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Physical Vibration Simulation of an Acoustic Environment with Six Shakers on an Industrial Structure

Randy Mayes
Daniel Rohe

Sandia National Laboratories
Albuquerque, New Mexico

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Motivation for Multi-Input Shaker Physical Simulation

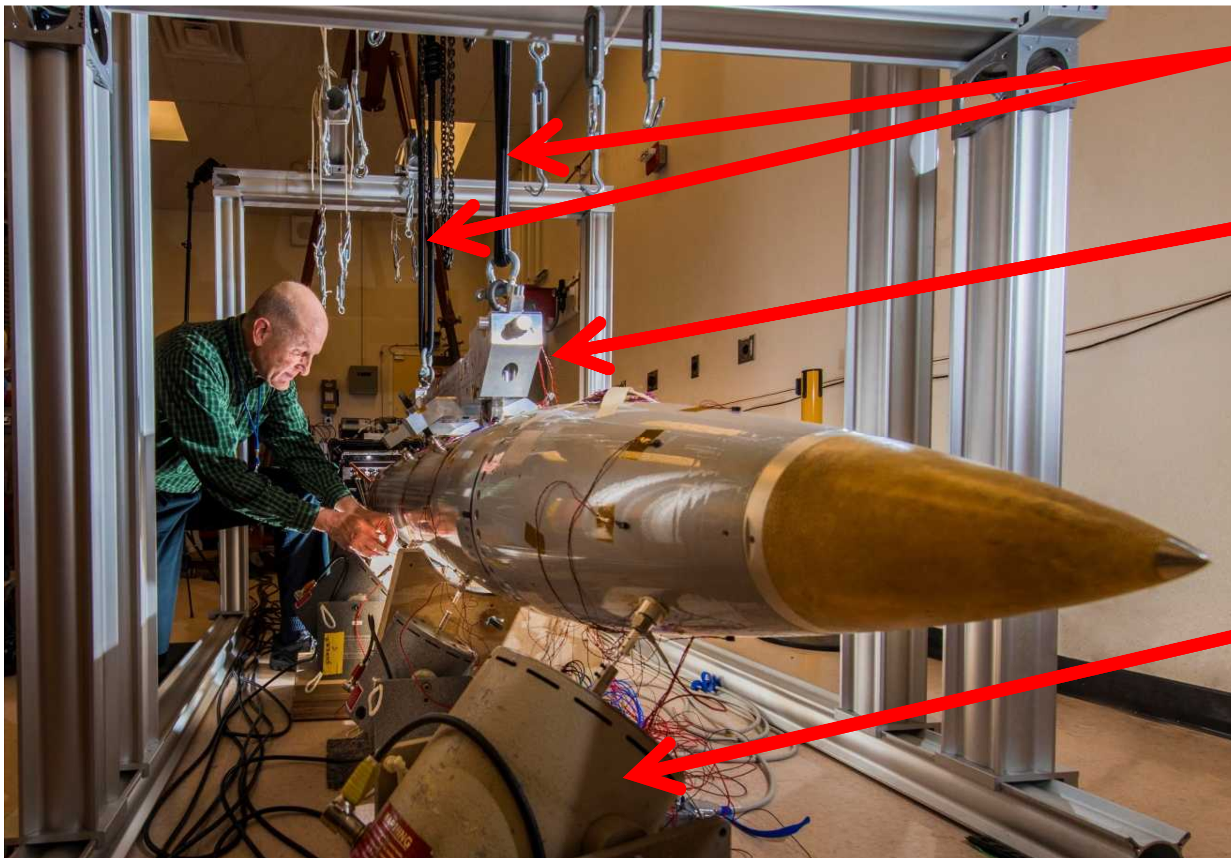
- **Single axis ground test shaker table simulations of environments for payloads have well-known shortcomings.**
  - Wrong boundary condition
  - Fail to replicate multi-axis inputs
  - Causes overtest in some frequency bands and undertest in others
  - Cannot represent aerodynamic forces
- **Daborne, et al. (IMAC in 2014) showed that an aerodynamic induced environment on a 1/3 scale model missile could be reproduced in a lab at 13 accelerometers on the structure with three shakers and similar mounting boundary conditions – Technique dubbed IMMAT.**
- **Here we attempt a similar simulation on 37 accelerometers inside an industrial payload with hundreds of modes up to 4,000 Hz. The control algorithm is slightly different in that it does not require specification of voltage input cross-spectra.**
- **If one can place the shakers in a way that the same modal forces are applied, then the same response can be obtained on a linear system.**

Acoustic Truth Test

- Direct Field Acoustic Test Method
- The truth test was generated using multiple speakers surrounding the test article and driving 6 control microphones to 127 dB
- Low coherence between drives
- 8 speaker stacks
- We picked 37 internal accelerometer responses obtained in this test that we wanted to reproduce in a MIMO shaker test in a modal laboratory

MIMO Simulation Test

- **4 Shakers were exciting the rack and 2 shakers radially excited the shell of the payload**



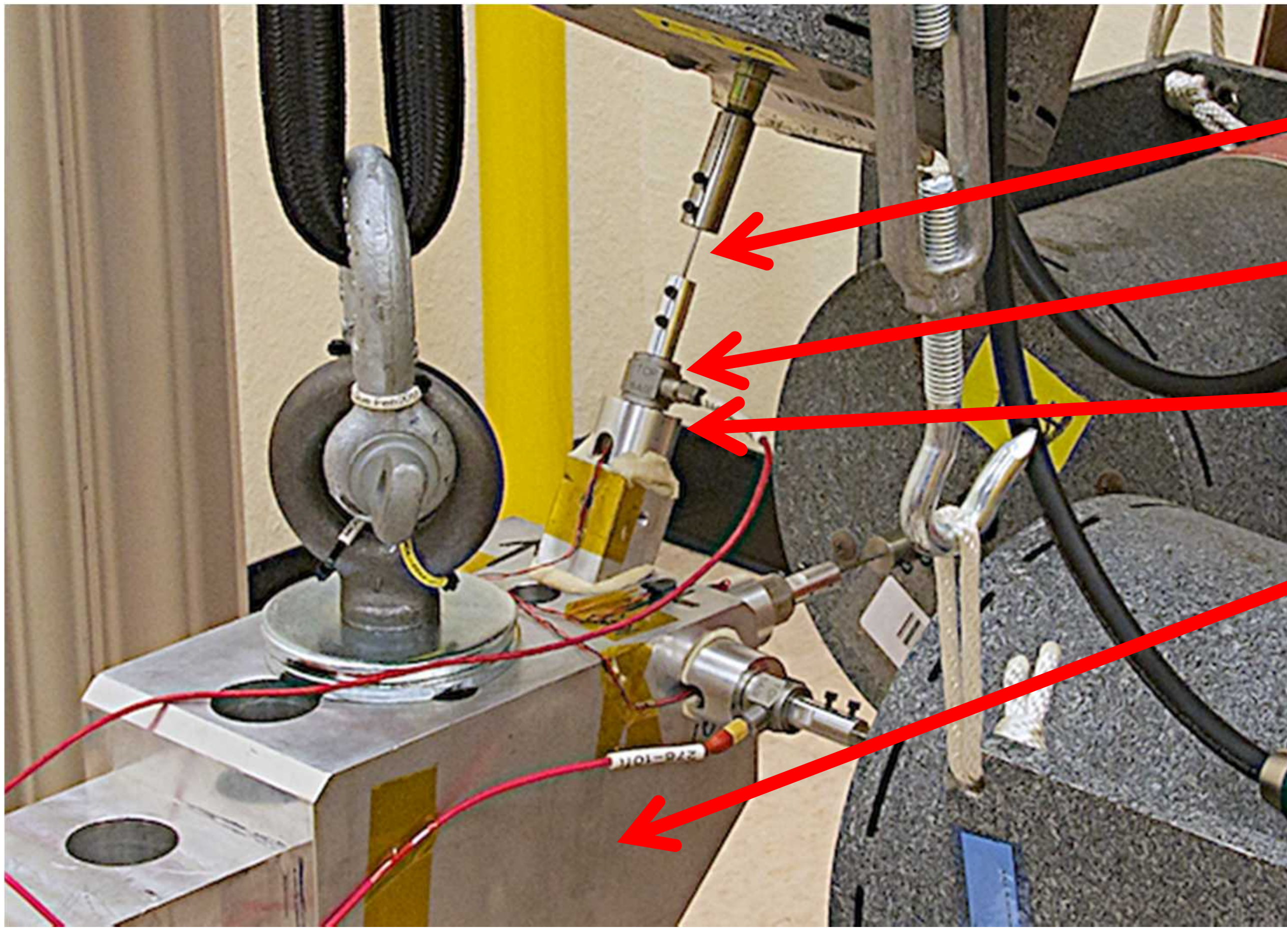
Bungee Cord Supports

Rack

MB 50

MIMO Shaker Setup on Forward End of Rack

- Axial, Lateral and semi-vertical shakers mounted at forward end of rack



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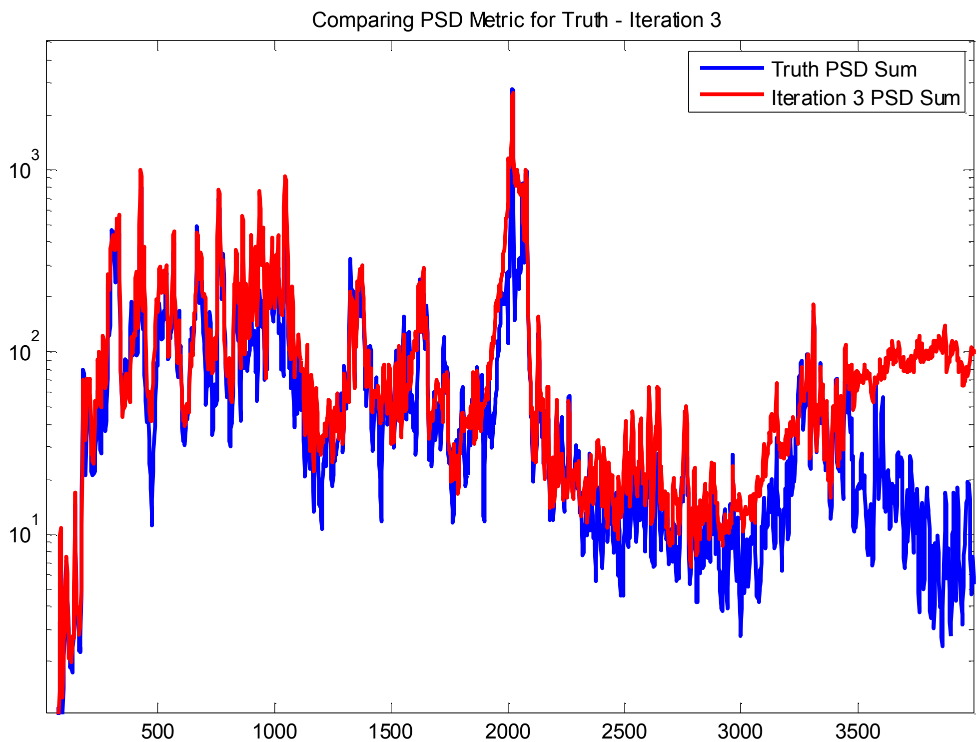
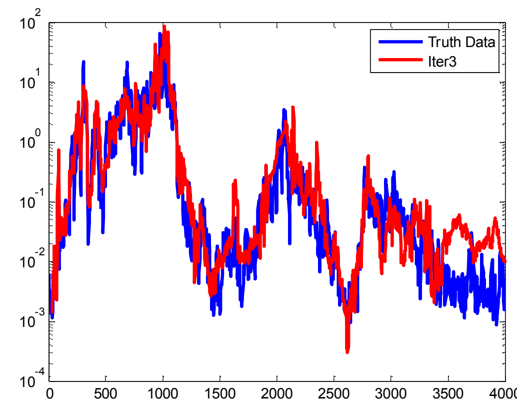
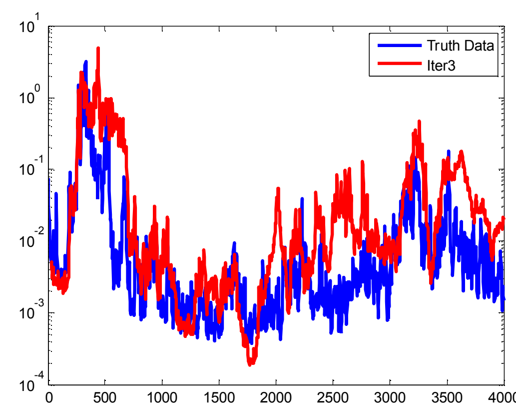
Metric Showing Control that was Achieved

- **37 internal accelerometers were target PSDs for the simulation**
- **Large plot shows the sum of all PSDs – Blue is from Acoustic Test, Red is from 3rd iteration of open loop MIMO control**





Best PSD



Worst PSD

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Algorithm to Estimate Drive Voltages for Simulation

- **Assume uncorrelated voltage autospectra**
- **Regular pseudoinverse required large voltage input**
- **Applied Tikhonov regularization with (*c*=0.01 times max value in S'S)**

37x6

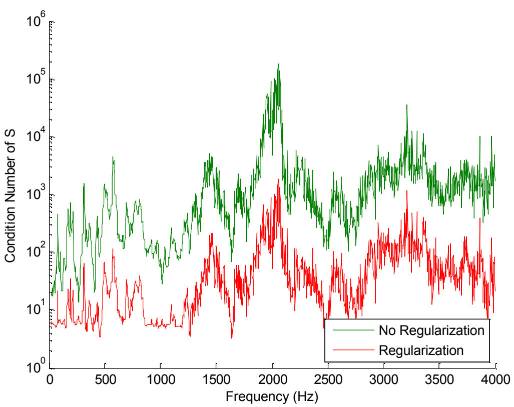
37x1

$$\bar{\ddot{x}}_{autospectra} = \left|\mathbf{H}_{xv}\right|^2 \bar{v}_{autospectra}$$

6x1

$$\mathbf{S} = \left|\mathbf{H}_{xv}\right|^2$$

$$\mathbf{S}^{+} = [\mathbf{S}'*\mathbf{S} + c*\mathbf{I}]^{-1} * \mathbf{S}'$$



Tikhonov Regularization

$$\mathbf{S}^{+} * \bar{\ddot{x}}_{autospectra} = \bar{v}_{autospectra\_estimate}$$

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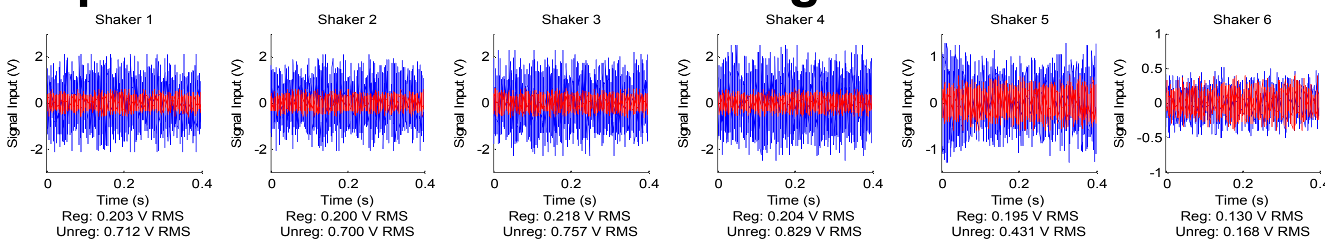
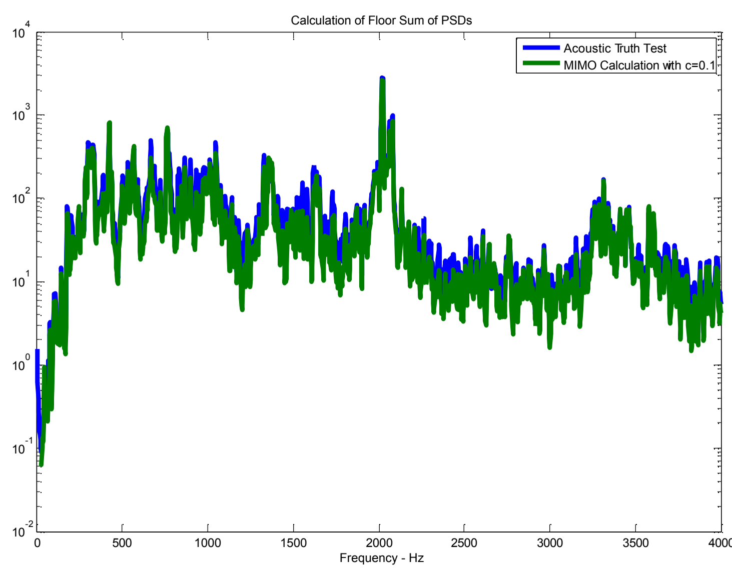
Drive Voltage Calculation

- To form one drive voltage for one block of data
  - A sine wave of proper amplitude was calculated for each frequency line
  - The phase at each frequency line was random
  - The sine waves were added together
- This was repeated for 100 blocks of data
- We iterated in three steps in open loop fashion, not allowing voltage at any frequency line to change by more than +100% - 67% of voltage of previous iteration. In hindsight, for this hardware this was overkill. Convergence could almost be achieved on the first iteration.
- Calculations were performed in MATLAB
- Simulation and data acquisition were implemented with VXI hardware and IDEAS test software

Power Requirements are Reduced with Tikhonov Regularization

- See difference in voltage time histories below without regularization and with regularization (*c*=.01) (factor of 4 difference in some rms levels)
- In analytical calculations, shaker placement and *c*=.1 reduced max power requirements 50% with little degradation of results





20-50 N rms

<0.5 watts

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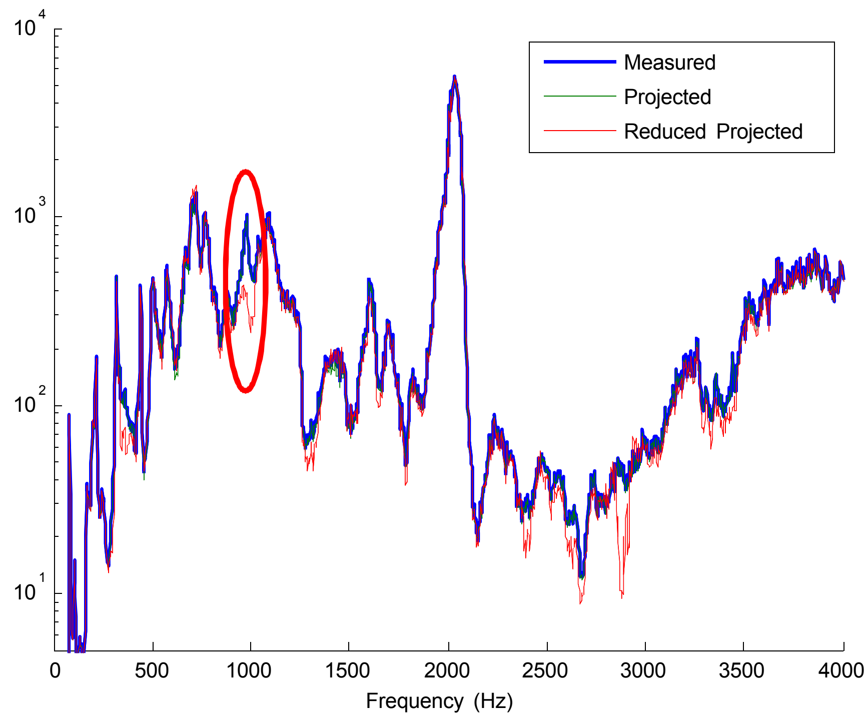
Calculated Sum of PSD metric utilizing only 12 control PSDs

- **In practice, some field tests might not have 37 acceleration PSDs available**
- **12 PSDs were picked randomly, to see how well control could be established for all 37 original accelerometers – sum of 37 PSDs shown below**



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Conclusions

- MIMO shaker simulations for complex systems are feasible with similar near field boundary conditions, even without knowledge or use of voltage input cross spectra
- Regularization reduces the force and power input requirements significantly with minimal loss of control
- Shaker placement effects required power
- Shaker force capability is limited more by mechanical impedance of attachment and amplifier capability than “rated force”
- These results are based on linear theory