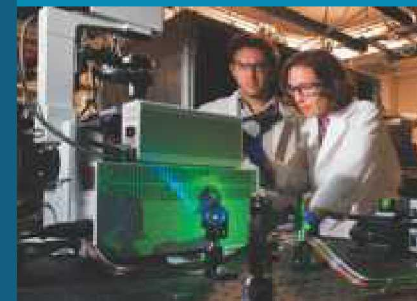
SAND2019-13088C

Combined Shaker-Acoustic Vibration Test Techniques



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PRESENTED BY

Ryan Schultz[1,2] & Peter Avitabile[2]

4-8 November 2019

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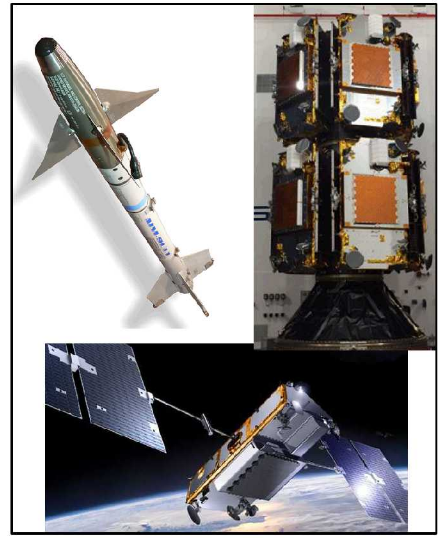
Outline

- Problem & Objective
- MIMO Theory
- Adjusting Inputs
- Acoustic Loads Theory
- Simulation Demonstration
- Experimental Demonstration
- Conclusions

Problem & Objective

Aero-acoustic

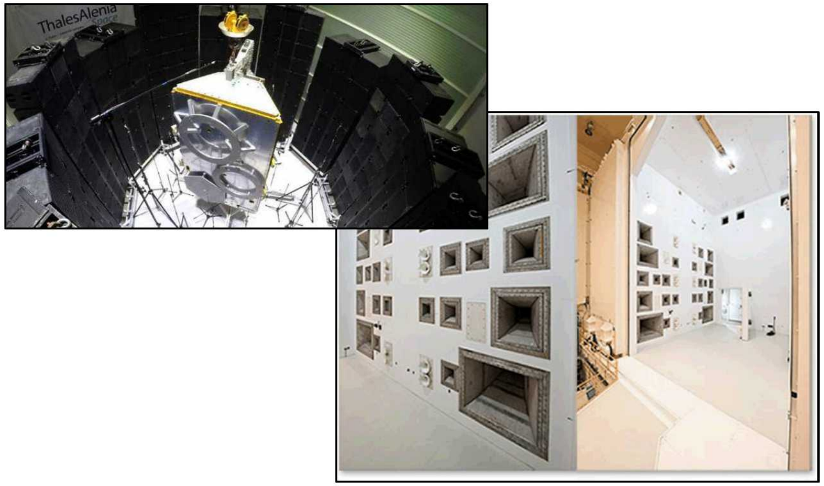
Acoustic



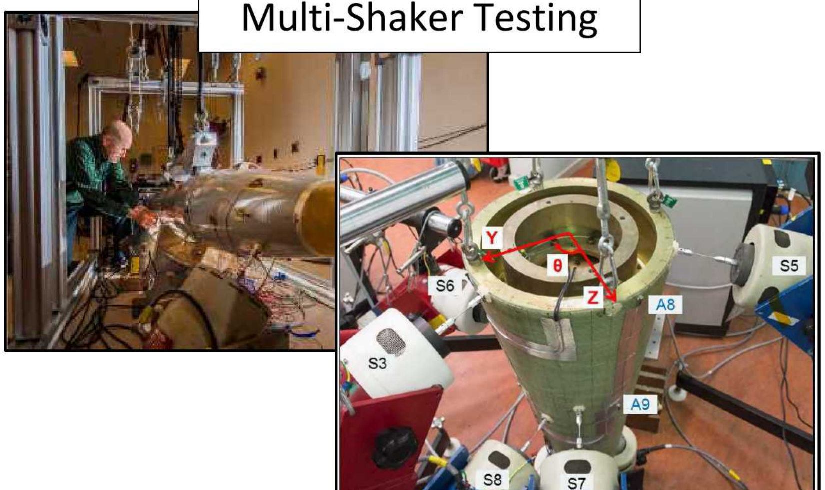
Excitation of Critical Systems & Components

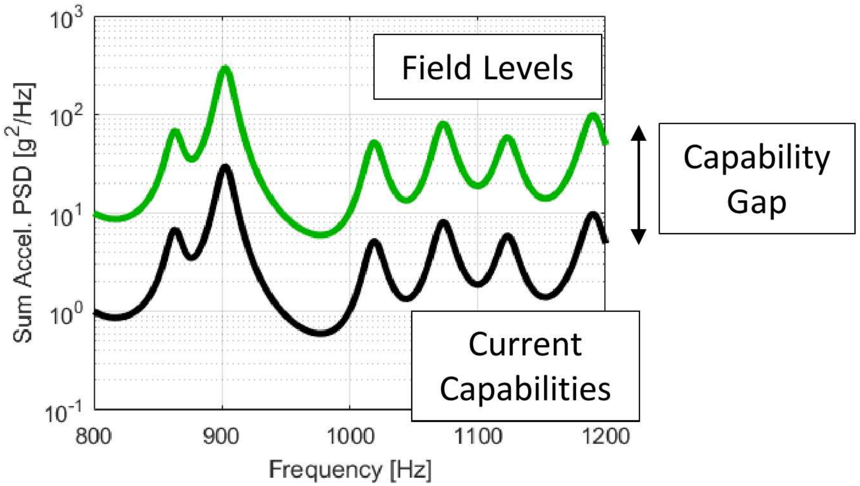
Problem & Objective

Acoustic Testing



Multi-Shaker Testing





Problem & Objective

- Can you combine multiple shaker inputs + acoustic inputs for a better MIMO ground test?
- How do you do that?
- Why is it better?
  - More level by supplementing an acoustic test with shakers
  - More accuracy by supplementing a shaker test with acoustics
- How do you balance the input energy to achieve specific objectives?

+

MIMO Theory

Linear systems & input estimation

MIMO Linear System Theory

Forward Problem:

$$\{X_y\} = [H_{yx}]\{X_x\}$$

$$[S_{yy}] = [H_{yx}][S_{xx}][H_{yx}]^H$$

Given inputs, get outputs

Inverse Problem:

$$\{X_x\} = [H_{yx}]^+\{X_y\}$$

$$[S_{xx}] = [H_{yx}]^+[S_{yy}][H_{yx}]^{+H}$$

Given outputs, get inputs

$\{X_x\}$ = Nx1, Input Linear Spectra
$\{X_y\}$ =Mx1, Output Linear Spectra
$[H_{yx}]$ =MxN, FRF Matrix
$[\cdot]^+$ = pseudo-inverse
$[\cdot]^H$ = Hermitian

MIMO Linear System Theory

Field Test (0):

$$[S_{yy0}] = [H_{yx0}][S_{xx0}][H_{yx0}]^H$$

Field Inputs, Field System
Target Responses

Lab Test (1):

$$[S_{xx1}] = [H_{yx1}]^+[S_{yy0}][H_{yx1}]^{+H}$$

$$[S_{yy1}] = [H_{yx1}][S_{xx1}][H_{yx1}]^H$$

Estimated Lab Inputs, Lab System
Lab Responses

Objective of a Lab Test:
Determine Lab inputs which make the Lab response match the Field response

Challenges:

- *Different systems,* $[H_{yx0}] \neq [H_{yx1}]$
- *Different boundary conditions*
- *Different loads (type, location)*
- *Controllability (enough input freedom)*

MIMO Linear System Theory: Combined Inputs

Combined Shaker-Acoustic Testing:
Two inputs combined to get desired response
(Stacking of two FRF matrices)

Shaker Inputs (v):

$$[S_{yy1}] = [H_{yv1}][S_{vv1}][H_{yv1}]^H$$

Typical multi-shaker MIMO test

Acoustic Inputs (w):

$$[S_{yy1}] = [H_{yw1}][S_{ww1}][H_{yw1}]^H$$

Typical acoustic test

Combined Inputs (v+w):

$$[S_{yy1}] = \left[[H_{yv1}][H_{yw1}]\right]\begin{bmatrix}[S_{vv1}] & [S_{vw1}] \\ [S_{wv1}] & [S_{ww1}]\end{bmatrix}\left[[H_{yv1}][H_{yw1}]\right]^H$$

Combined shaker-acoustic test

MIMO Linear System Theory: Combined Inputs

Input Estimation for Combined Inputs:
Same as any MIMO input estimation problem

Forward Problem:

$$[S_{yy1}] = \left[[H_{yv1}][H_{yw1}]\right]\begin{bmatrix}[S_{vv1}] & [S_{vw1}] \\ [S_{wv1}] & [S_{ww1}]\end{bmatrix}\left[[H_{yv1}][H_{yw1}]\right]^{H}$$

Inverse Problem:

$$\begin{bmatrix}[S_{vv1}] & [S_{vw1}] \\ [S_{wv1}] & [S_{ww1}]\end{bmatrix} = \left[[H_{yv1}][H_{yw1}]\right]^{+}[S_{yy0}]\left[[H_{yv1}][H_{yw1}]\right]^{+H}$$

Challenges:

- *Estimated inputs are simply a least-squares solution, no control over the amount of shaker vs. acoustic input energy*
- *There can be coupling between the two input types, which may be difficult to implement*

Adjusting Inputs

Solve the problem, then mess with the answer…

Adjusting Inputs

Input estimation gives an answer
What if we don't like it?

Inverse Problem:

$$\begin{bmatrix} [S_{vv1}] & [S_{vw1}] \\ [S_{wv1}] & [S_{ww1}] \end{bmatrix} = \left[[H_{yv1}][H_{yw1}]\right]^{+} \left[S_{yy0}\right] \left[[H_{yv1}][H_{yw1}]\right]^{+H}$$

What if we want more shaker energy (v)
or more acoustic energy (w)?

Adjusting Inputs

Adaptive-Gain Algorithm
Adjust the input energy, then re-scale to match response

Form Gain Matrix:

$$[g(\omega)] = \begin{bmatrix} g_1(\omega) & 0 & 0 \\ 0 & g_2(\omega) & 0 \\ 0 & 0 & g_3(\omega) \end{bmatrix}$$

g_i is gain on the i-th input
Can be constant or function of frequency

Estimate Inputs:

$$[S_{xx1,A}] = [H_{yx1}]^{+}[S_{yy0}][H_{yx1}]^{+H}$$

Apply Gain Matrix:

$$[S_{xx1,B}] = [g][S_{xx1,A}][g]$$

$$[S_{yy1,B}] = [H_{yx}][S_{xx1,B}][H_{yx}]^{H}$$

Adjust Input APSDs:

$$\sigma_g = \{G_{yy1,B}\}^{+}\{G_{yy0}\}$$

$$[S_{xx1}] = \sigma_g[S_{xx1,B}]$$

Note: APSD, $\{G_{yy}\}$, is the diagonal of the CPSD, $[S_{yy}]$

Adjusting Inputs

For Shaker-Acoustic Test:
One gain for the shakers, another for the acoustics

Example: 2 Shakers, 1 Acoustic Input:

$$[H_{yvw}] = [\{H_{yv_1}\} \quad \{H_{yv_2}\} \quad \{H_{yw}\}]$$

FRF is Noutputs x 3

Form Gain Matrix:

$$[g(\omega)] = \begin{bmatrix} g_{v1}(\omega) & 0 & 0 \\ 0 & g_{v2}(\omega) & 0 \\ 0 & 0 & g_w(\omega) \end{bmatrix}$$

Scenario 1: More Shaker Energy

$$[g(\omega)] = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Scenario 2: More Acoustic Energy

$$[g(\omega)] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2 \end{bmatrix}$$

Note: Required gain values are problem-dependent &
too large or too small values can be problematic!

Adjusting Inputs: Adaptable-Gain Algorithm

Automatically Adjusting Gain:
Solve the problem with shakers alone, then determine the gain values based on the response error

Solve the Shaker-Only Problem:

$$[S_{xx}] = [H_{yx}]^{+}[S_{yy}][H_{yx}]^{+H}$$

Assess the Response Error:

$$dB_{error} = 10\log_{10}\left(\frac{\sum\{G_{yy1}\}}{\sum\{G_{yy0}\}}\right)$$

$$norm_{error} = \frac{dB_{error}}{threshold}$$

Set the Gain Based on the Error

$$g_w = g_0 * norm_{error}$$

Acoustic input gain
If error is large, gain is large

Apply the Gains

$$[\hat{S}_{xx1}] = [g][S_{xx1}][g]$$

$$\sigma_g = \{G_{yy1}\}^{+}\{G_{yy0}\}$$

$$[S_{xx1}] = \sigma_g[\hat{S}_{xx1}]$$

Acoustic Loads Theory

In one slide…hold on

Making Acoustic Loads for a Simulation

Generate a spatially-correlated input matrix
Perfect diffuse acoustic field has a known spatial correlation

Spatial Correlation:

$$R_{ij} = \frac{\sin(kr_{ij})}{kr_{ij}}$$

k = wavenumber
r_{ij} = distance between points

As a Pressure CPSD Matrix:

$$[S_{PP}] = \begin{bmatrix} R_{11}P_{11} & \cdots & R_{1N}P_{1N} \\ \vdots & \ddots & \vdots \\ R_{N1}P_{N1} & \cdots & R_{NN}P_{NN} \end{bmatrix}$$

P_{ii} = pressure at the i-th location

Apply as Forces:

$$[S_{FF}] = [A^2][S_{PP}]$$

(simplification)

Use as Any Input CPSD:

$$[S_{yy}] = [H_{yx}][S_{xx}][H_{yx}]^H$$

$$[S_{xx}] = [S_{FF}]$$

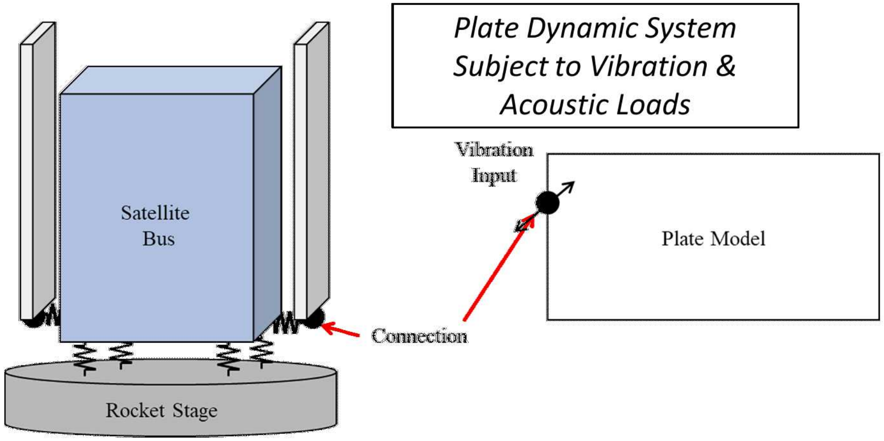
Simulation Demonstration

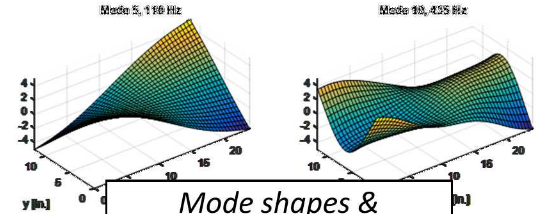
Let’s see how it works

Simulated Field Environment

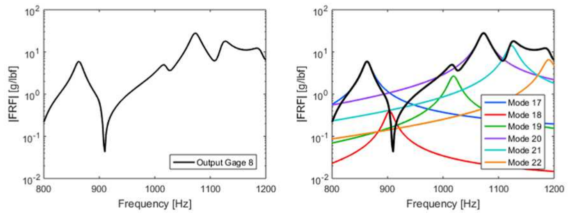
Contrive a complicated set of loads applied to a model to get a simulated field response – use this for simulated tests

Plate Dynamic System Subject to Vibration & Acoustic Loads

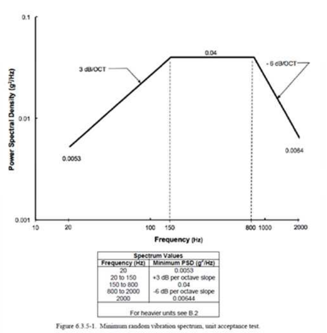




Mode shapes & synthesized FRFs



Vibration Input



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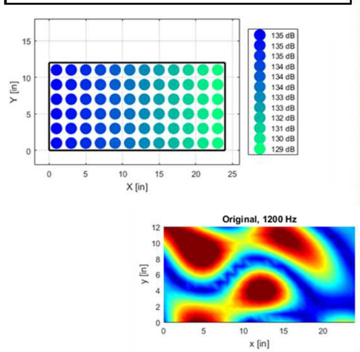
Shaped Acoustic Field



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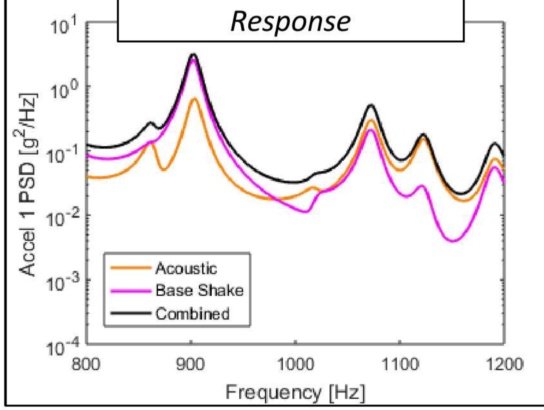
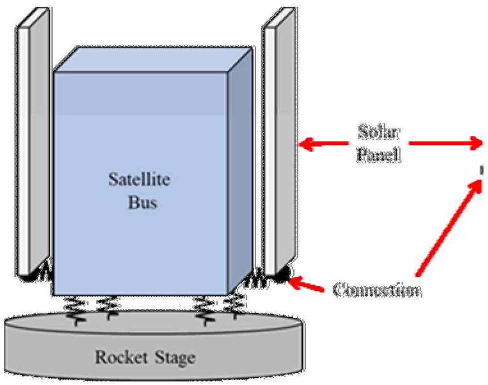
Simulated Field Response

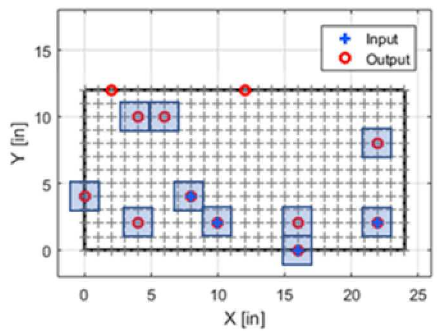


Simulated Field Environment

Simulated field environment gives target response at various locations on the model – use these for combined-inputs tests

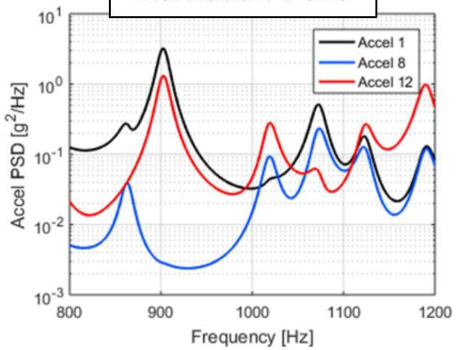


Response Locations on the Plate Model

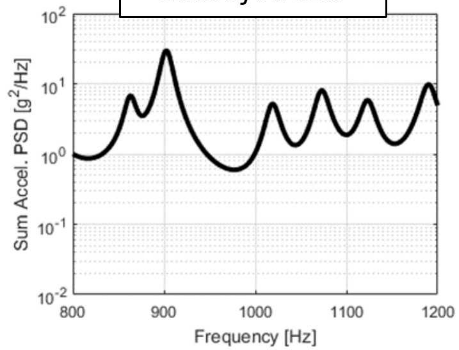


Response, $[S_{yy0}]$, can be viewed many ways

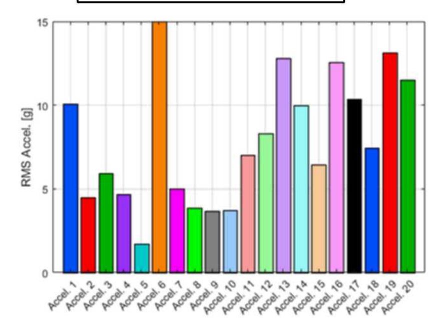
Individual APSDs



Sum of APSDs



Individual RMS



Simulated Combined Shaker-Acoustic Test

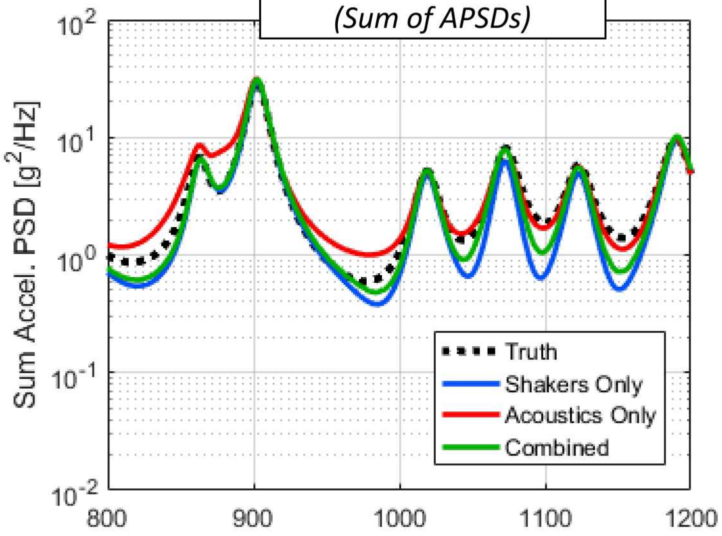
Inverse Problem:

$$\begin{bmatrix} [S_{vv1}] & [S_{vw1}] \\ [S_{wv1}] & [S_{ww1}] \end{bmatrix} = \left[[H_{yv1}][H_{yw1}] \right]^{+} [S_{yy0}] \left[[H_{yv1}][H_{yw1}] \right]^{+H}$$

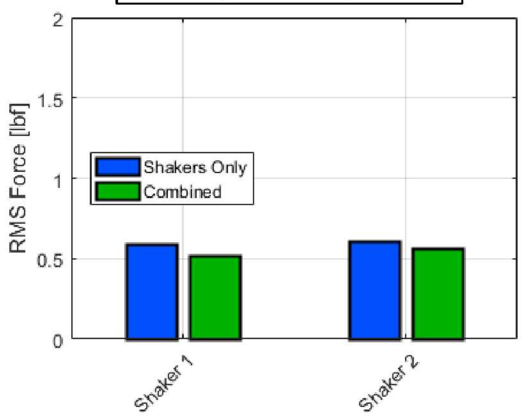
Forward Problem:

$$[S_{yy1}] = \left[[H_{yv1}][H_{yw1}] \right] \begin{bmatrix} [S_{vv1}] & [S_{vw1}] \\ [S_{wv1}] & [S_{ww1}] \end{bmatrix} \left[[H_{yv1}][H_{yw1}] \right]^{H}$$

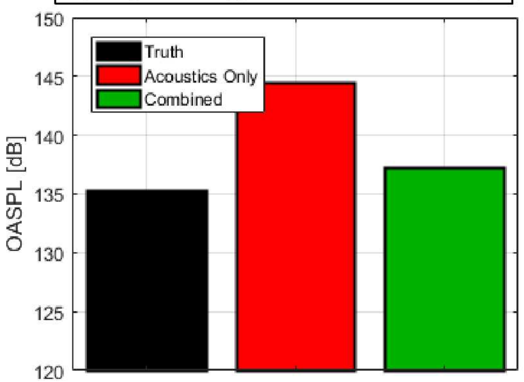
Response Comparison (Sum of APSDs)



RMS Input Force (2 Shakers)



Sound Pressure Level (Uniform Diffuse Acoustic Field)



Simulated Combined Shaker-Acoustic Test

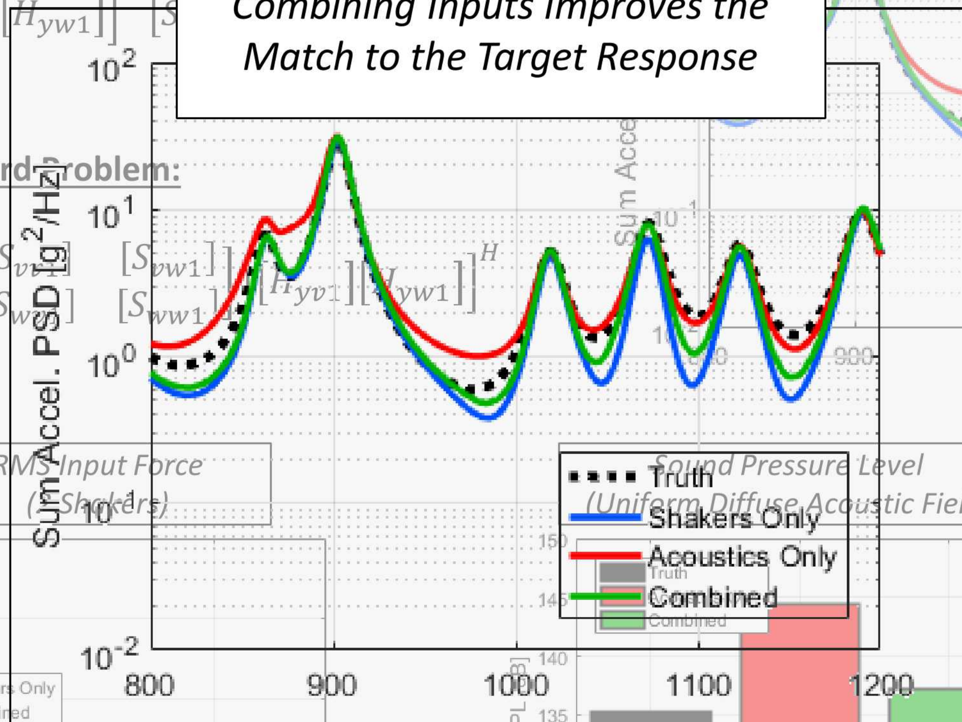
Inverse Problem:

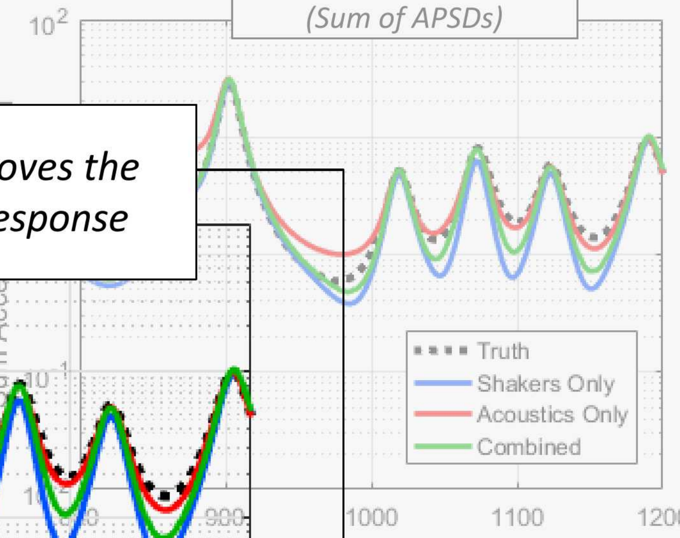
$$\begin{bmatrix}[S_{vv1}] & [S_{vw1}] \\ [S_{wv1}] & [S_{ww1}]\end{bmatrix} = \left[[H_{yv1}][H_{yw1}]\right]^{+} [S$$

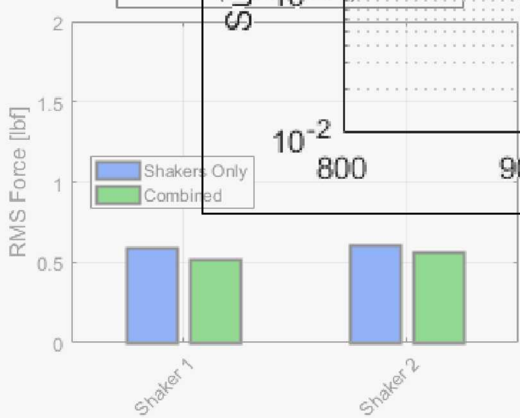
Forward Problem:

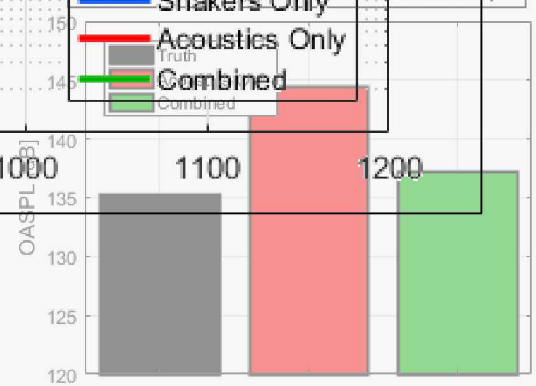
$$[S_{yy1}] = \left[[H_{yv1}][H_{yw1}]\right]\begin{bmatrix}[S_{vv1}] & [S_{vw1}] \\ [S_{wv1}] & [S_{ww1}]\end{bmatrix}\left[[H_{yv1}][H_{yw1}]\right]^{H}$$

Combining Inputs Improves the Match to the Target Response

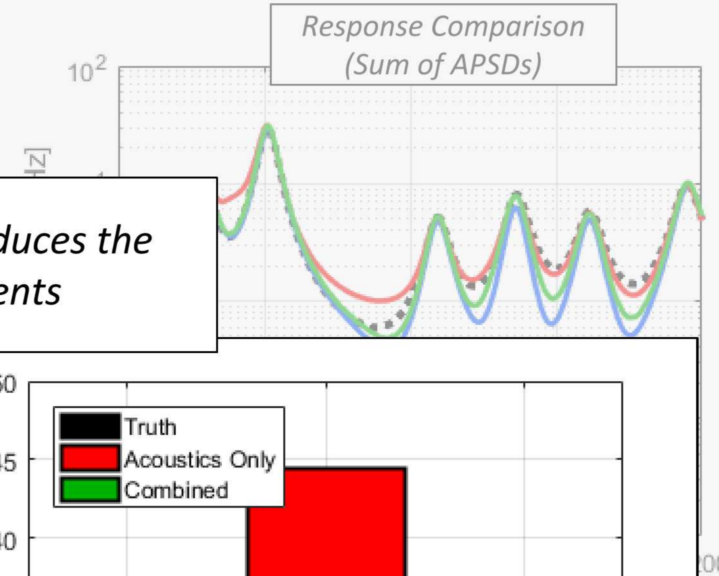








Simulated Combined Shaker-Acoustic Test



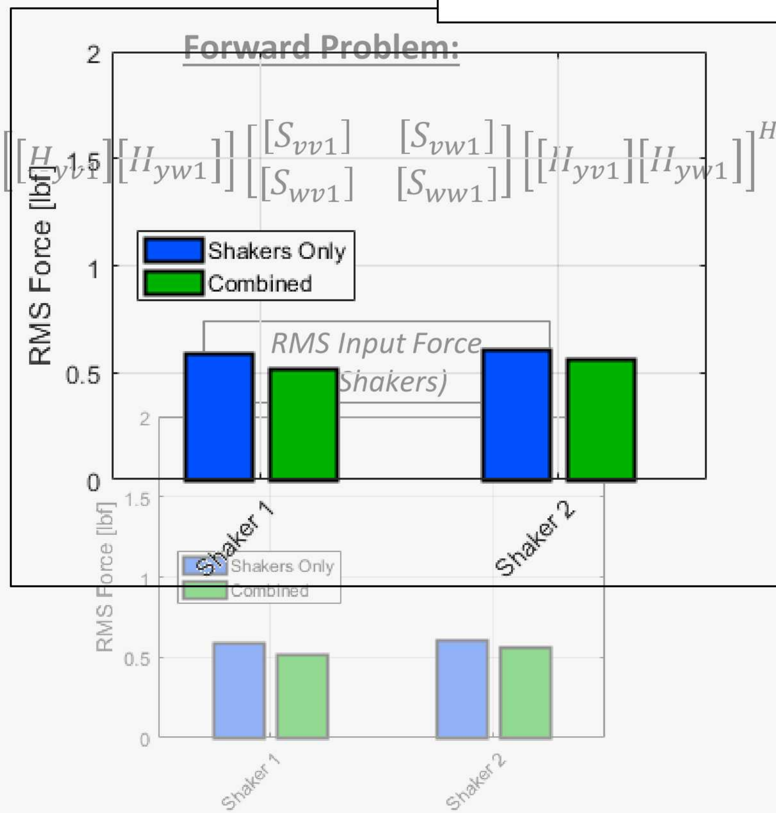
Inverse Problem:

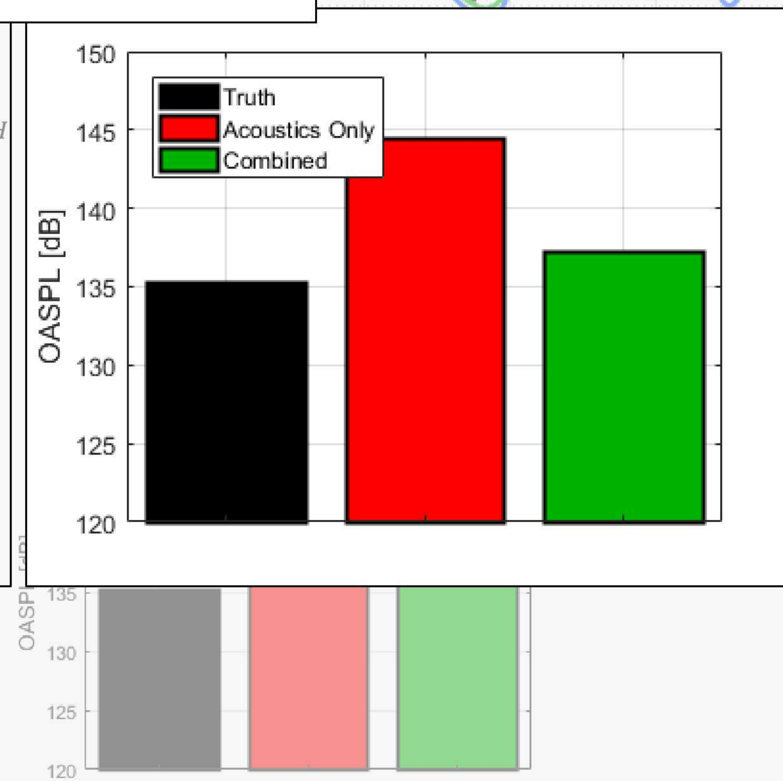
$$\begin{bmatrix}[S_{vv1}] & [S_{vw1}]\\ [S_{wv1}] & [S_{ww1}]\end{bmatrix} = \left[[H_{yv1}][H_{yw1}]\right]^{+} [$$

Combining Inputs Reduces the Input Requirements

Forward Problem:

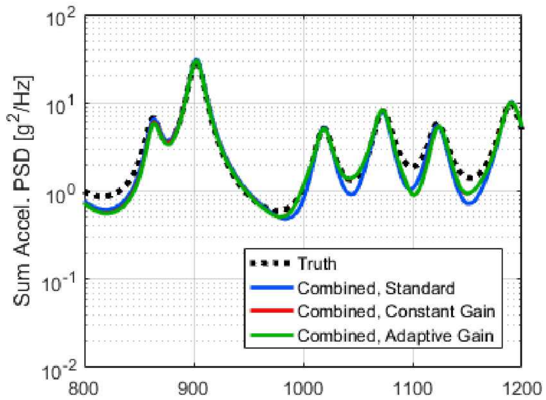
$$[S_{yy1}] = \left[[H_{yv1}][H_{yw1}]\right]\begin{bmatrix}[S_{vv1}] & [S_{vw1}]\\ [S_{wv1}] & [S_{ww1}]\end{bmatrix}\left[[H_{yv1}][H_{yw1}]\right]^{H}$$



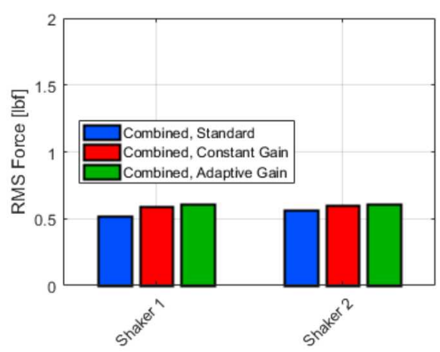


Simulated Test with Adaptive Gain

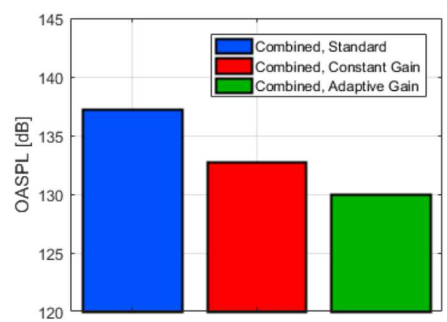
Response Comparison (Sum of APSDs)



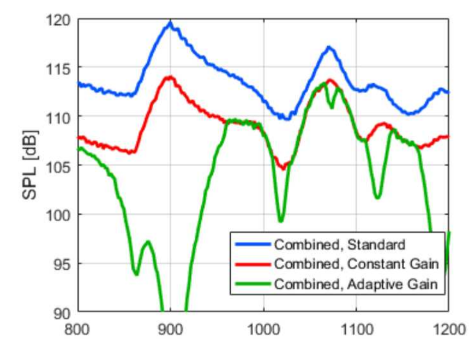
RMS Input Force (2 Shakers)



Sound Pressure Level (Uniform Diffuse Acoustic Field)



Sound Pressure Level (vs. Frequency)



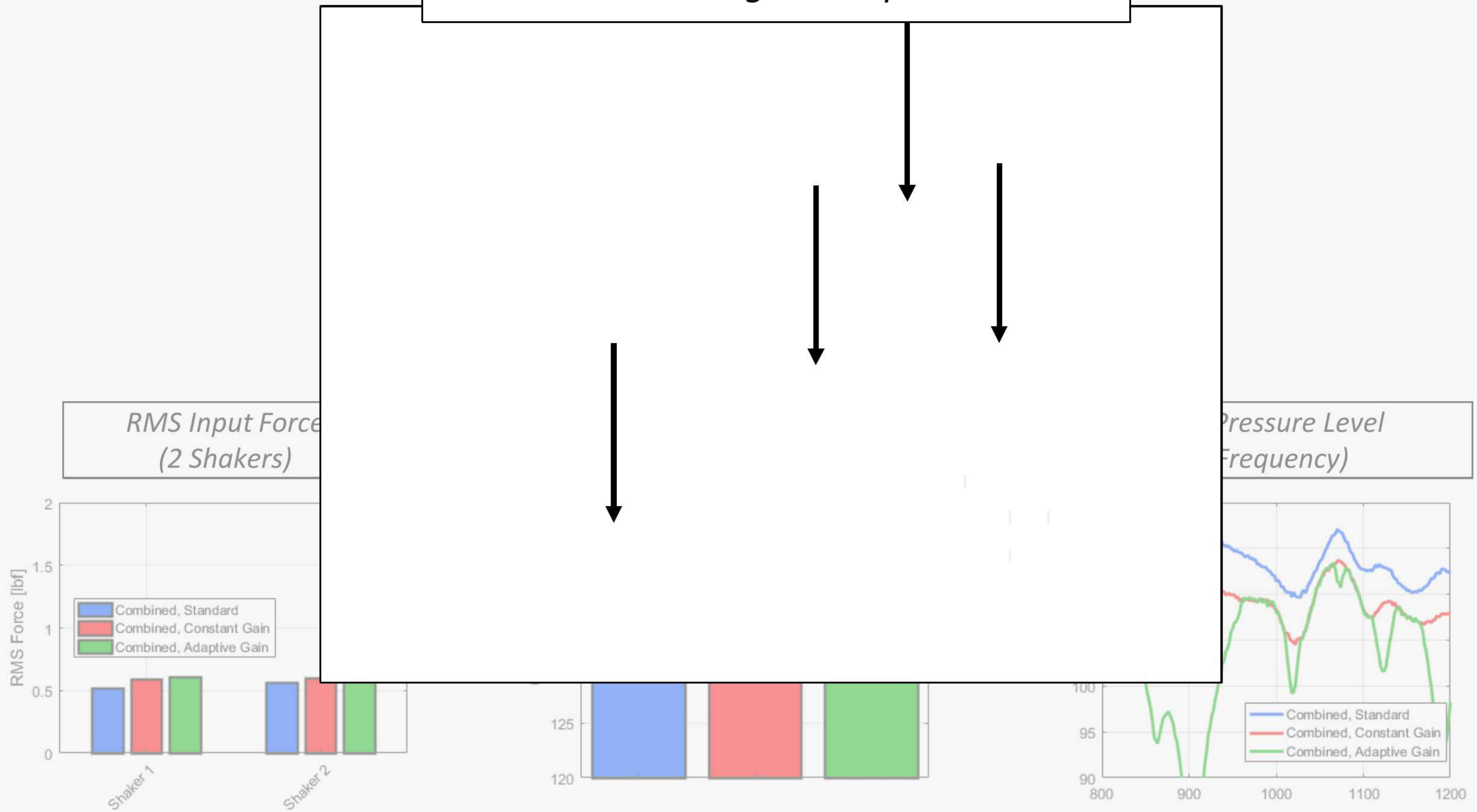
Adaptive gain automatically notches acoustic input when not needed

Simulated Test with Adaptive Gain

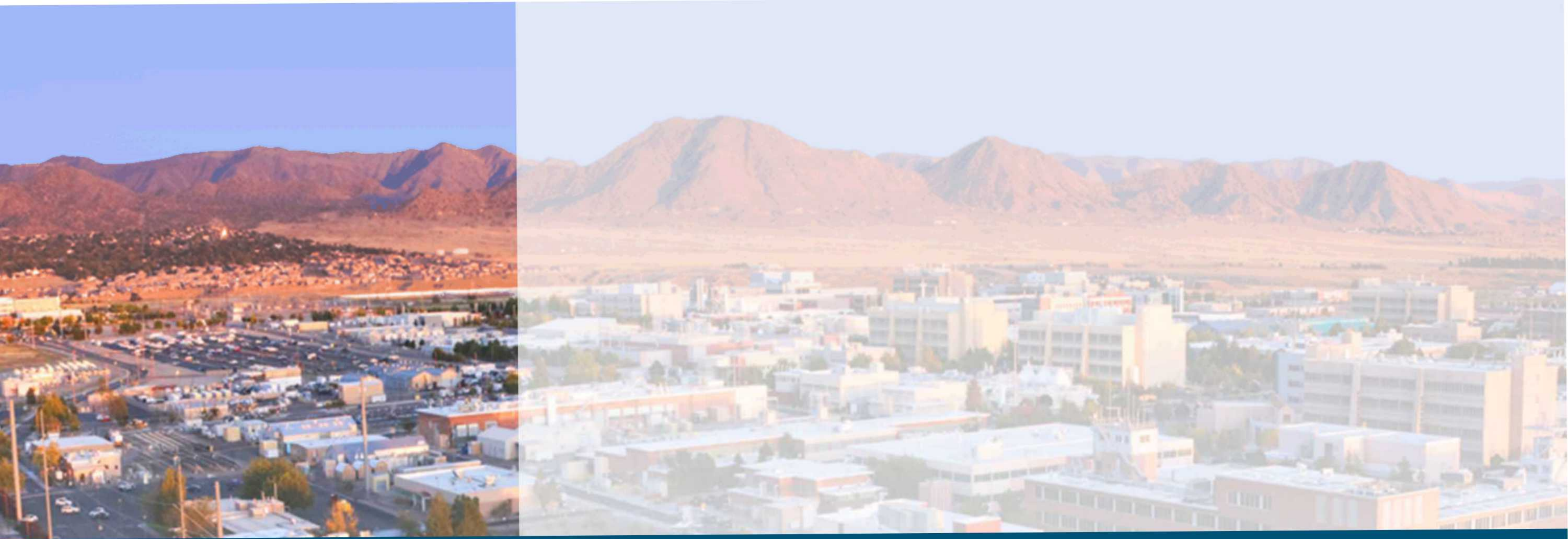
Algorithm notches acoustic input at frequencies where shakers are effective at matching the response

RMS Input Force (2 Shakers)

Pressure Level Frequency)



Adaptive gain automatically notches acoustic input when not needed

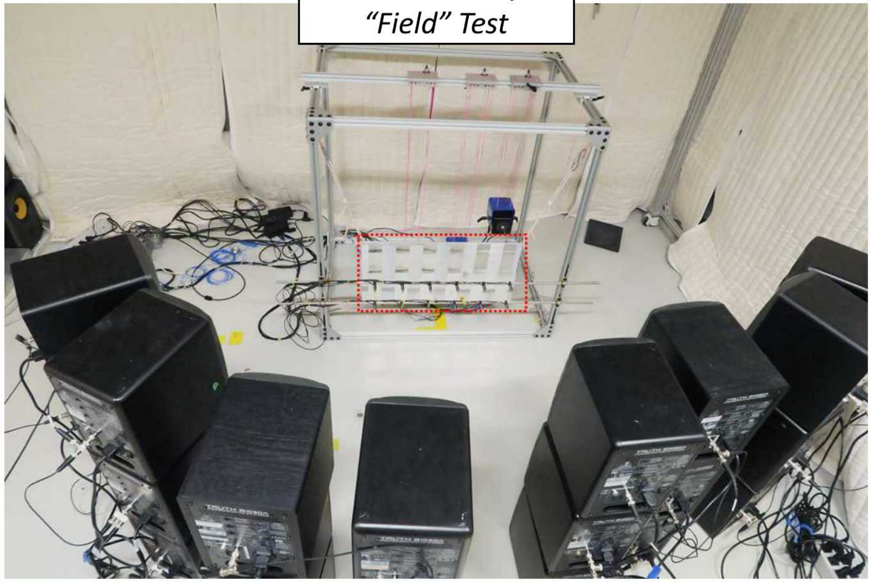


Experimental Demonstration

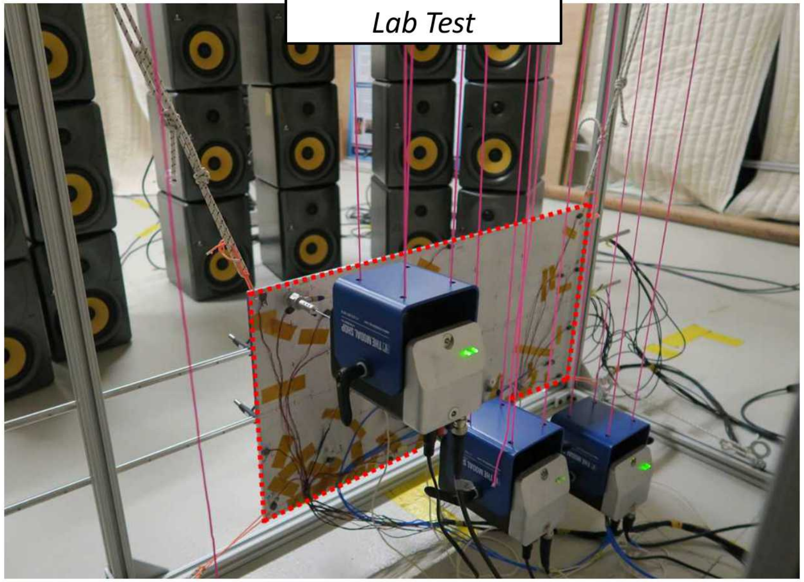
In real life now…

Experiment: "Field" & Lab Tests

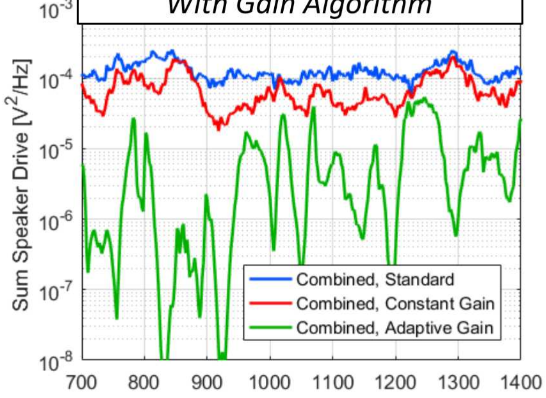
Acoustic-Only "Field" Test



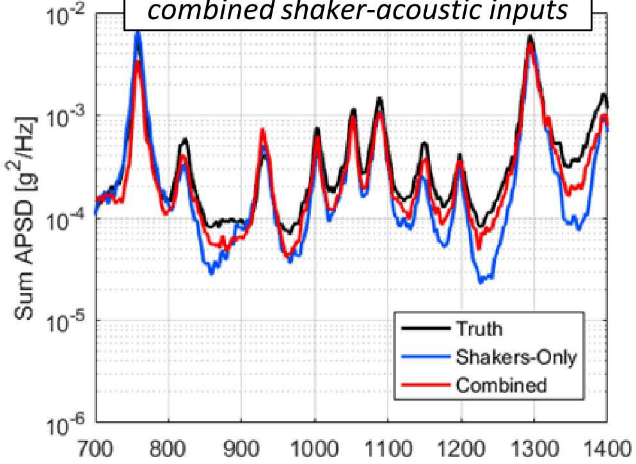
Shaker-Acoustic Lab Test

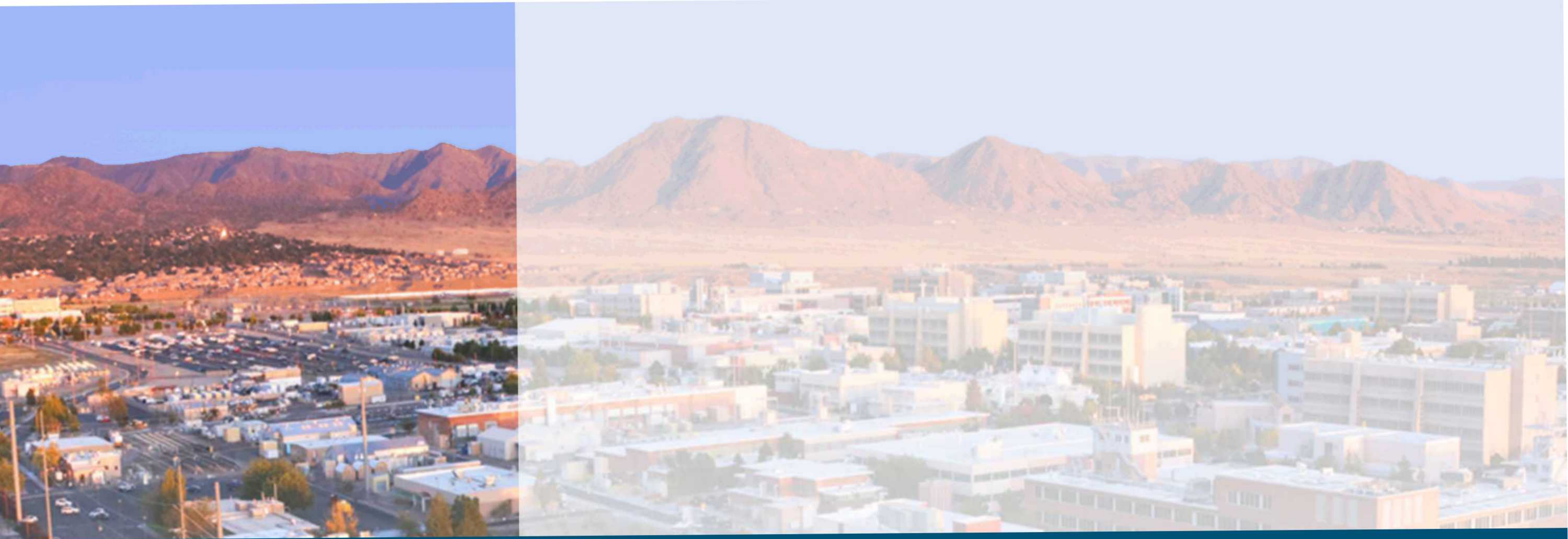


Speaker Drive Signals Reduced With Gain Algorithm



Response is matched well by combined shaker-acoustic inputs





Conclusions

Wrap it up

Conclusions

- Combined-inputs MIMO vibration testing could provide benefits over shaker-only or acoustic-only tests
- Use Cases:
  - SPLs are too high for speakers, add some shakers to supplement
  - Shaker-driven response isn't accurate enough, add acoustic to supplement
- The combined inputs problem is just a form of general MIMO input estimation
- Balance of shaker & acoustic inputs can be changed by applying a gain matrix
  - Adaptive-gain algorithm automatically picks gain values based on the accuracy of the shaker-driven response, fills in with acoustic energy as-needed
- Demonstrated effectiveness using simulations and an experiment
- Future Work:
  - Demonstrate these techniques at scale – larger, more complicated structure & higher response levels
  - Explore different use cases for the combined inputs problem

Questions?

Thank you to my advisor & co-author, Dr. Peter Avitabile

UMASS LOWELL

Forward Problem:

$$[S_{yy1}] = \left[[H_{yv1}][H_{yw1}]\right]\begin{bmatrix}[S_{vv1}] & [S_{vw1}] \\ [S_{wv1}] & [S_{ww1}]\end{bmatrix}\left[[H_{yv1}][H_{yw1}]\right]^{H}$$

Inverse Problem:

$$\begin{bmatrix}[S_{vv1}] & [S_{vw1}] \\ [S_{wv1}] & [S_{ww1}]\end{bmatrix} = \left[[H_{yv1}][H_{yw1}]\right]^{+}[S_{yy0}]\left[[H_{yv1}][H_{yw1}]\right]^{+H}$$