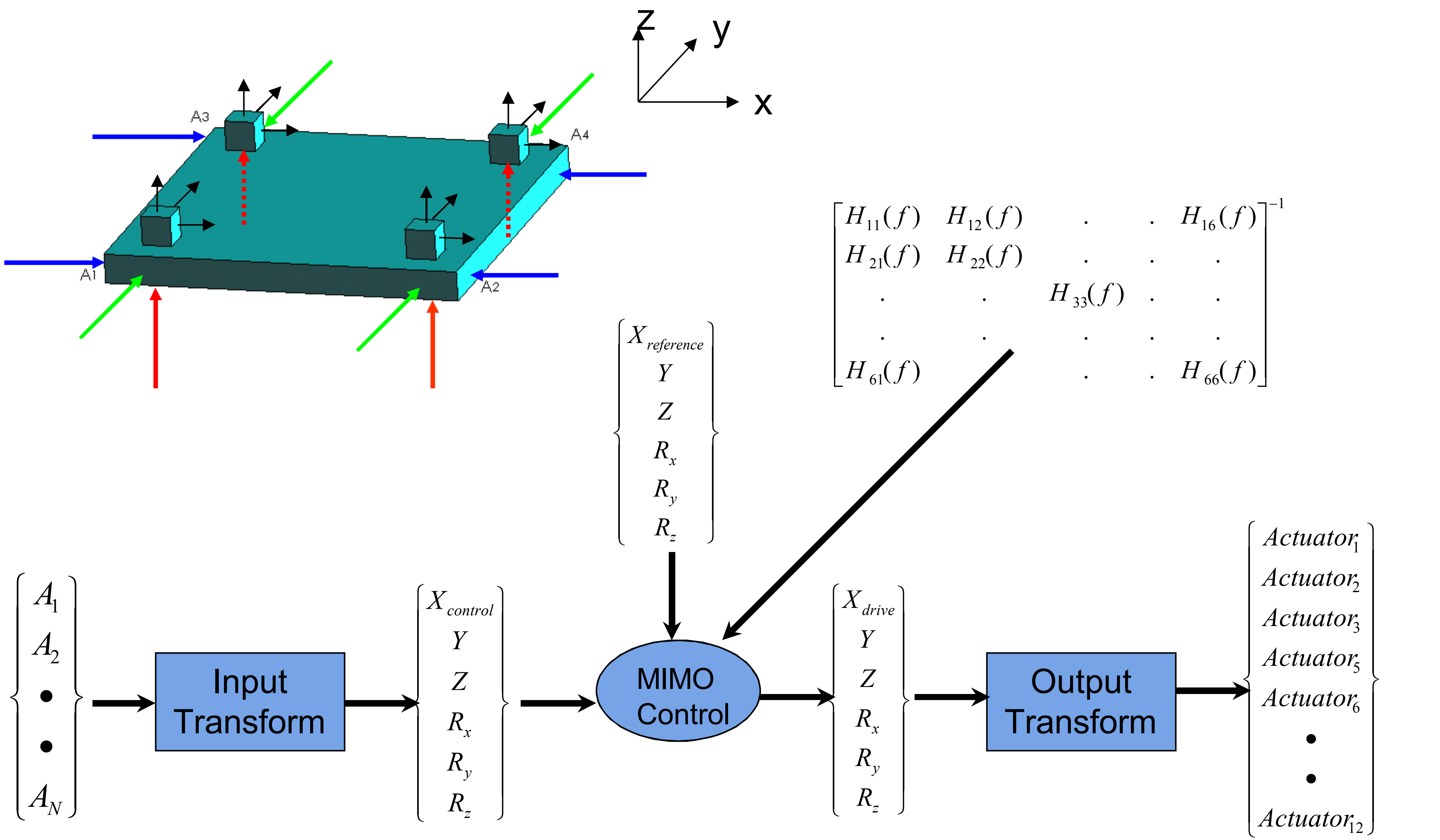
$$R_z = \tfrac{1}{8}\left(A_{1x} + A_{2x} - A_{3x} - A_{4x} - A_{1y} + A_{2y} - A_{3y} + A_{4y}\right)\tfrac{g}{r}$$

Elastic Modes

$$\psi = \tfrac{1}{4}\left(A_{1z} - A_{2z} - A_{3z} + A_{4z}\right)\tfrac{g}{r}$$



Input/Output Transformation Control Approach With Over-determined System Provides Versatility



The Specification Writing Challenge

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

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 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

If input is underdetermined:

- Pick cross spectral densities to minimize drive energy to system (minimize trace of drive matrix)
- Leave inputs uncorrelated (zero coherence, random phase)

Three Translation Axis Test (X,Y,Z)

$$[S_{mn}] = \begin{bmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{yx} & S_{yy} & S_{yz} \\ S_{zx} & S_{zy} & S_{zz} \end{bmatrix}$$

$$[S_{mn}] = \begin{bmatrix} S_{xx} & 0 & 0 \\ 0 & S_{yy} & 0 \\ 0 & 0 & S_{zz} \end{bmatrix}$$

$$[S_{mn}] = \begin{bmatrix} S_{xx} & S_{xy} & S_{xz} & 0 & 0 & 0 \\ S_{yx} & S_{yy} & S_{yz} & 0 & 0 & 0 \\ S_{zx} & S_{zy} & S_{zz} & 0 & 0 & 0 \\ 0 & 0 & 0 & \approx 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \approx 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \approx 0 \end{bmatrix}$$

$$[S_{mn}] = \begin{bmatrix} S_{xx} & 0 & 0 & 0 & 0 & 0 \\ 0 & S_{yy} & 0 & 0 & 0 & 0 \\ 0 & 0 & S_{zz} & 0 & 0 & 0 \\ 0 & 0 & 0 & \approx 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \approx 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \approx 0 \end{bmatrix}$$

Cross Spectral Density in Terms of Coherence and Phase

$$S_{mn}(f) = \left|S_{mn}(f)\right| e^{i\phi_{mn}(f)}$$

$$\gamma_{mn}^2(f) = \frac{\left|S_{mn}(f)\right|^2}{S_{mm}(f)S_{nn}(f)}$$

$$\left|S_{mn}(f)\right| = \left(\gamma_{mn}^2(f)S_{mm}(f)S_{nn}(f)\right)^{1/2}$$

$$S_{mn}(f) = \left(\gamma_{mn}^2(f)S_{mm}(f)S_{nn}(f)\right)^{1/2} e^{i\phi_{mn}(f)}$$

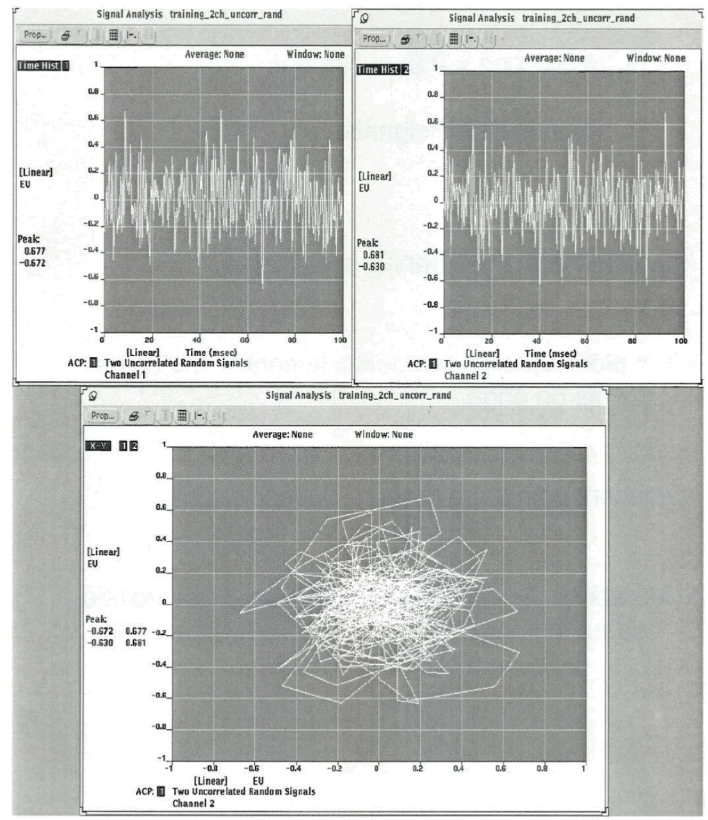
2-D Examples

$$[S_{mn}] = \begin{bmatrix} S_{xx} & S_{xy} \\ S_{yx} & S_{yy} \end{bmatrix}$$

$$[S_{mn}] = \begin{bmatrix} S_{xx} & 0 \\ 0 & S_{yy} \end{bmatrix}$$

Equal Power Spectrums with Zero Coherence (Random Phase)

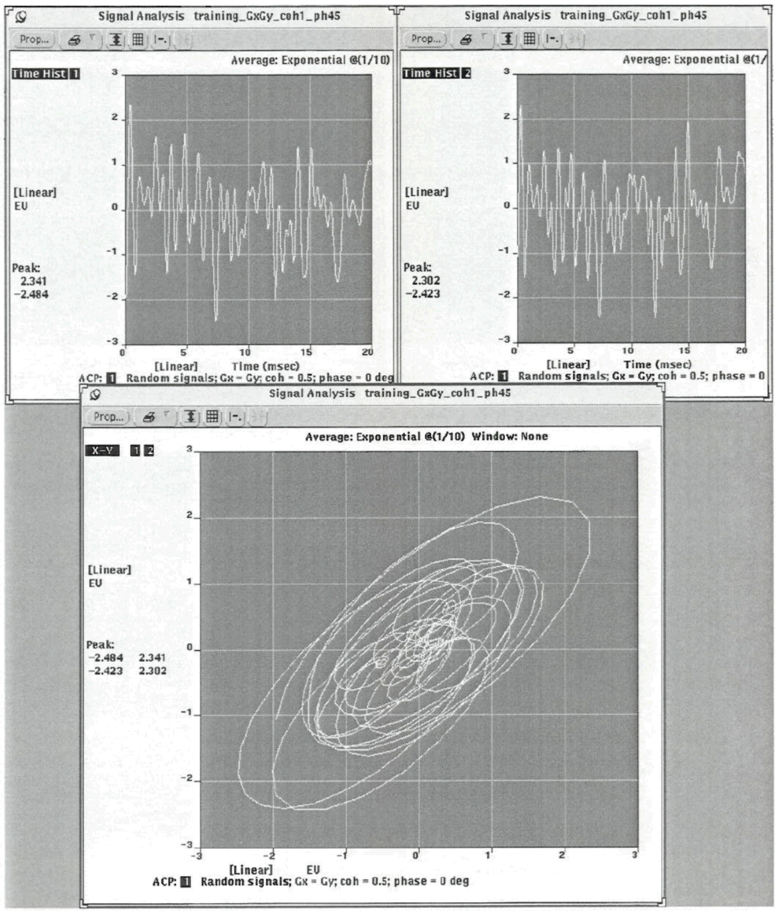
$S_{xx} = S_{yy}$; Coh=0; phase =x



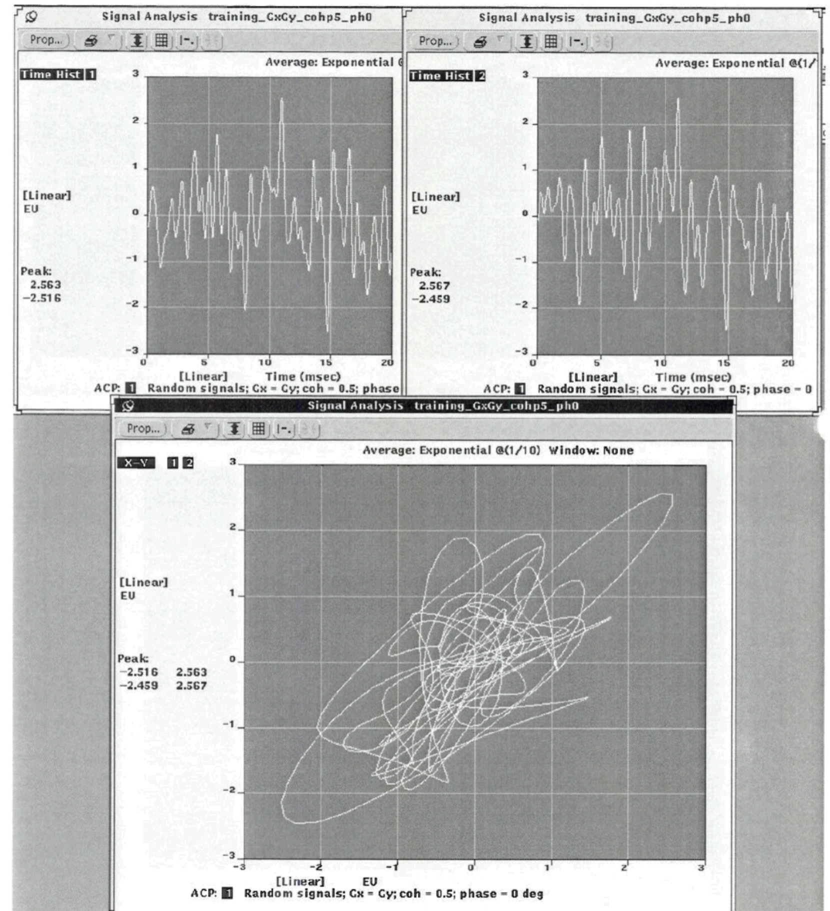
2D-Example of Random Phase

2-D Examples of Non-Zero Cross Spectrums

$S_{xx} = S_{yy}$; coh=1.0; phase =90°



$S_{xx} = S_{yy}$; coh=0.5; phase =0



Addressing the 6DOF Challenge – Effects of Variability

- Partner with the University of Maryland and Army Test and Evaluation Command (ATEC) and Aviation and Missile Research, Development and Engineering Center (AMRDEC)
- Design and build a variety of structures that are of interest to Sandia
- Construct multiple copies of the same structure to address part-to-part variability
- Run tests on the parts, focusing on control schemes
- Have another facility with the same machine run the same tests on the same test articles
- Evaluate how conservative or unconservative uniaxial testing really is by comparing uniaxial tests to multi-axis tests

Addressing the 6DOF Challenge – Control Methods

- Using the variety of structures of interest to Sandia, test them using different control schemes
- Determine which control schemes are appropriate for which parts
- May have an influence on how we specify tests

Addressing the 6DOF Challenge – Specification Writing

- Will attempt to derive 6DOF environments combining different flights or flights and simulations
  - Main difficulty is that phase information is critical to deriving 6DOF specs, but it is not obvious how to account for that when combining multiple sources of data
  - Critical to have really good computer models to achieve this
- Perform system level ground test with enough instrumentation to accurately derive multi-axis test specifications for a component, then perform simulation
- Use part of the system level data, supplemented with model data to derive specifications
- Apply the methodology on actual field data from a real system

Summary

- 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.
- Research will:
  - Improve understanding of component and system dynamic behavior in the field and in the laboratory
  - Change the way Sandia collects field data and from such data, derives test specifications
  - Allow realistic simulation and testing in multiple degrees of freedom simultaneously, thus fully replicating field environments.

Questions