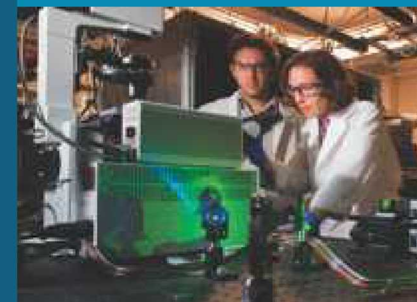
SAND2019-13066C

Explorations in Multiple-Input Shaker Shock Testing



PRESENTED BY

Ryan Schultz, 4-8 November 2019

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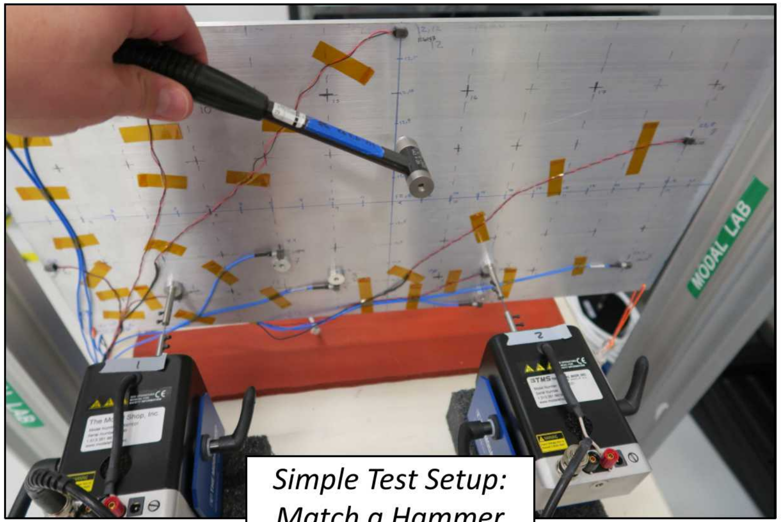
Outline

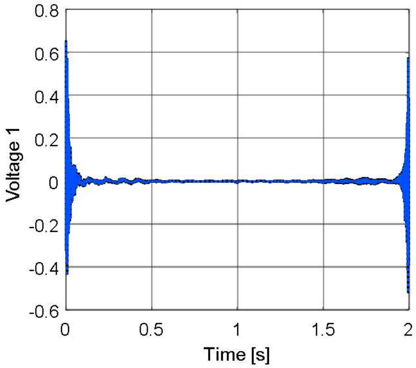
- Problem & Objective
- (Basic) MIMO Transient Theory
- Example Dynamic System
- Simulated Field and Laboratory Tests
- Explorations of Test Design Effects
  - Convolution Error
  - Effect of the number of shakers
  - Effect of the location of shakers
- Conclusions

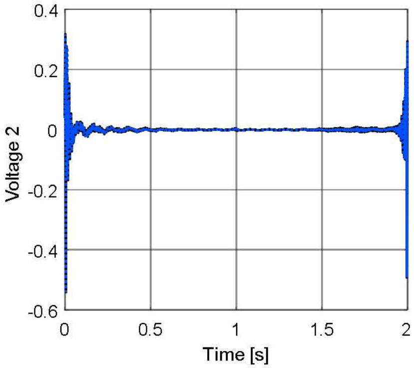
Motivation: A MIMO Test with Issues

- Tasked with running a MIMO shock test on some complicated hardware
- Started by trying to run a MIMO shock test on some simple hardware
- It wasn't that simple…
  - Big errors
  - Small errors
- Not sure what affects what – what should I change to get a better result?

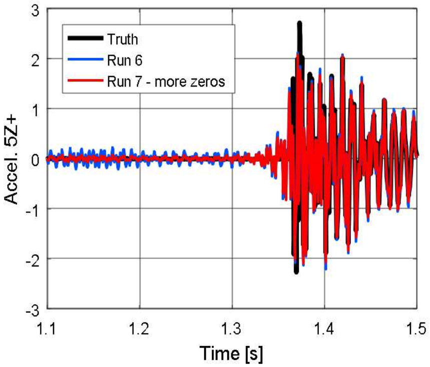


Simple Test Setup: Match a Hammer Hit with 2 Shakers



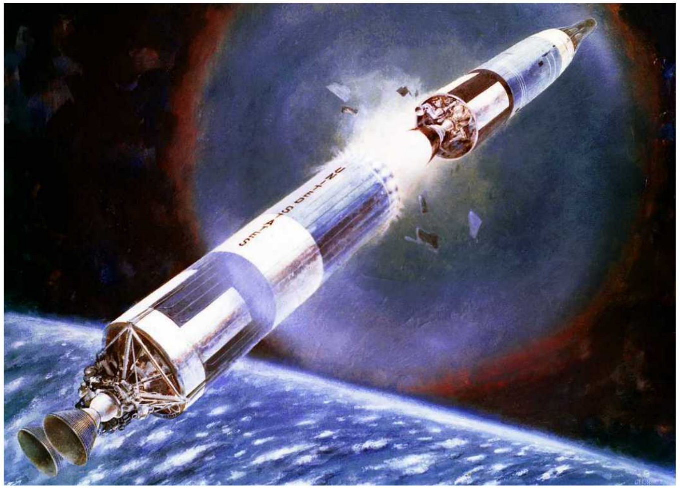


Estimated Inputs Look Weird…



Early-Time Response Doesn't Match

Problem & Objective



Shocks occur in various forms during flight & transportation:
The inputs are not always single-axis
Can we test in a better way using MIMO techniques?

Objective:

- Learn about MIMO transient (shock) problems & how to solve them
- Make a simulation-based test design process
- Demonstrate how test design factors affect results

https://www.flickr.com/photos/mrdanbeaumont/45363893181
http://www.abdonline.com/news-analysis/defense/drop-everything-as-bombs-evolve-so-do-bomb-racks/

MIMO Transient Theory

Just the basics for now…

(Basic) MIMO Transient Theory

Forward Problem:

$$\begin{tikzcd} \{X_y\} = [H_{yx}]\{X_x\} \arrow[d, shift right=2, "DFT"'] \\ \{y\} = [h_{yx}] \otimes \{x\} \arrow[u, shift right=2, "IDFT"'] \end{tikzcd}$$

Given inputs, get outputs

Inverse Problem:

$$\begin{tikzcd} \{X_x\} = [H_{yx}]^{+}\{X_y\} \arrow[d, shift right=2, "DFT"'] \\ \{x\} = [h_{yx}]^{+} \otimes \{y\} \arrow[u, shift right=2, "IDFT"'] \end{tikzcd}$$

Given outputs, get inputs

$\{X_x\}$ = Nx1, Input Linear Spectra
$\{X_y\}$ =Mx1, Output Linear Spectra
$[H_{yx}]$ =MxN, FRF Matrix
$[h_{yx}]$ = MxN, Impulse Response Matrix
$\{x\}$ = Nx1, Input Time Histories
$\{y\}$ = Mx1, Output Time Histories
$[\cdot]^{+}$ = pseudo-inverse

(Basic) MIMO Transient Theory

- How to solve a forward MIMO transient problem:
  - *Start with inputs in the time domain:* $\{x\}$
  - *Convert to the frequency domain (DFT):* $\{X_x\} = \mathcal{F}(\{x\})$
  - *Multiply by FRF matrix to get the outputs:* $\{X_y\} = [H_{yx}]\{X_x\}$
  - *Convert to the time domain (IDFT):* $\{y\} = \mathcal{F}^{-1}(\{X_y\})$

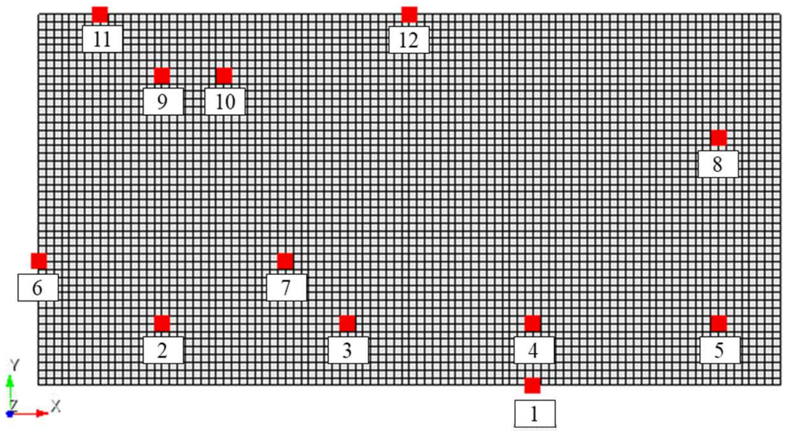
- How to solve a inverse MIMO transient problem:
  - *Start with target response (outputs) in the time domain:* $\{y_0\}$
  - *Convert to the frequency domain (DFT):* $\{X_{y0}\} = \mathcal{F}(\{y_0\})$
  - *Multiply by pseudo-inverse of the FRF matrix to get the inputs:* $\{X_{x1}\} = [H_{yx}]^{+}\{X_{y0}\}$
  - *Multiply by the FRF matrix to get the outputs:* $\{X_{y1}\} = [H_{yx}]\{X_{x1}\}$
  - *Convert to the time domain (IDFT):* $\{y_1\} = \mathcal{F}^{-1}(\{X_{y1}\})$

Example Dynamic System

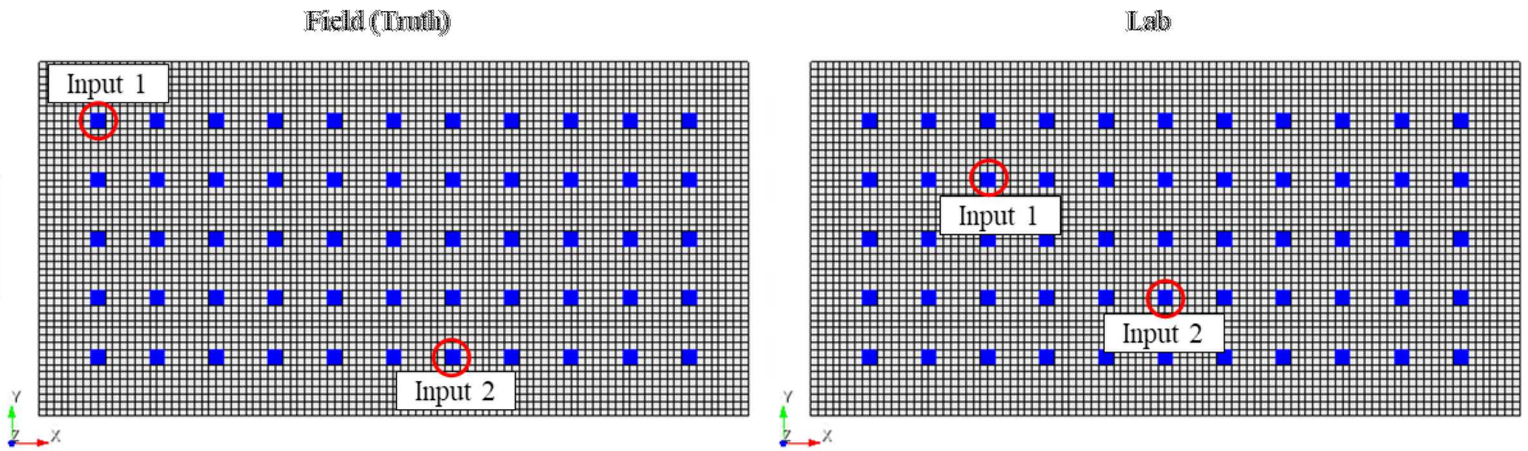
Get some FRFs to play with

Plate Model

12 Outputs (Accelerometers)



2 Sets of 2 Inputs (Shakers)



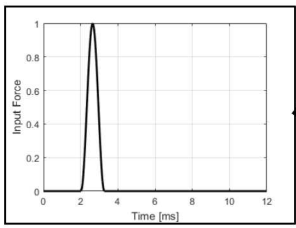
- *12x24x1/4 inch aluminum plate*
- *Free-free BCs*
- *12 outputs*
- *Grid of possible inputs*
- *Model modes at inputs & outputs let us synthesize FRF matrices*
- *Desired bandwidth: 1500 Hz*
- *Time response via Newmark integration at 32,768 Hz*

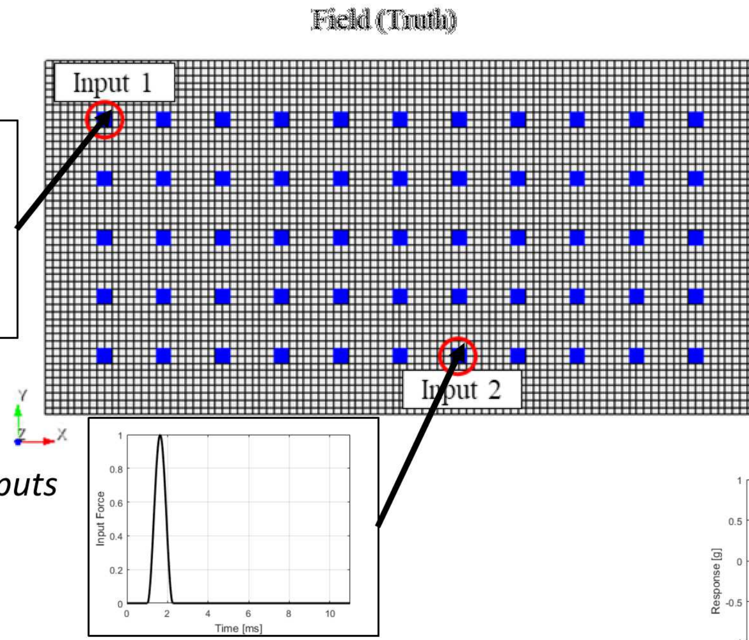
Simulated Field & Laboratory Tests

Cheaper than the real thing

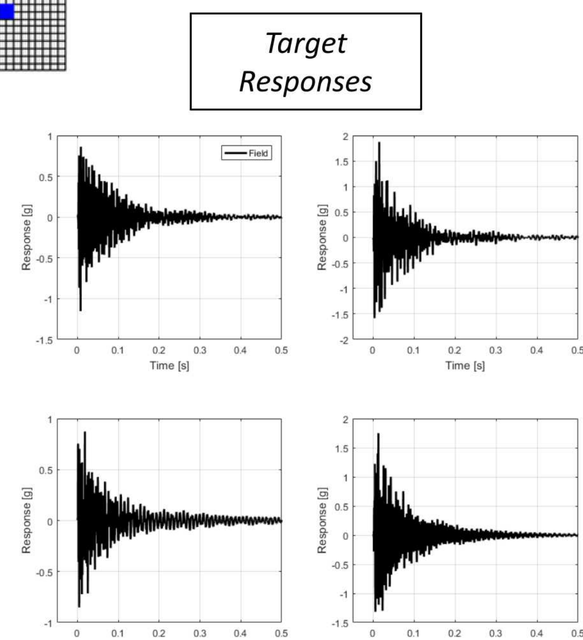
Simulated Field Test

- Objective: Obtain target response time histories from some transient inputs





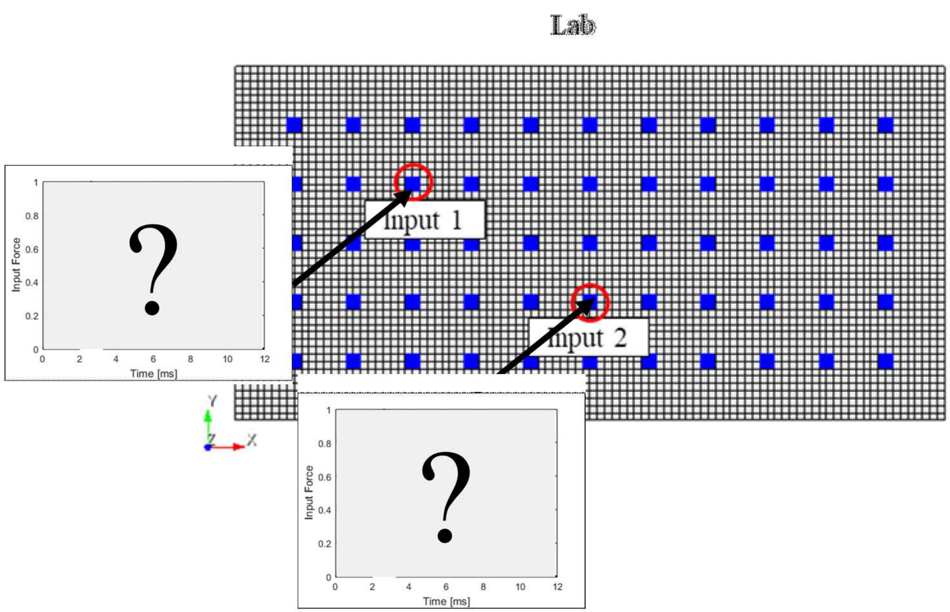
- *1 ms haversine force inputs*
- *Different start times*
- *Different locations*



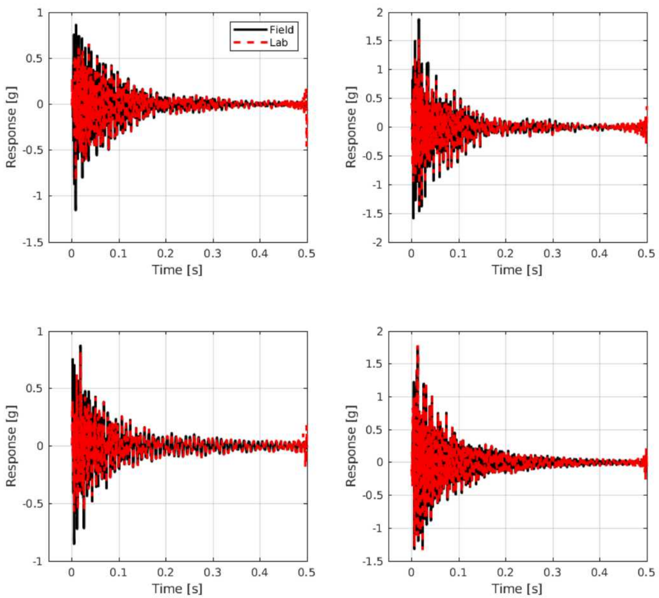
Simulated Lab Test

- Pick input locations
- Solve input estimation problem
- Predict response due to those inputs

Compare Field & Lab Responses



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

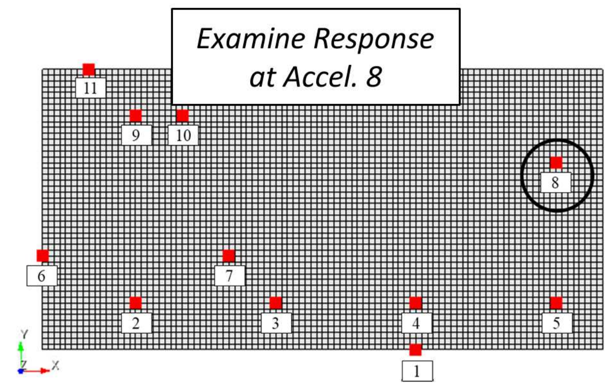


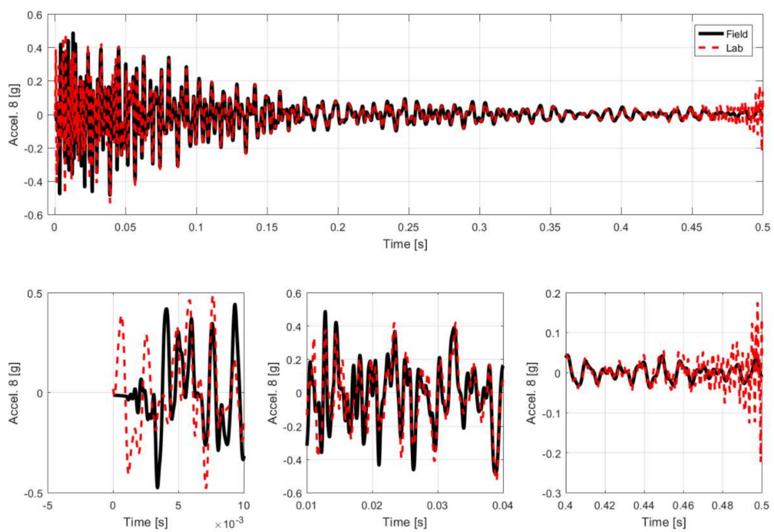
Explorations of Test Design Effects

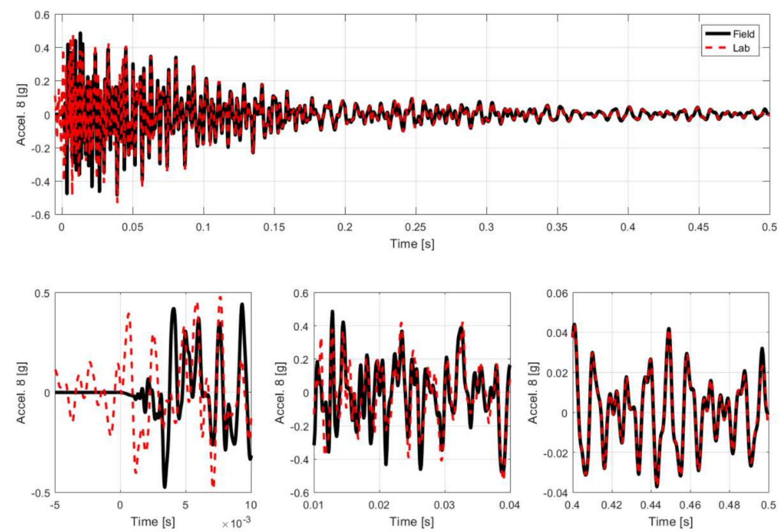
What affects what?

Convolution Error

- Convolution wrap-around can cause errors at the ends of the frame
- Here, this shows up as large inputs & responses at the end of the frame
- Solution: Add zeros to the start & end of the target response
  - $\{y_0\} = \{\{0\}; \{y_0\}; \{0\}\}$
  - Wrap-around is multiplied by zeros, removing the effects







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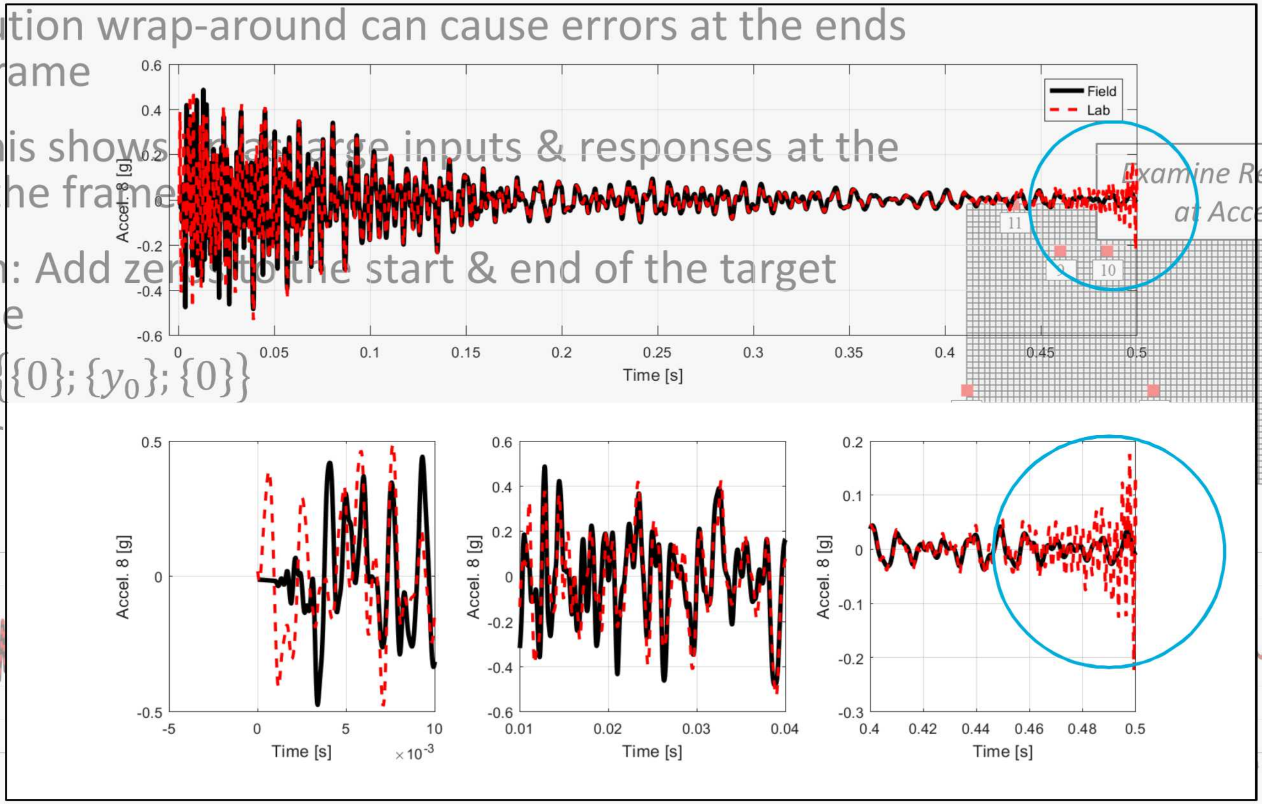
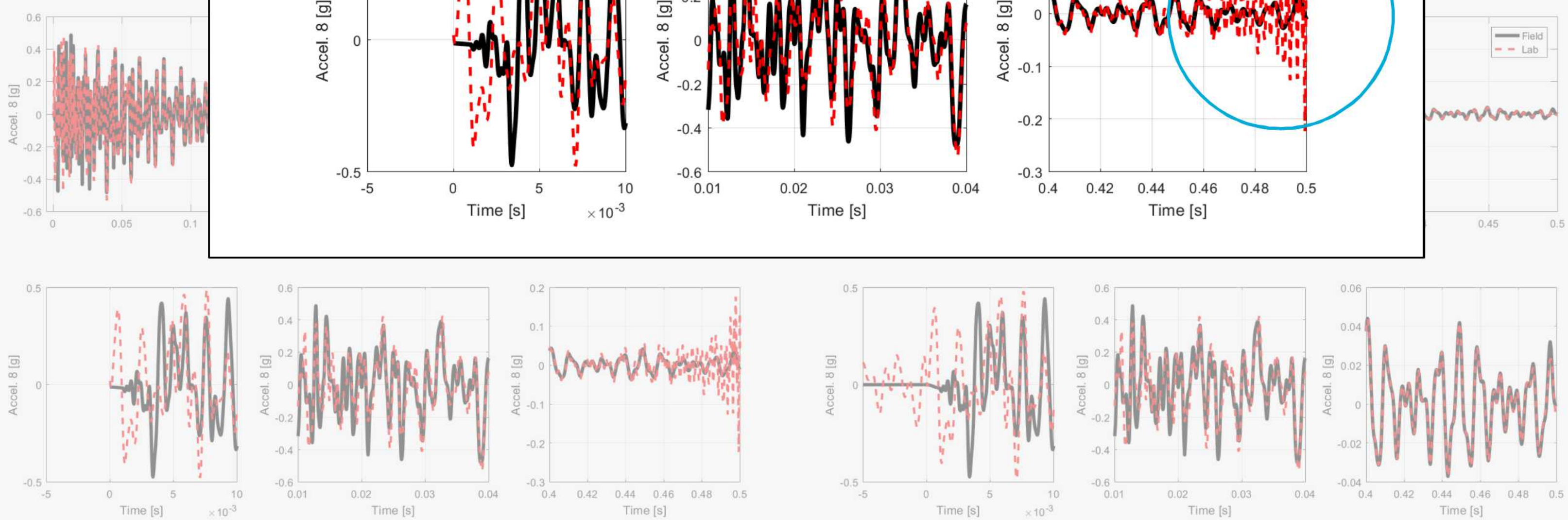
  - Wrap-ar





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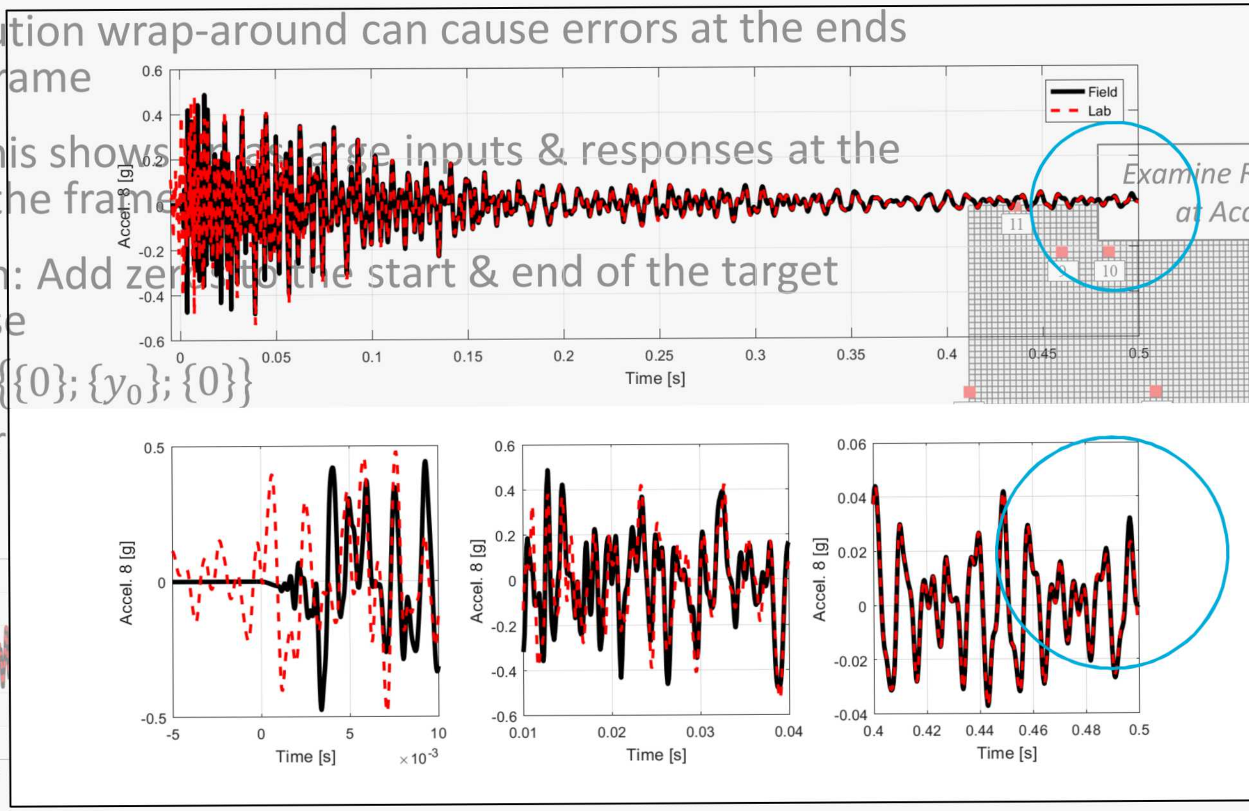
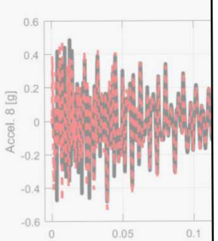
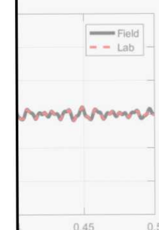
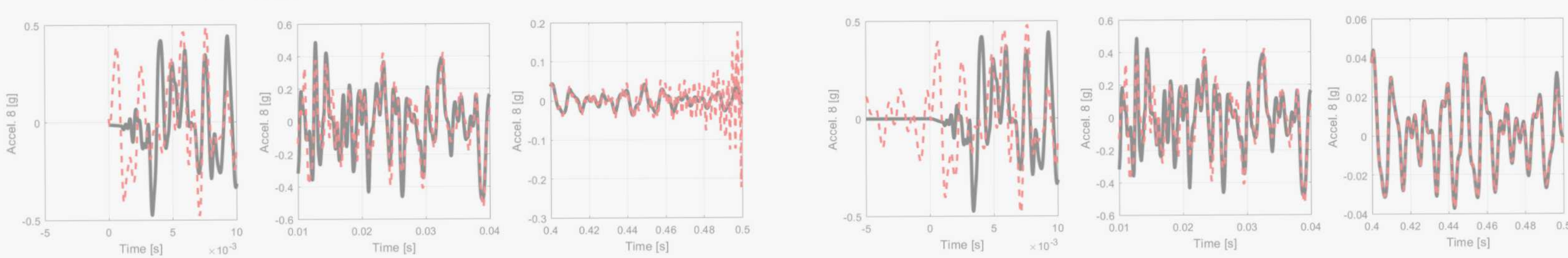


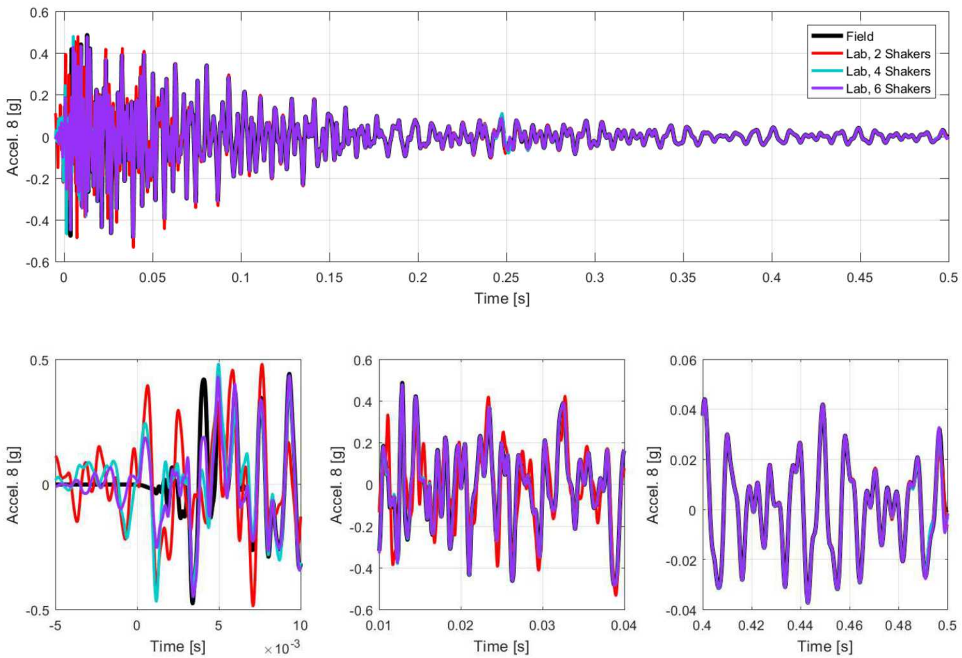






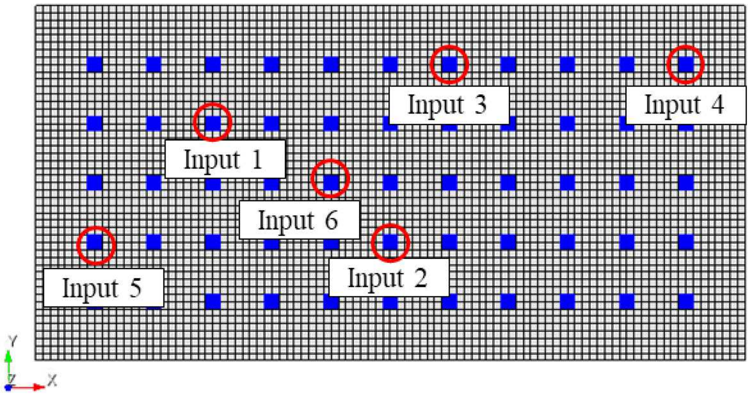
Effects of the Number of Inputs

- Key test design question: *How many shakers do we need & where do they go?*
- Simulate Lab test with 2, 4, and 6 shakers
- More shakers is better, but may not result in a perfect response



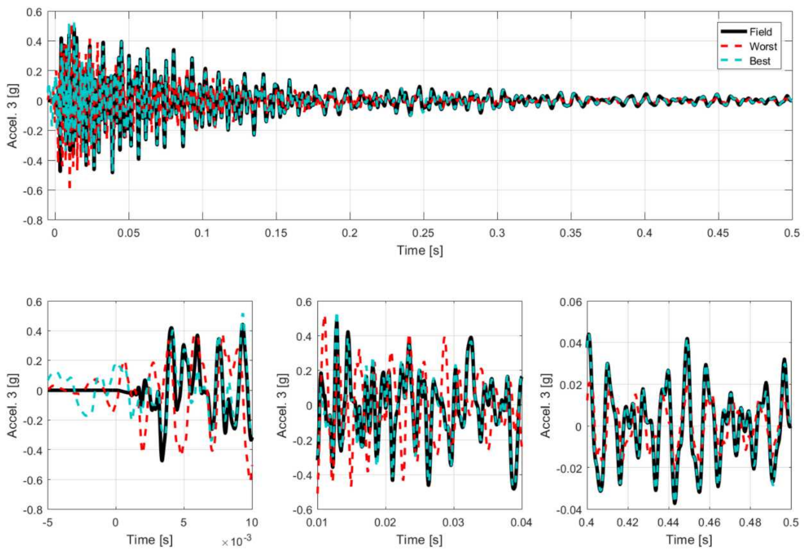
Early-time response improves with more inputs

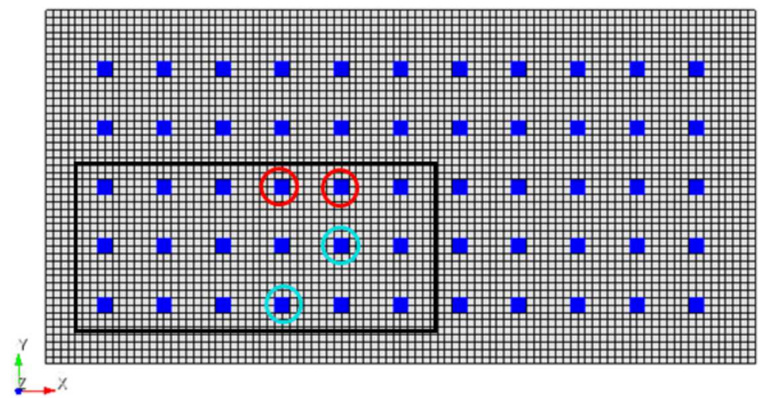
Late-time response is equivalent

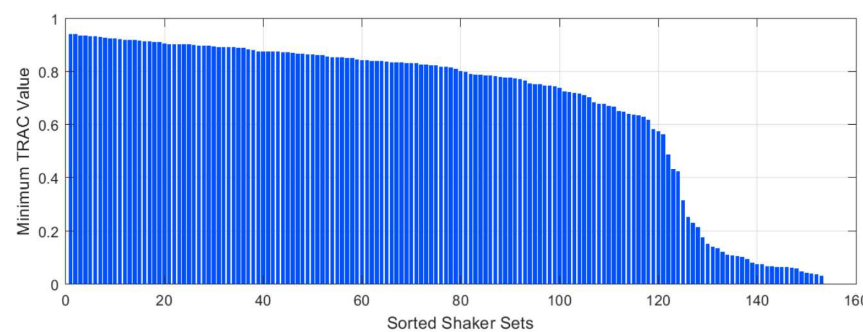


Effects of the Locations of Inputs

- Key test design question: *How many shakers do we need & where do they go?*
- Simulate Lab test with 2 shakers at various locations
- 2 inputs from 18 candidate locations = 153 combos
- Compare results with TRAC at 4 accels – pick best & worst locations







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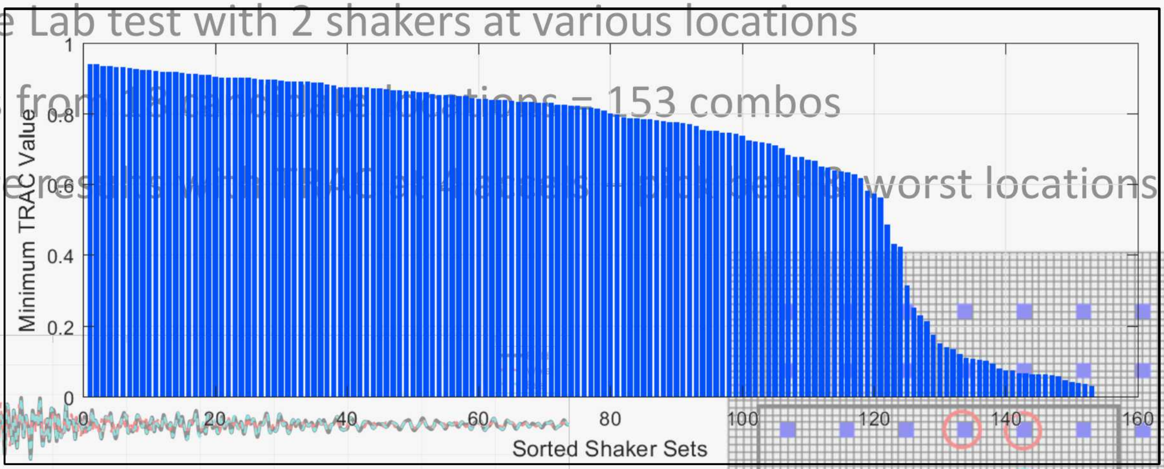

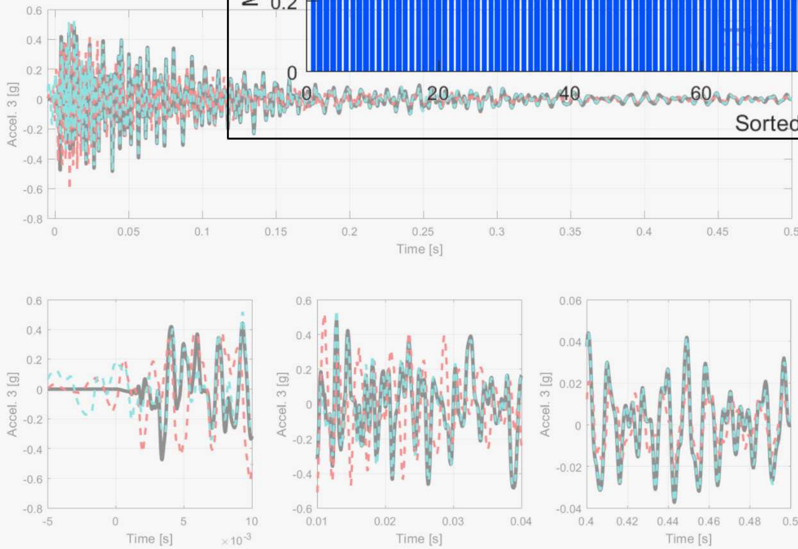

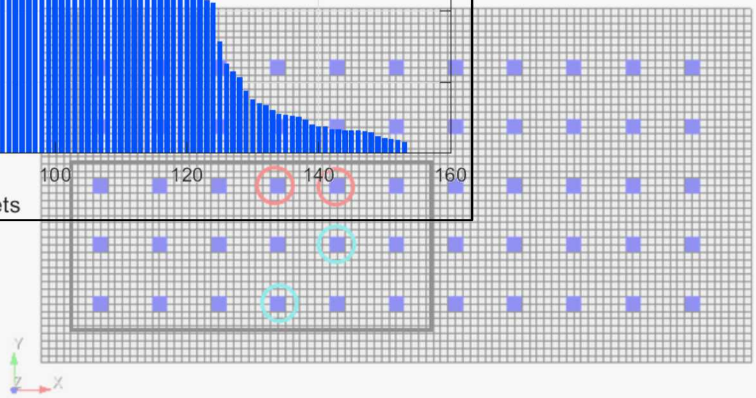

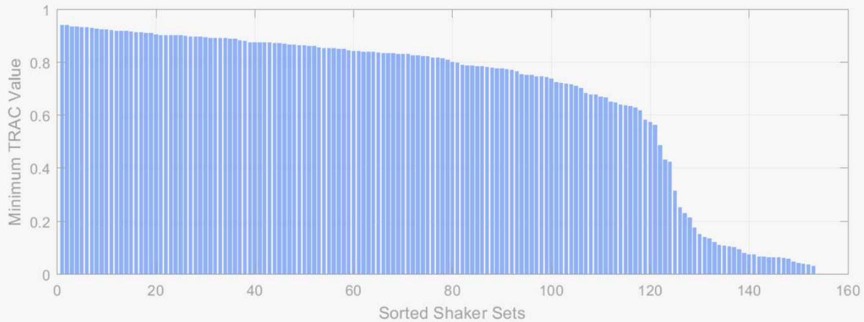

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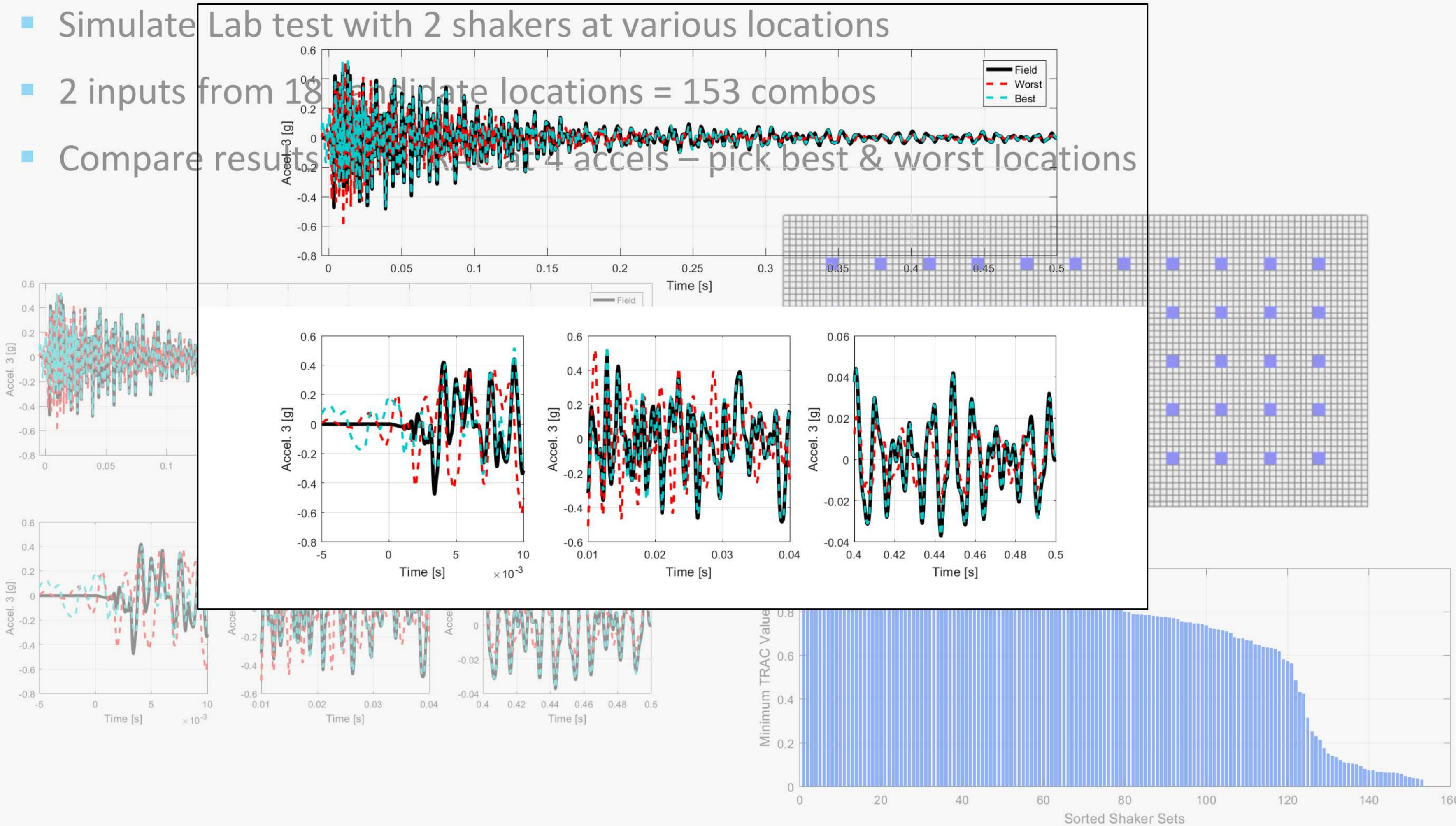


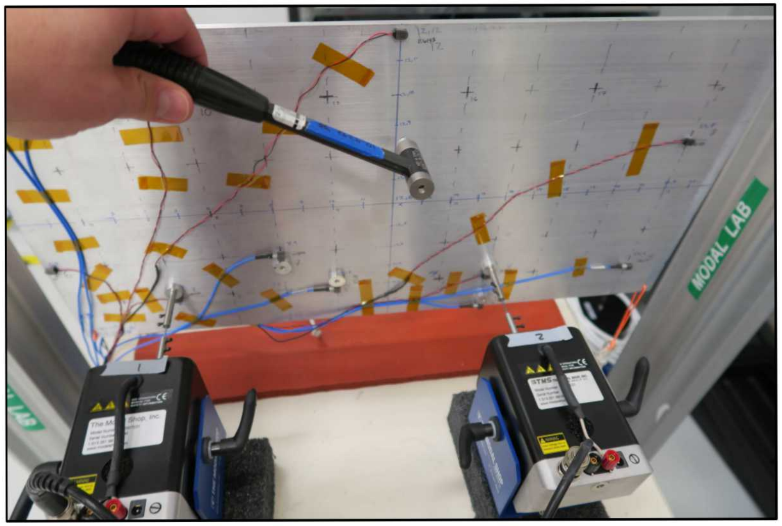
Conclusions

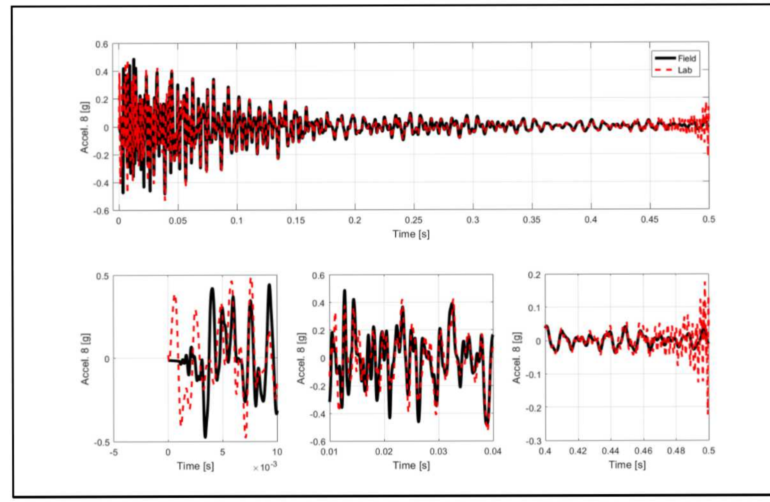
What did we learn?

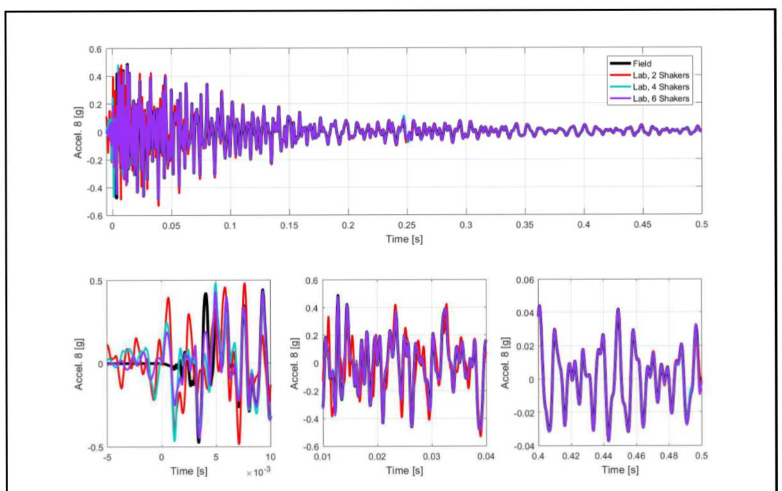
Conclusions & Lessons Learned

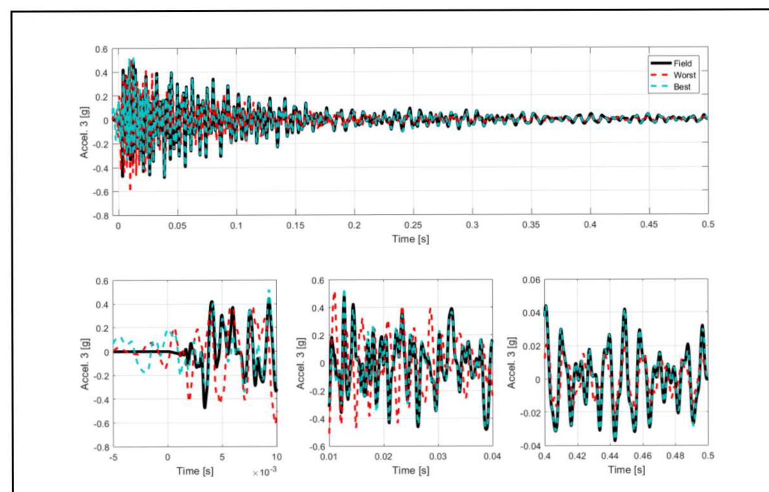
- A simple example can be really useful when learning how to do something new
- Models are really useful for designing & understanding complicated test behavior. We plan to use a model-based test design approach for MIMO
- Some of this should have been obvious, but this was still a good exercise
- You must zero-pad the target response to avoid convolution wrap around errors
- Just like with MIMO random vibration problems, MIMO transient problems are very sensitive to the number and location of inputs. It is worth the design time to pick some good input locations and avoid some bad input locations
- Future Work:
  - Arbitrary-length signals/waveform replication using COLA
  - Investigate multi-output metrics for transient problems
  - Assess shaker capabilities vs. environment requirements

Questions?


MODAL LAB


Field
Lab
Accel. 8 [g]
Time [s]
×10^-3


Field
Lab, 2 Shakers
Lab, 4 Shakers
Lab, 6 Shakers
Accel. 8 [g]
Time [s]
×10^-3


Field
Worst
Best
Accel. 3 [g]
Time [s]
×10^-3