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Title: Rapid, Approximate Multi-Axis Vibration Testing

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Rapid, Approximate Multi-Axis Vibration Testing

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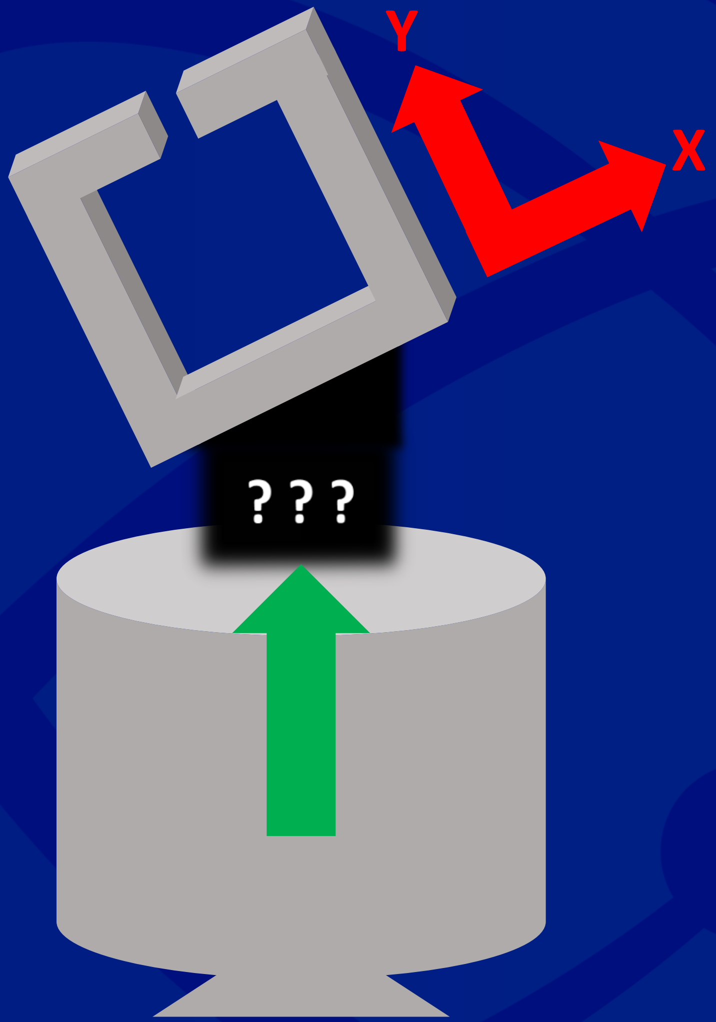


LA-UR-TBD

Problem:

Sequential single-axis testing provides a poor approximation of service environments.

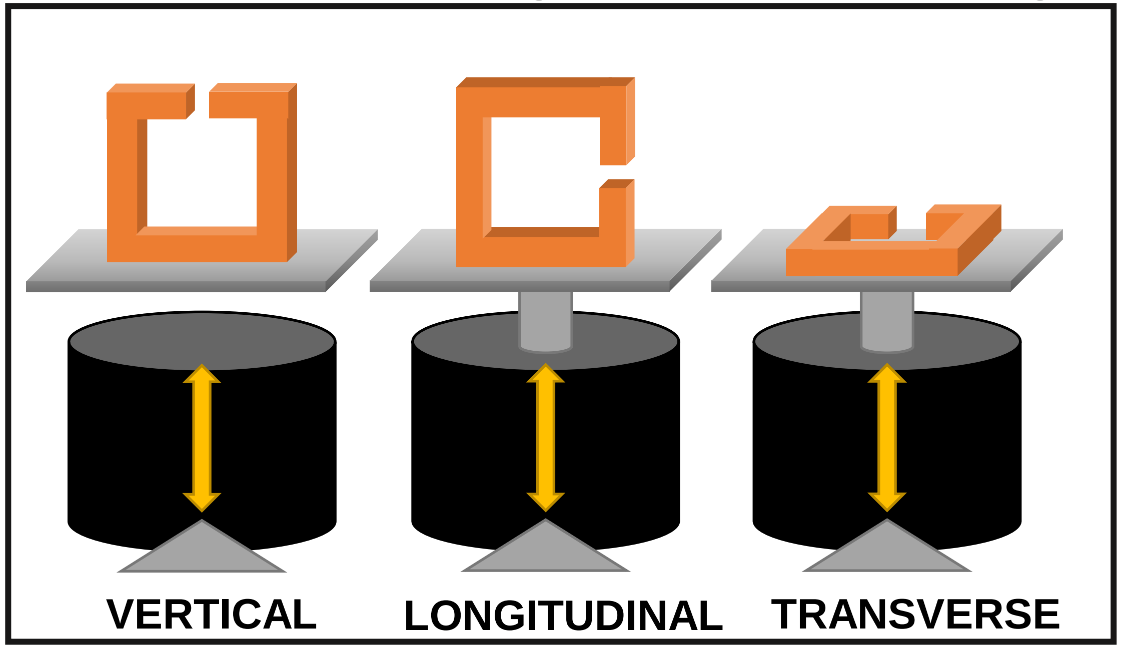
Multi-axis vibration tests are not yet standard practice.

Question:

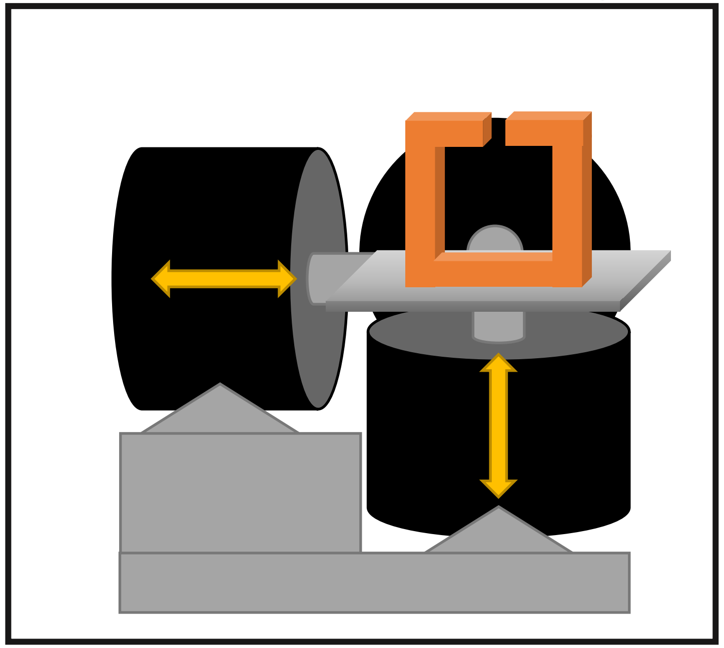
How good do multi-axis tests need to be to replace single-axis testing in practice?

Is the simplest possible multi-axis test close to single-axis testing in test quality?

Sequential Single-Axis Testing



Multi-Axis Testing



Problem:

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Question:

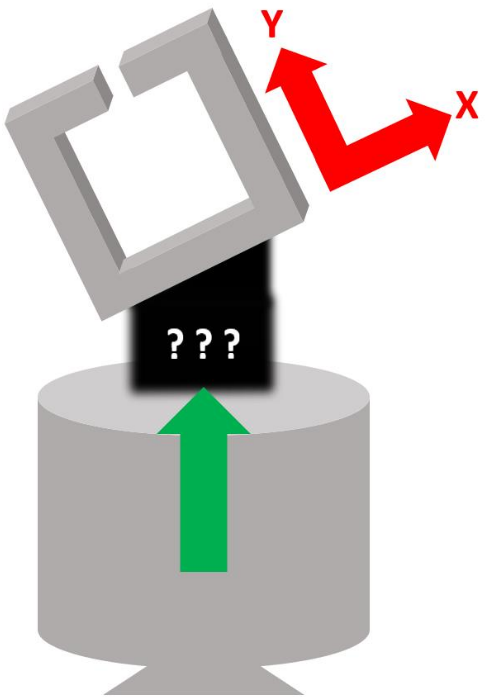
How good do multi-axis tests need to be to replace single-axis testing in practice?

Is the simplest possible multi-axis test close to single-axis testing in test quality?

Preliminary Study:

Can single-axis testing techniques provide a sufficient rapid approximation to a multi-axis test?

How much can we improve multi-axis test quality by optimizing passive test fixture hardware instead of adding active excitation sources?



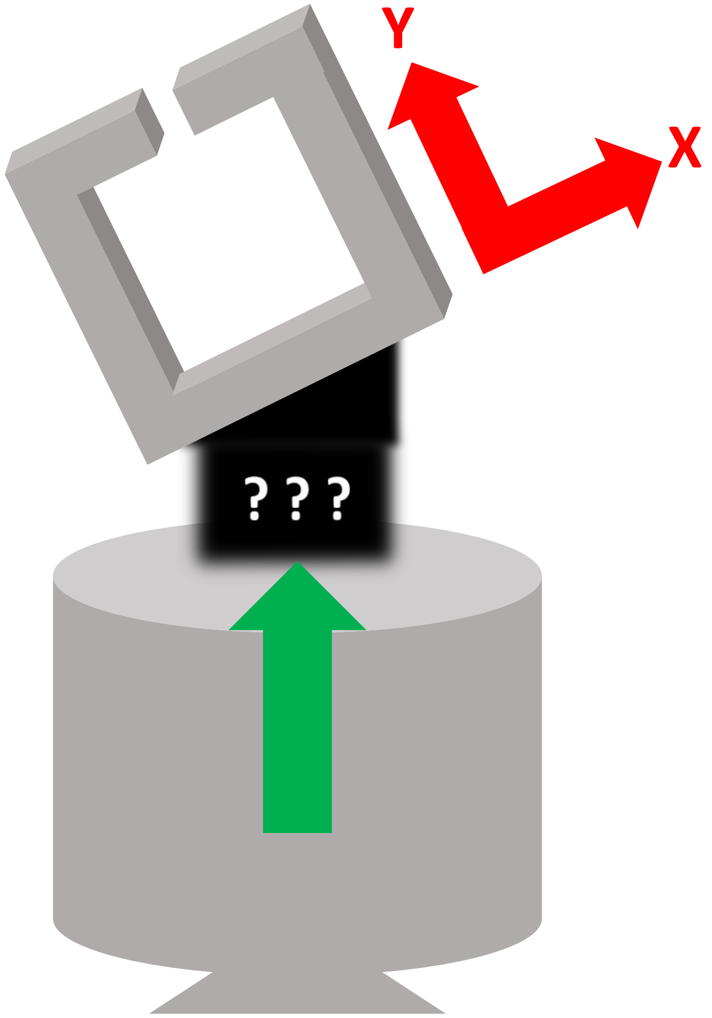
Approach

Three steps to approximate a multi-axis test:

1. Employ single-input, multiple output (SIMO) test strategy with outputs in multiple axes

2. Optimize excitation angle

3. Optimize test fixture design for each test environment



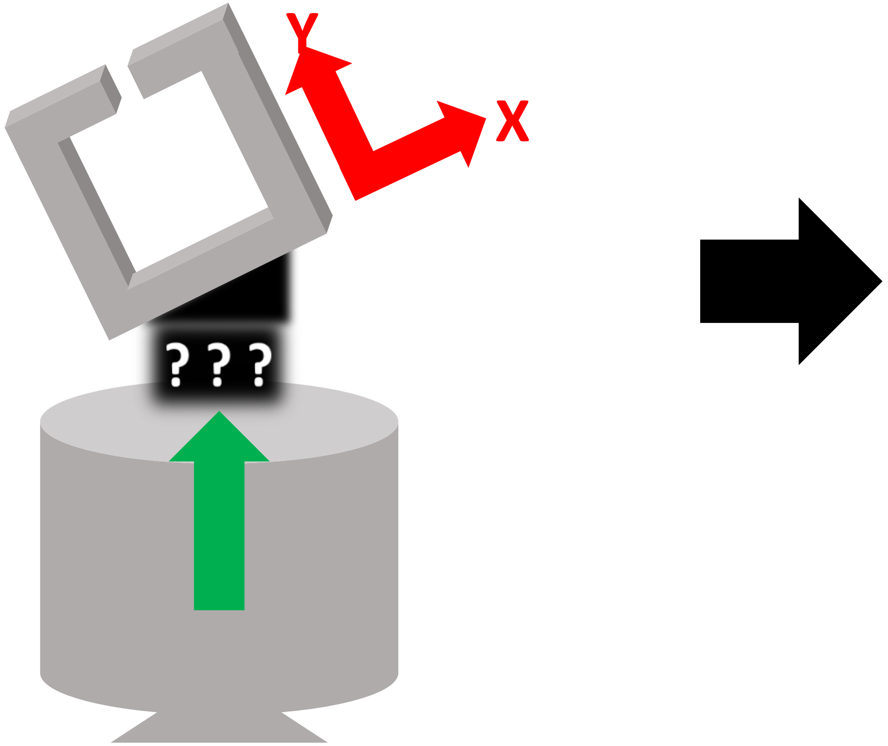
Objective

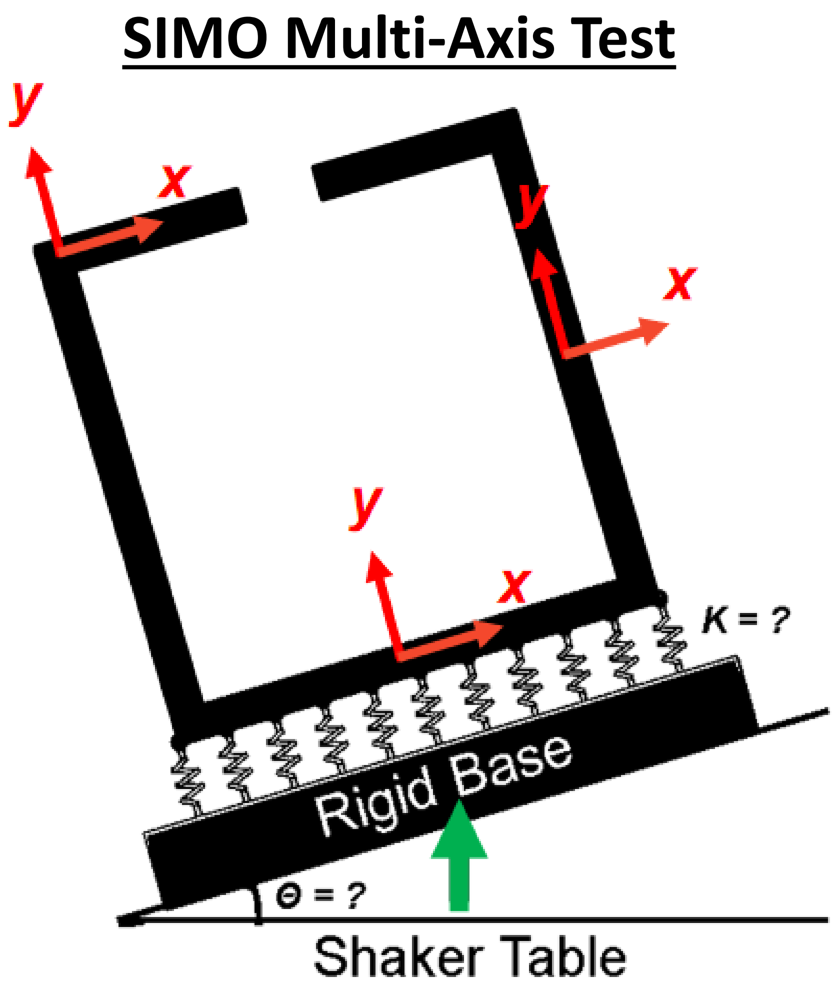
Assess viability of a rapid, approximate multi-axis vibration testing technique utilizing standard single-axis testing hardware.

- Rapid Test Setup and Execution
  - Single test event instead of three sequential single-axis test setups and executions
  - Much simpler compared to multi-excitation schemes and MIMO control strategies.
- Approximate
  - Error is expected as in all multiple-output vibration tests.
  - How much can error be mitigated through test fixture design?
  - What level of error is acceptable compared to traditional single-axis testing practice?
- Multi-Axis
  - All response directions are intentionally excited by a single source by optimally orienting excitation axis for each test environment.

Simulation Study

The proposed method was modeled for a 2D BARC base test article as shown.

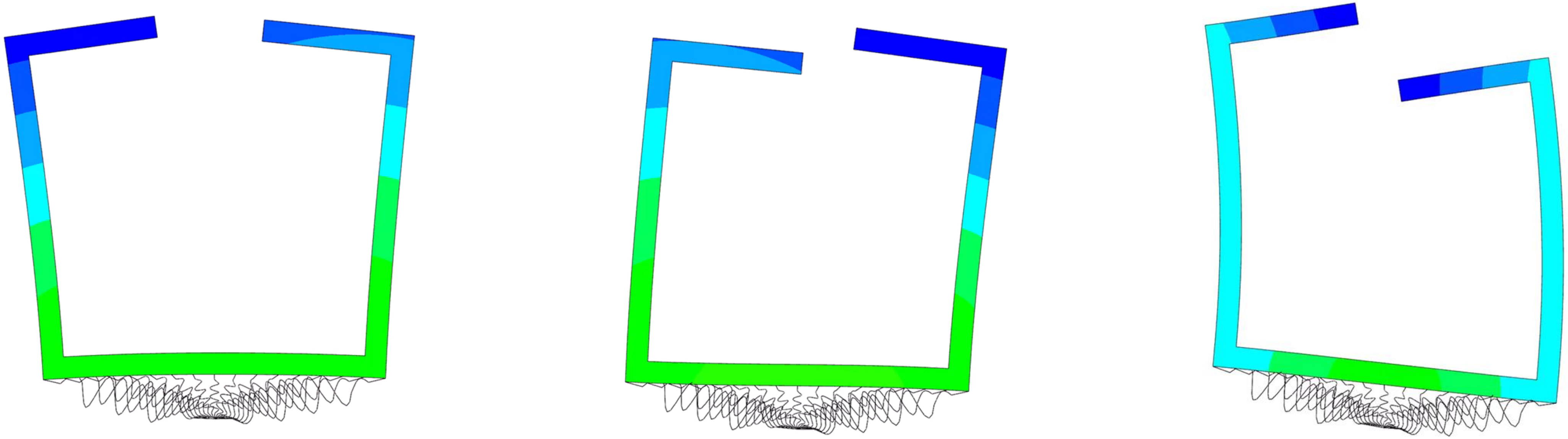




Simulation Study

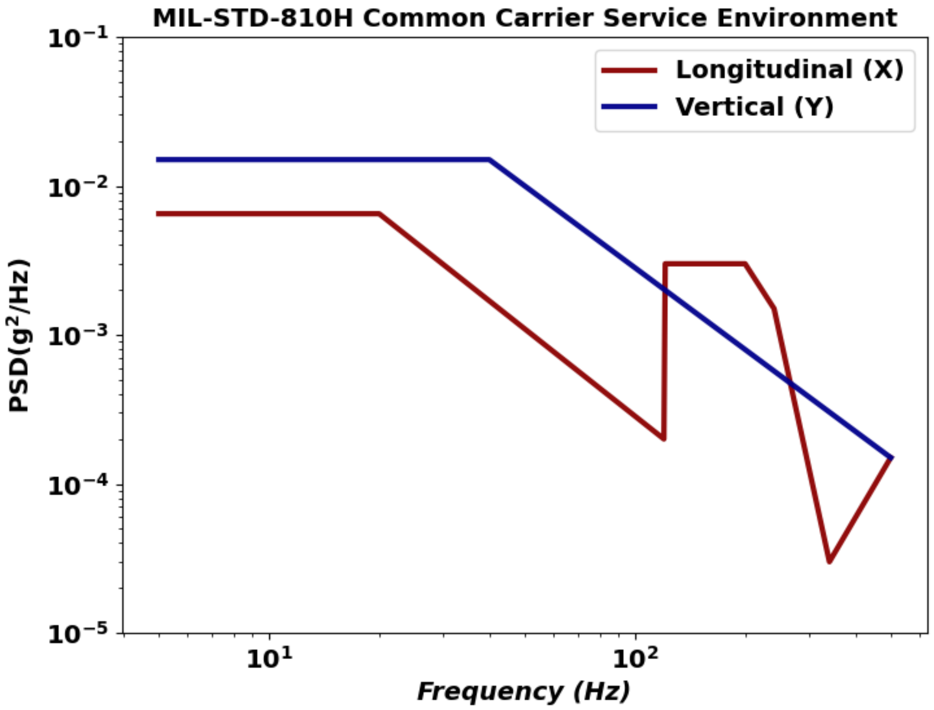
Simulations were carried out using an Abaqus FEA model consisting of:

1. 2-D BARC without the removable component
2. Test fixture, idealized by sixteen springs
3. Rigid base, representing a vertically-oriented, single-axis shaker



Service Environment

- A **service environment** is the real environment the test article is expected to experience in its lifetime defined as a set of target Power Spectral Densities (PSD) at one or more locations.



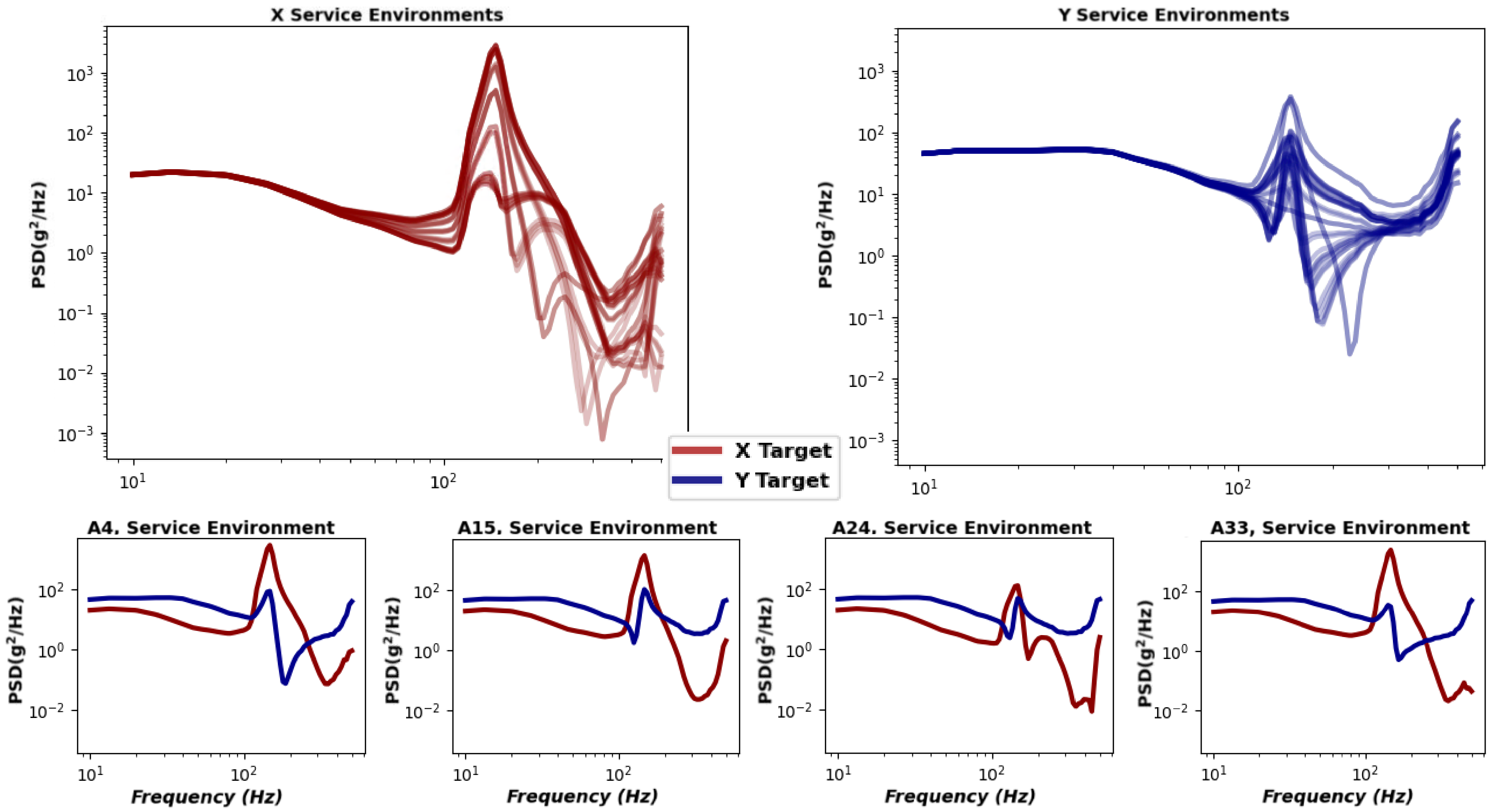
Defense Logistics Agency, 2019

- This a common transportation environment base excitation profile from MIL-STD-810H.

- Conducted MIMO simulation to generate a set of response targets from this base excitation…
  1. Apply X and Y excitations simultaneously to the base of the model.
  2. Measure acceleration responses on the BARC.

- Targets were generated using a flexible boundary condition (k_x and $k_y = 10^6\ N/m$).

Service Environment



Test Quality Metrics

RMS dB Error (RDBE):

RDBE is a scalar metric that represents the average mismatch between a response PSD and a target PSD across all frequencies.

$$RDBE = \sqrt{\frac{\sum_{i=1}^{n} (10 \log_{10} \frac{\hat{y}_i}{y_i})^2}{n}}$$

Percentage of Frequency Lines within a 3 dB Tolerance (FTOL):

FTOL is a scalar metric that counts the percentage of frequency lines where the response PSD differs from the target PSD by less than 3 dB.

$$\%\, FL = 100 * \frac{1}{n} \sum_{i=1}^{n} \begin{cases} 1 \; if \; \left| 10 \log_{10} \frac{\hat{y}_i}{y_i} \right| \leq 3 \; dB \\ 0 \; if \; \left| 10 \log_{10} \frac{\hat{y}_i}{y_i} \right| > 3 \; dB \end{cases}$$

In both equations, $\hat{y}_i$ is the value of a response PSD at the i^{th} frequency line, and y_i is the value of the target PSD at the i^{th} frequency line. There are n total frequency lines.

Test Control Simulation

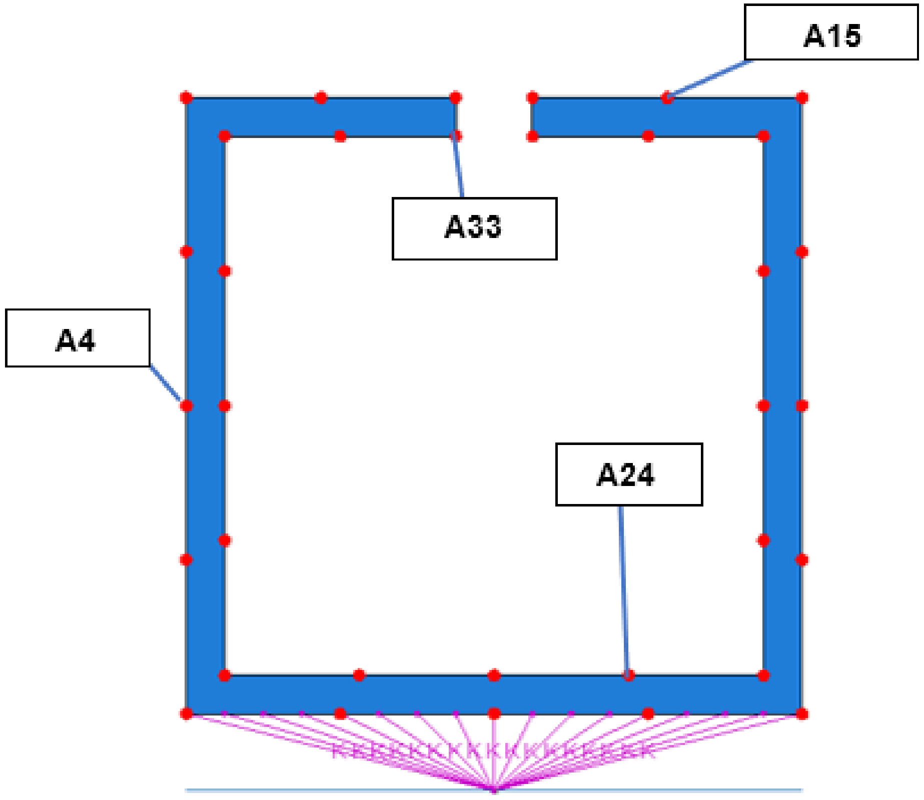
- The locations where measured response is used to derive and control the shaker input PSD are **control locations**.

- The shaker input PSD was derived to achieve the lowest possible RDBE between a target response and measured response at selected control locations.

- **Single Control Location**
  - Common test practice
  - Successfully achieves target response at one location

- **All Control Locations**
  - Better overall test
  - Uncommon in practice due to specification and control software limits

Measurement Locations



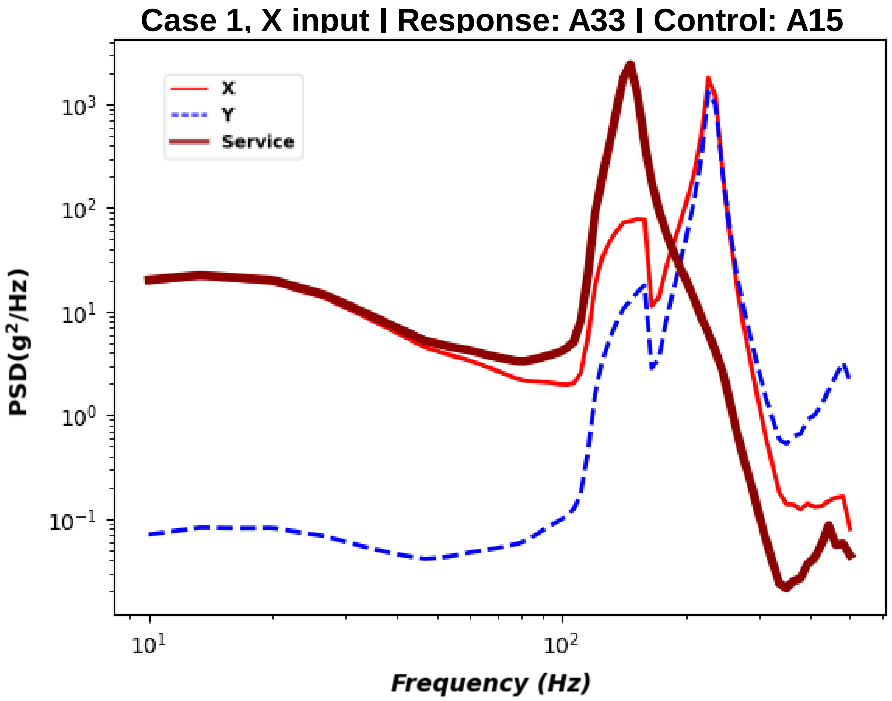
Test Control Simulation

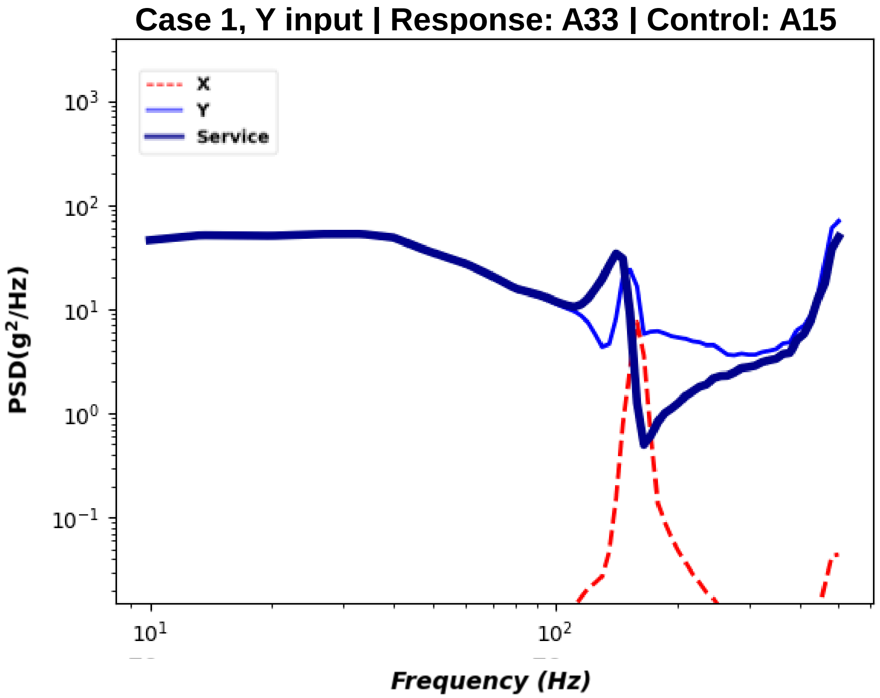
- For single control location sequential tests, choosing the best location improves the RDBE by 2.2 dB and the FTOL by 3.9% over the worst location.
- In all cases, errors are presented as an average across all response locations.

Sequential Single-Axis (Worst performing control location)				**Sequential Single-Axis** (Best performing control location)			
	X-Error (avg)	Y-Error (avg)	**Mean Error**		X-Error (avg)	Y-Error (avg)	**Mean Error**
RDBE	9.9 dB	3.2 dB	**6.6 dB**	**RDBE**	5.6 dB	3.2 dB	**4.4 dB**
FTOL	64.6%	83.9%	**74.3%**	**FTOL**	71.6%	84.7%	**78.2%**

Test Control Simulation

With single point control, responses at non-control DOF may be highly undesirable.





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Test Control Simulation

When the test is controlled to all locations, the RDBE decreases to **3.8 dB**.

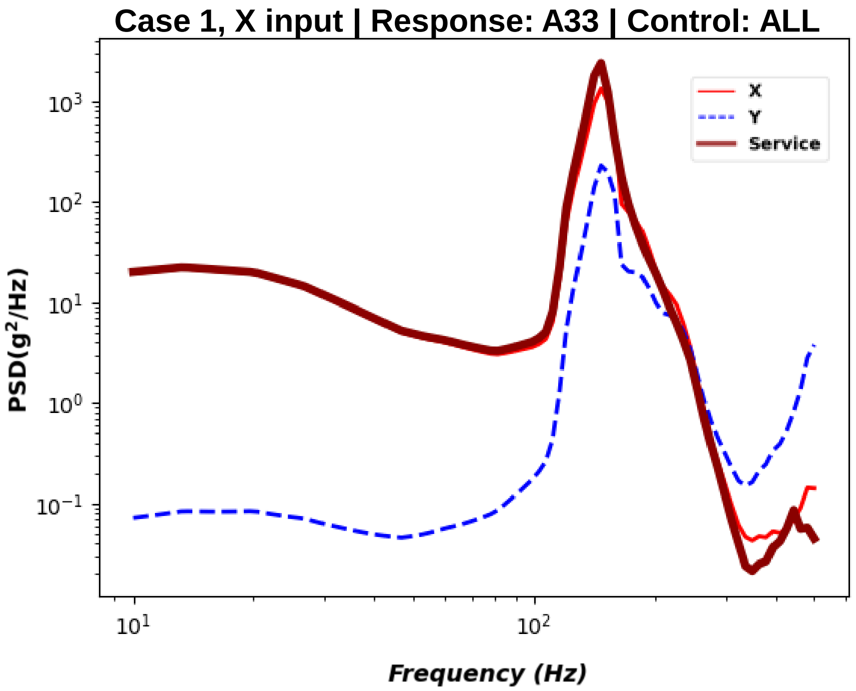
Sequential Single-Axis (All control locations)			
	X-Error (avg)	Y-Error (avg)	**Mean Error**
RDBE	5.1 dB	2.6 dB	**3.8 dB**
FTOL	70.3%	85.2%	**77.8%**

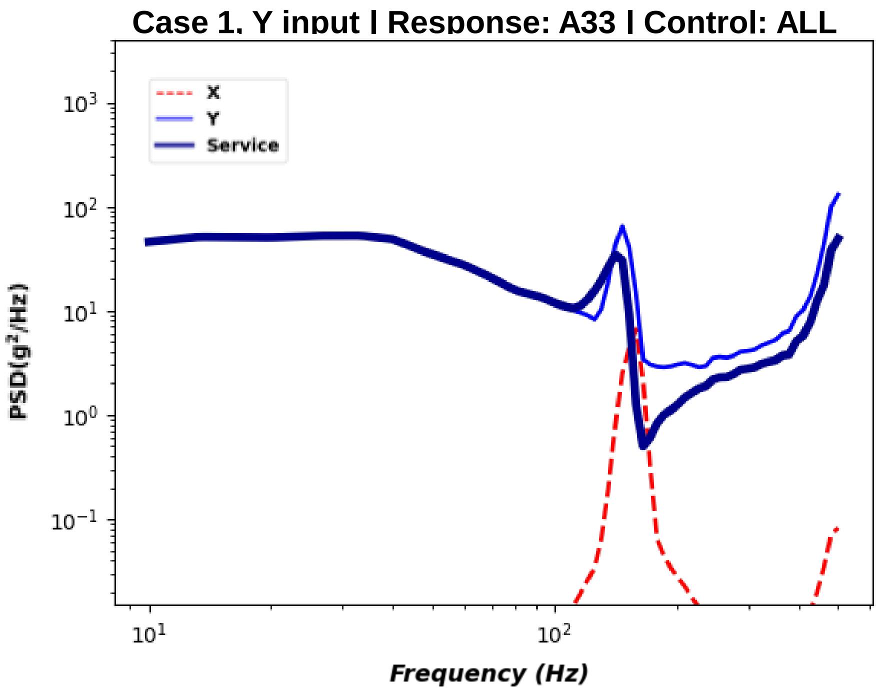
Sequential Single-Axis (Worst performing control location)			
	X-Error (avg)	Y-Error (avg)	**Mean Error**
RDBE	9.9 dB	3.2 dB	**6.6 dB**
FTOL	64.6%	83.9%	**74.3%**

Sequential Single-Axis (Best performing control location)			
	X-Error (avg)	Y-Error (avg)	**Mean Error**
RDBE	5.6 dB	3.2 dB	**4.4 dB**
FTOL	71.6%	84.7%	**78.2%**

Test Control Simulation

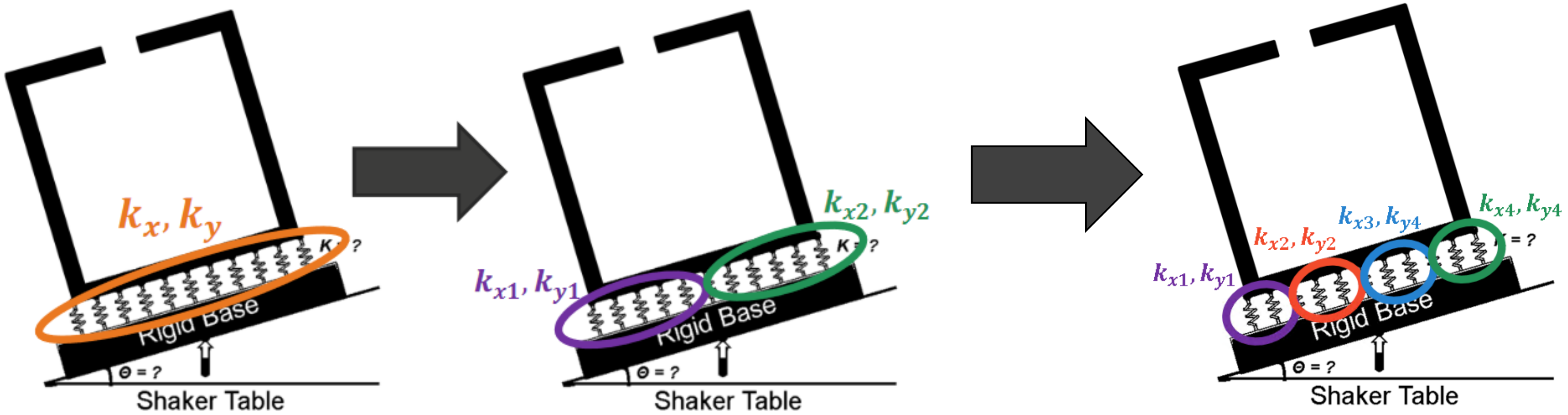
The all control location strategy is used throughout the study to eliminate control location effects.





Case Studies

Case	Test Fixture Design	Optimization Parameters	
		Sequential Single-Axis	SIMO Multi-Axis
1	Rigid	-	θ
2	Optimized (2 parameters)	k_x, k_y	k_x, k_y, θ
3	Optimized (4 parameters)	$k_{x1}, k_{x2}, k_{y1}, k_{y2}$	$k_{x1}, k_{x2}, k_{y1}, k_{y2}, \theta$
4	Optimized (8 parameters)	$k_{x1}, k_{x2}, k_{x3}, k_{x4},$ $k_{y1}, k_{y2}, k_{y3}, k_{y4}$	$k_{x1}, k_{x2}, k_{x3}, k_{x4}$ $k_{y1}, k_{y2}, k_{y3}, k_{y4}, \theta$

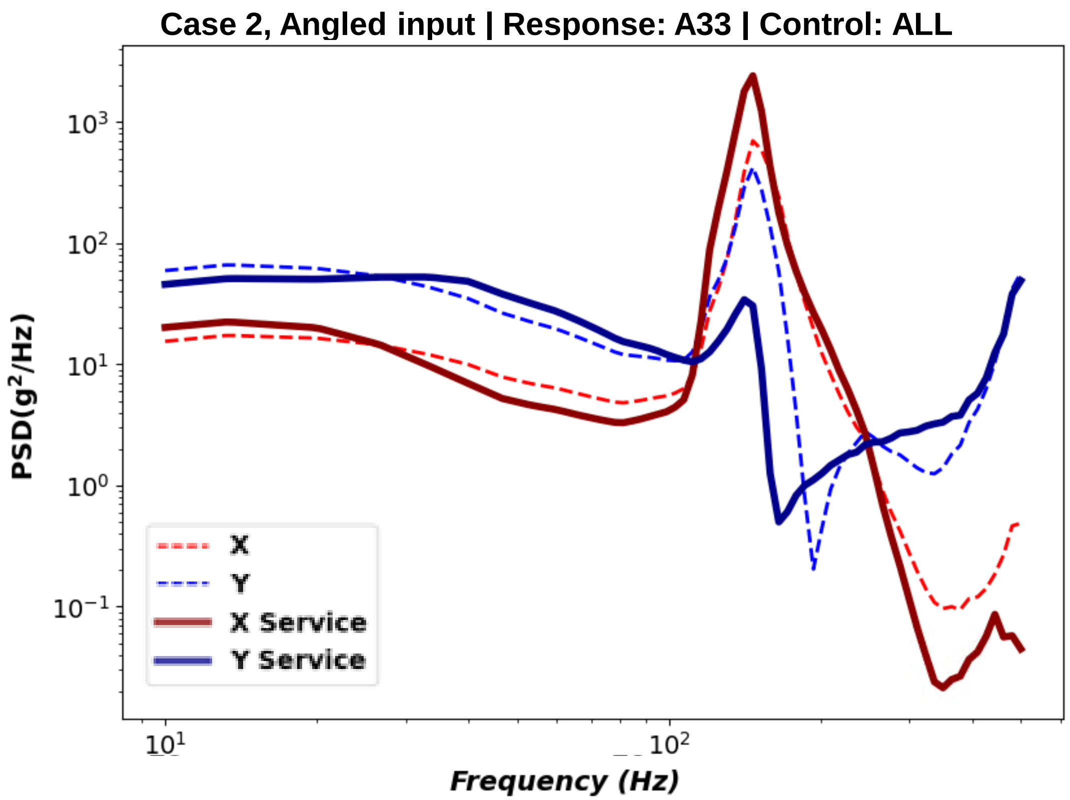


Case Study 1 (rigid)

- The SIMO multi-axis test's **RDBE increases by 1.0 dB** while the **FTOL falls by 3.8%**.

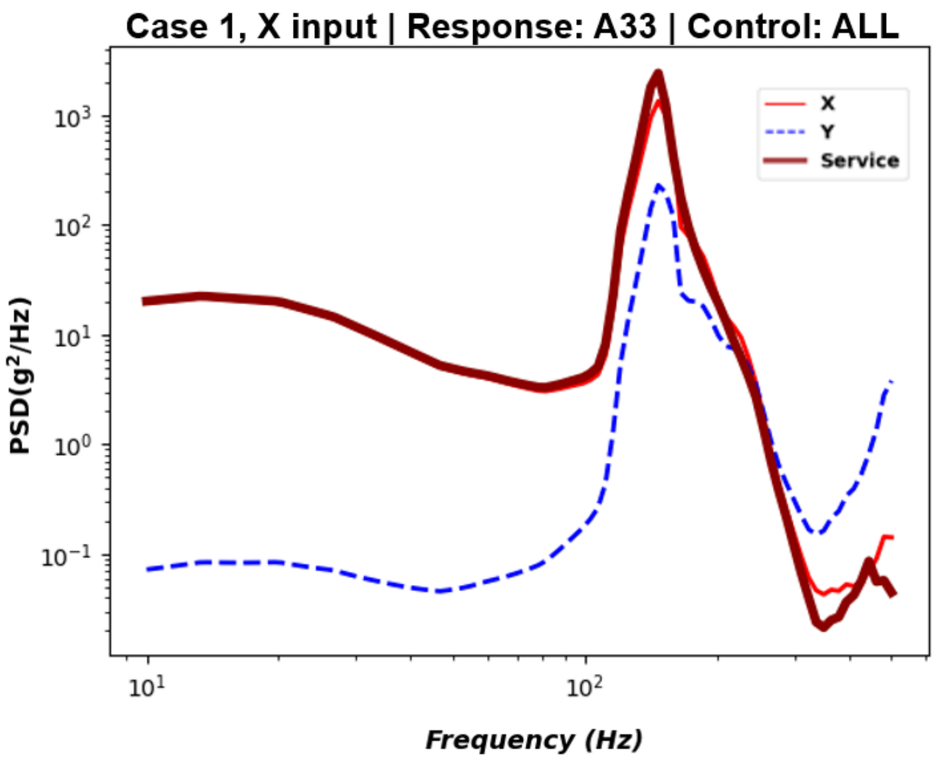
Sequential Single-Axis (All control locations)				**SIMO Multi-Axis** (All control locations)			
	X-Error (avg)	Y-Error (avg)	**Mean Error**		X-Error (avg)	Y-Error (avg)	**Mean Error**
RDBE	5.1 dB	2.6 dB	**3.8 dB**	**RDBE**	5.7 dB	3.9 dB	**4.8 dB**
FTOL	70.3%	85.2%	**77.8%**	**FTOL**	69.2%	78.7%	**74.0%**

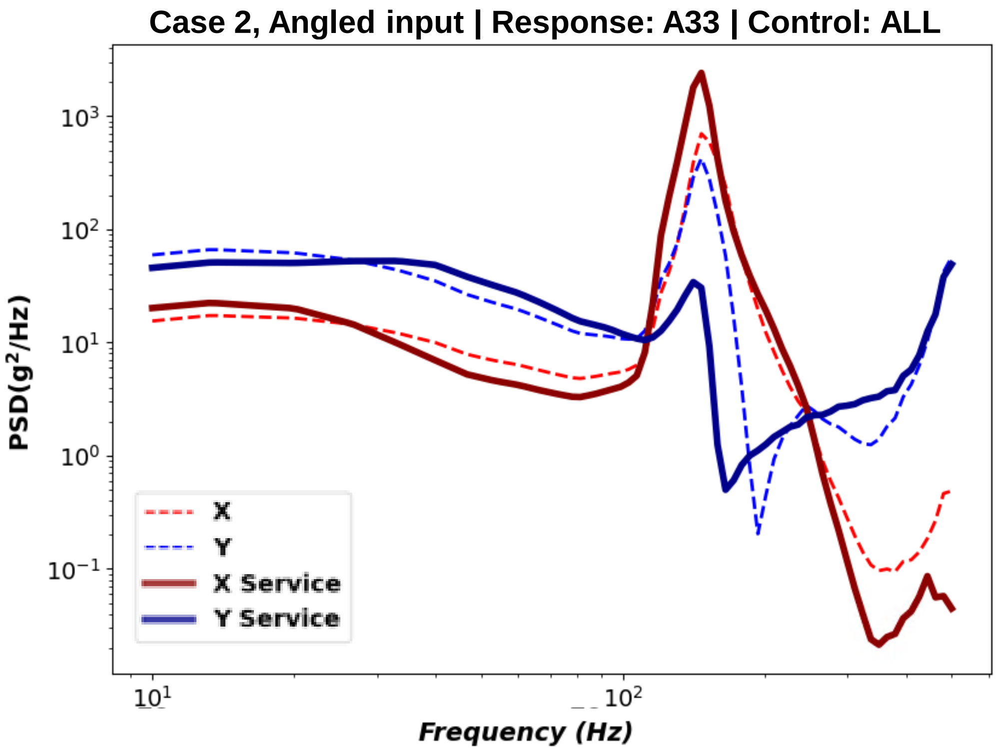
Case Study 1 (rigid)



Case Study 1 (rigid)

Sequential X-Axis Test (All control locations)	SIMO Multi-Axis Test (All control locations)





Is a 1.0 dB (26%) increase in error acceptable for the SIMO multi-axis test to eliminate unavoidable cross-axis responses in the sequential test?
Can we do better with an optimized test fixture?

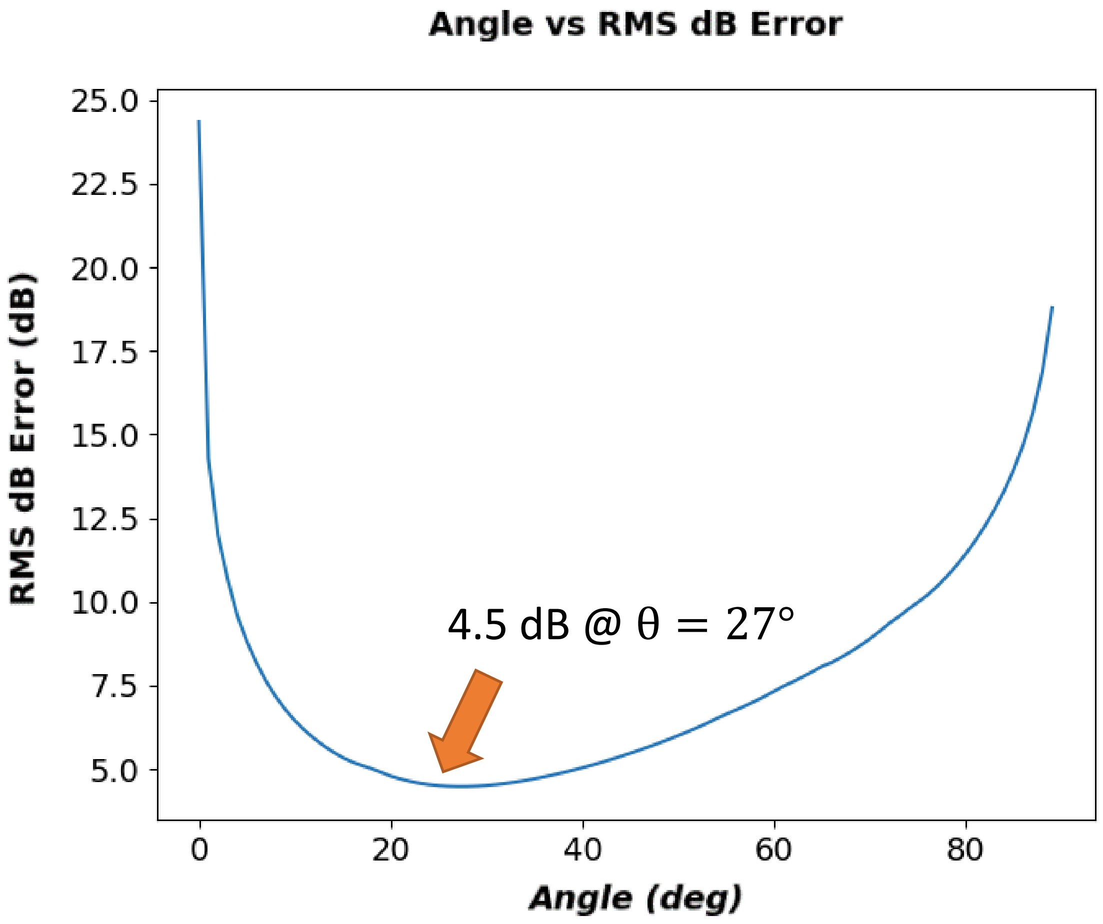
Case Study 2 (2 parameters)

Optimizing the test fixture stiffness with two parameters:

1. Improved the sequential test by 0.1 dB and 2.2%.
2. Improved the SIMO test by 0.3 dB and 1.6%.

	Mean Error	
	Sequential Single-Axis	**SIMO Multi-Axis**
RDBE	3.7 dB	4.5 dB
FTOL	80.0%	75.6%

Case Study 2 (2 parameters)

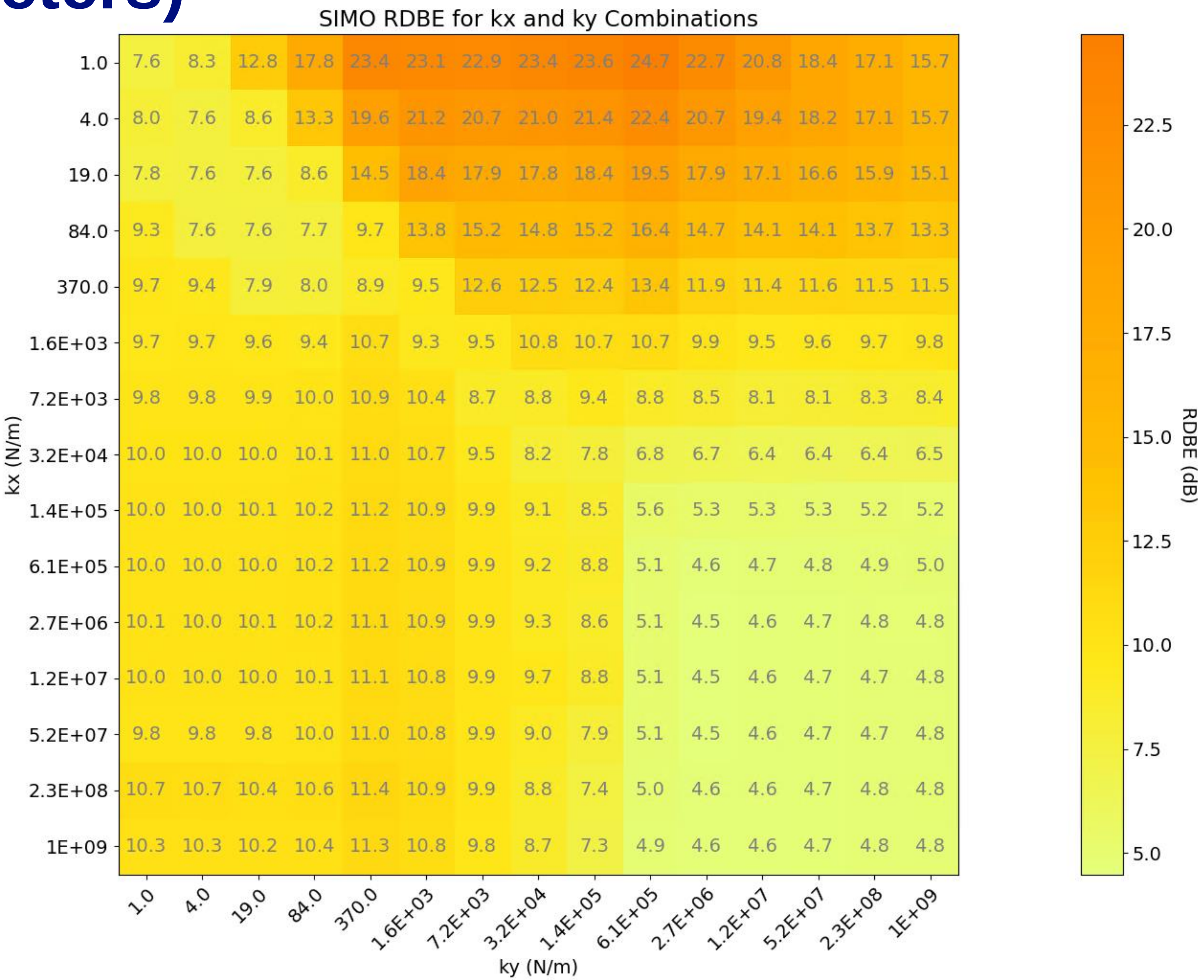


- The SIMO test's angle optimization has a clear minimum.

Case Study 2 (2 parameters)

- The SIMO solution space was smooth with a clear minimum region.

- The minimum region provides good values to start a local optimization.



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Case Study 2 (2 parameters)

- The SIMO solution space was smooth with a clear minimum region.

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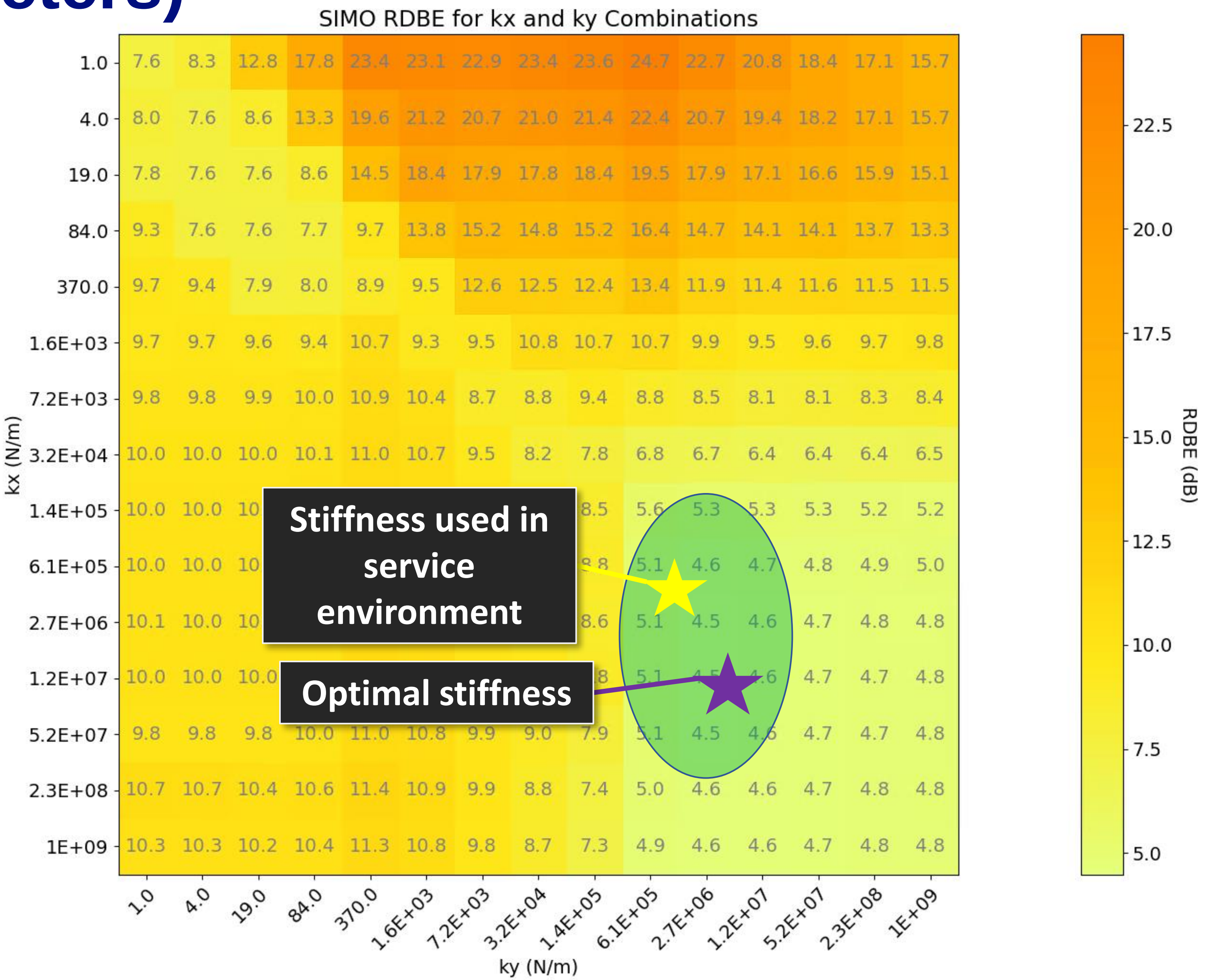
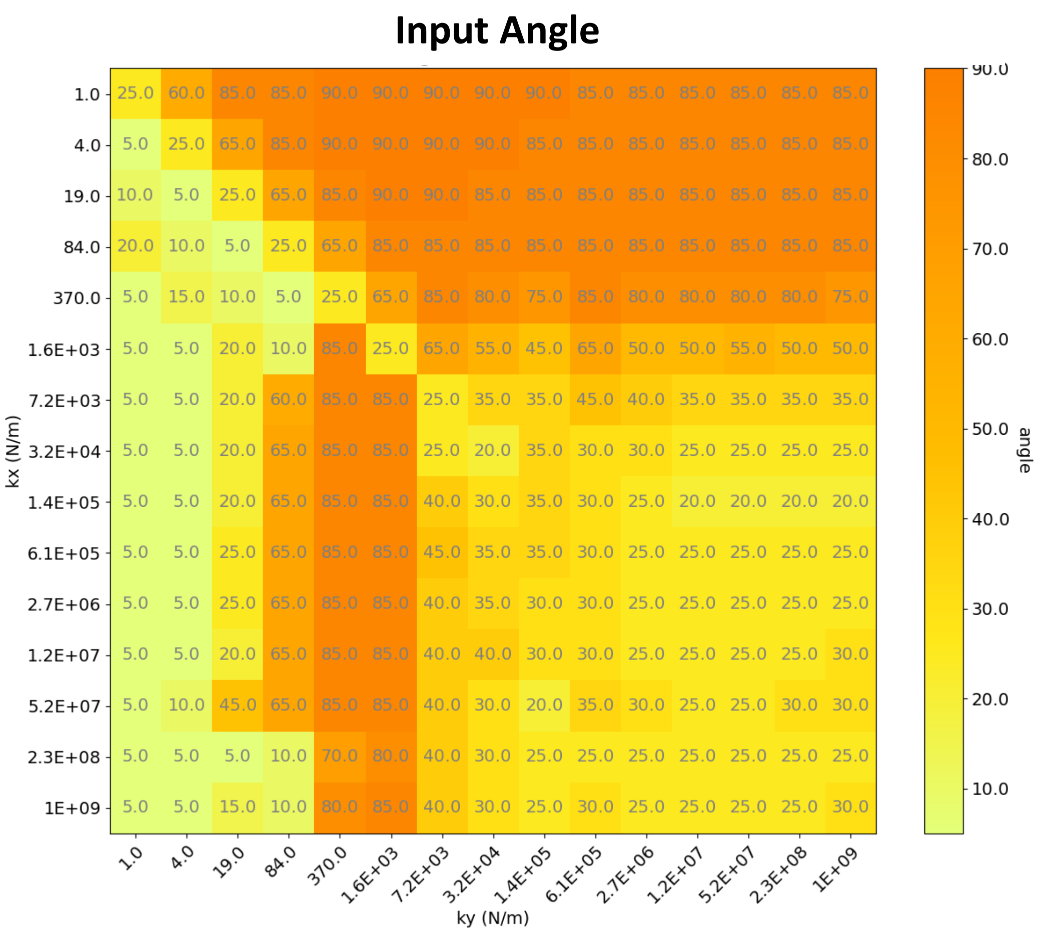
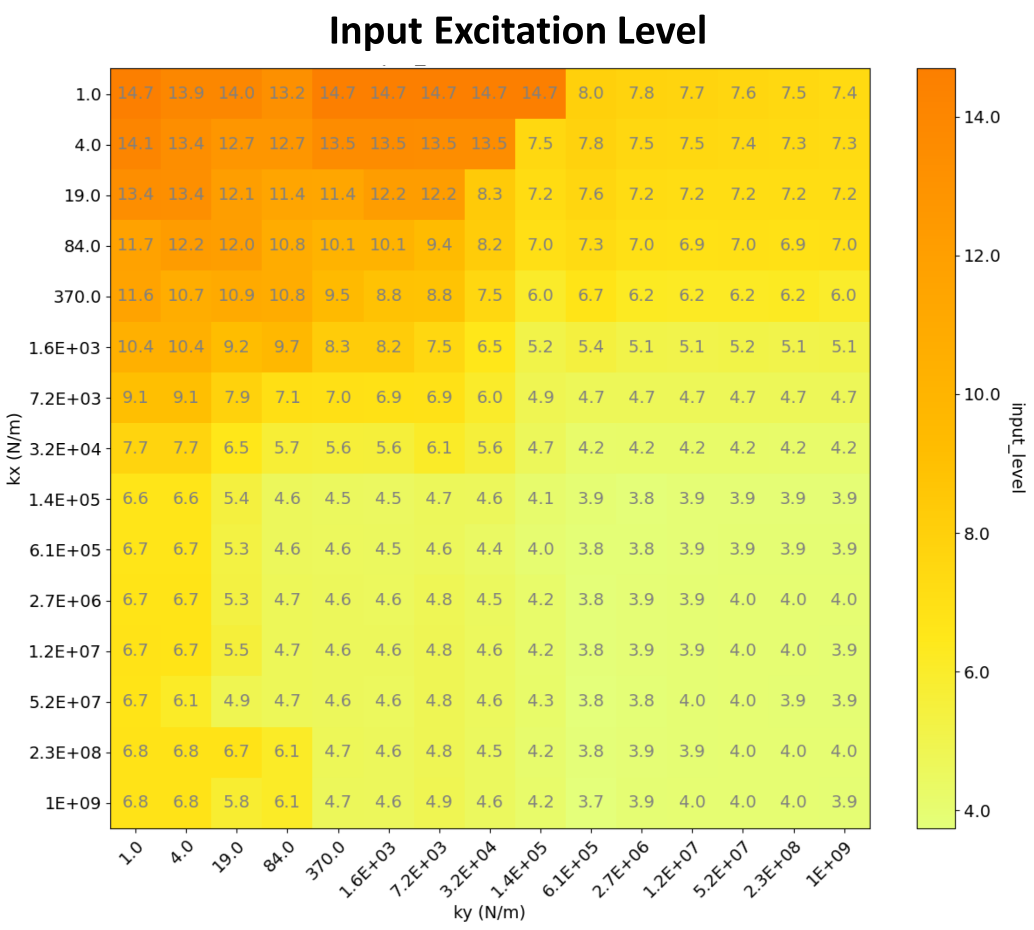
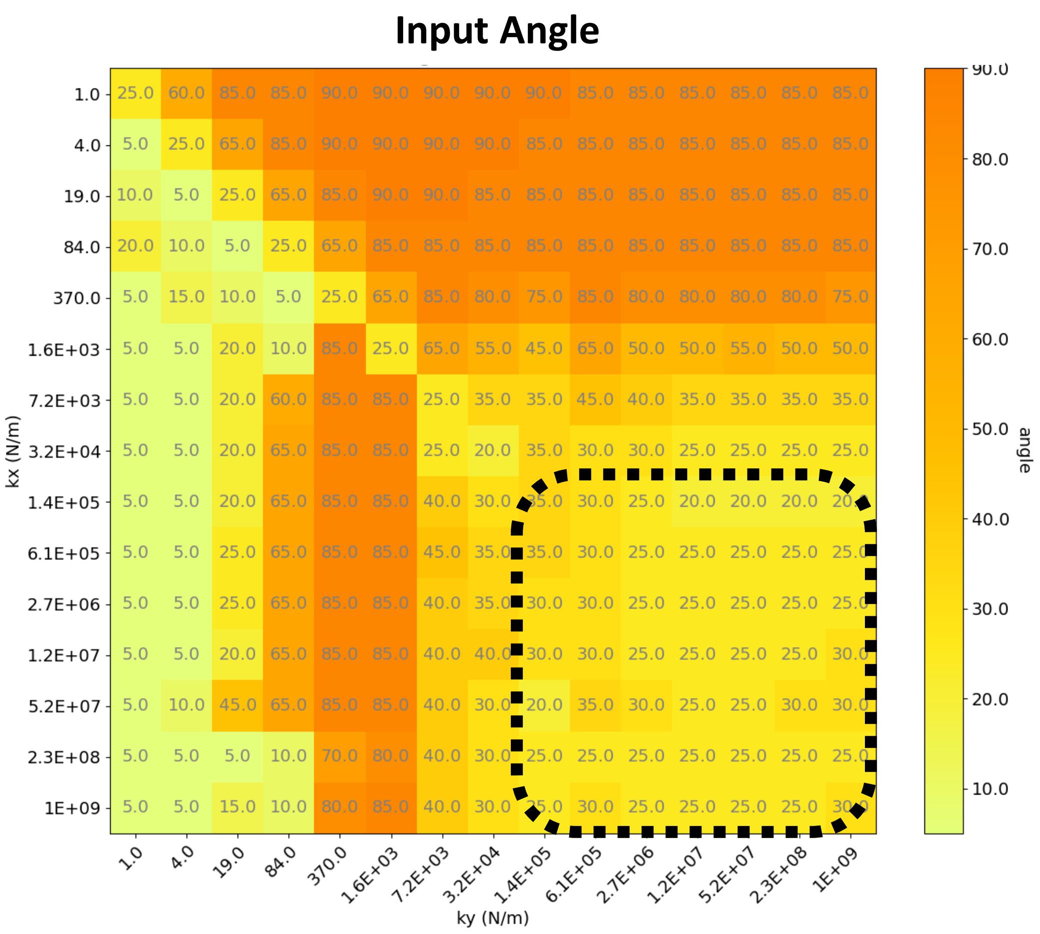


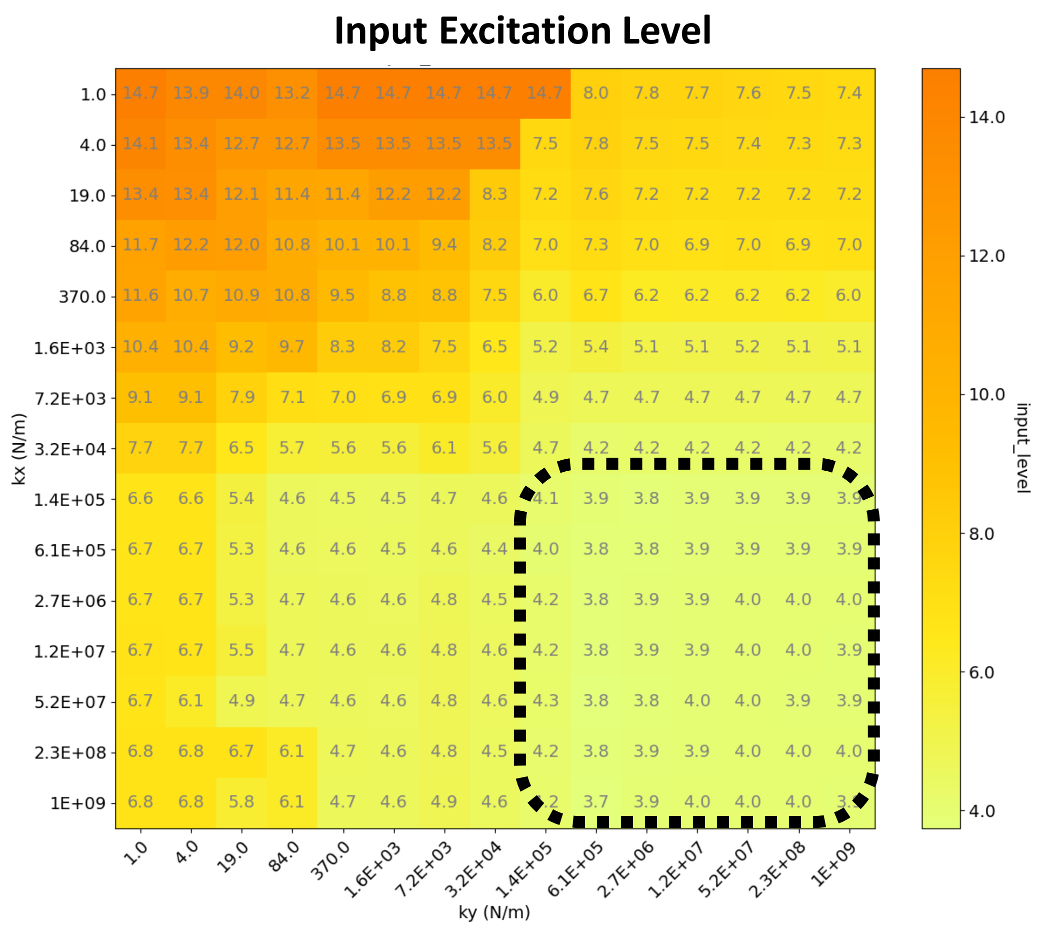
Case Study 2 Input Angle & Excitation Level





Case Study 2 Input Angle & Excitation Level

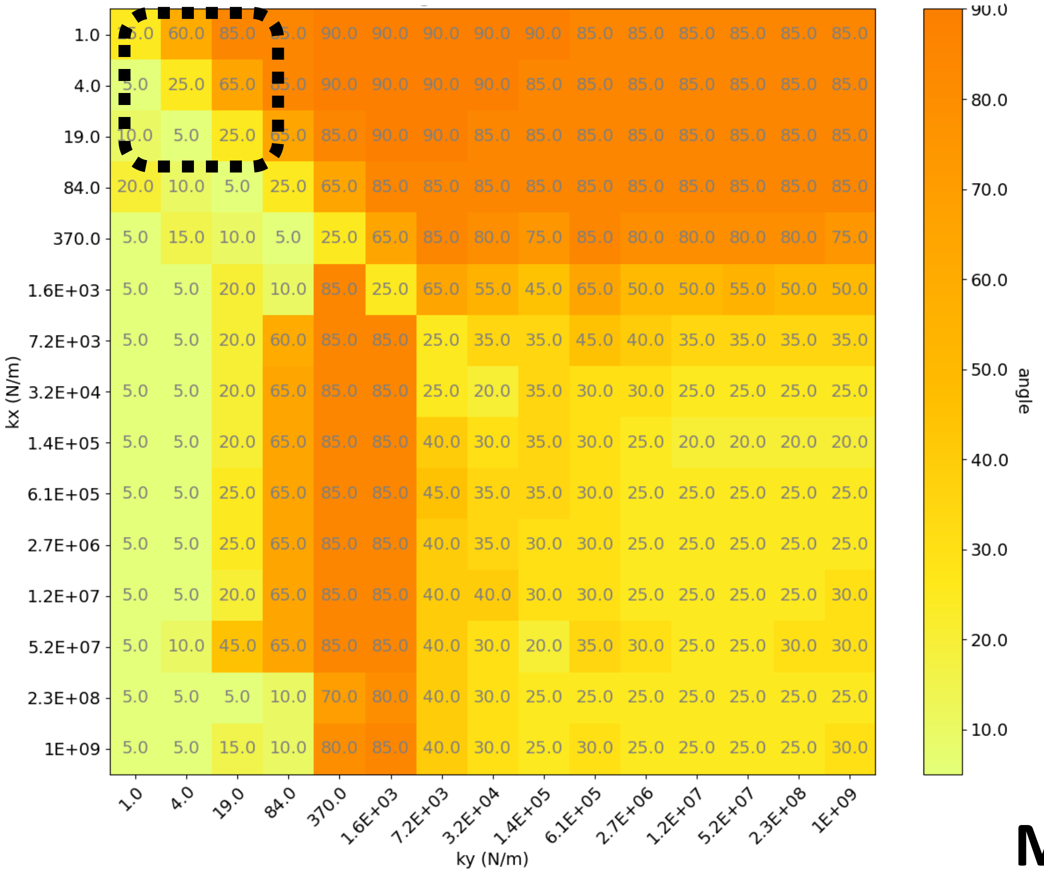




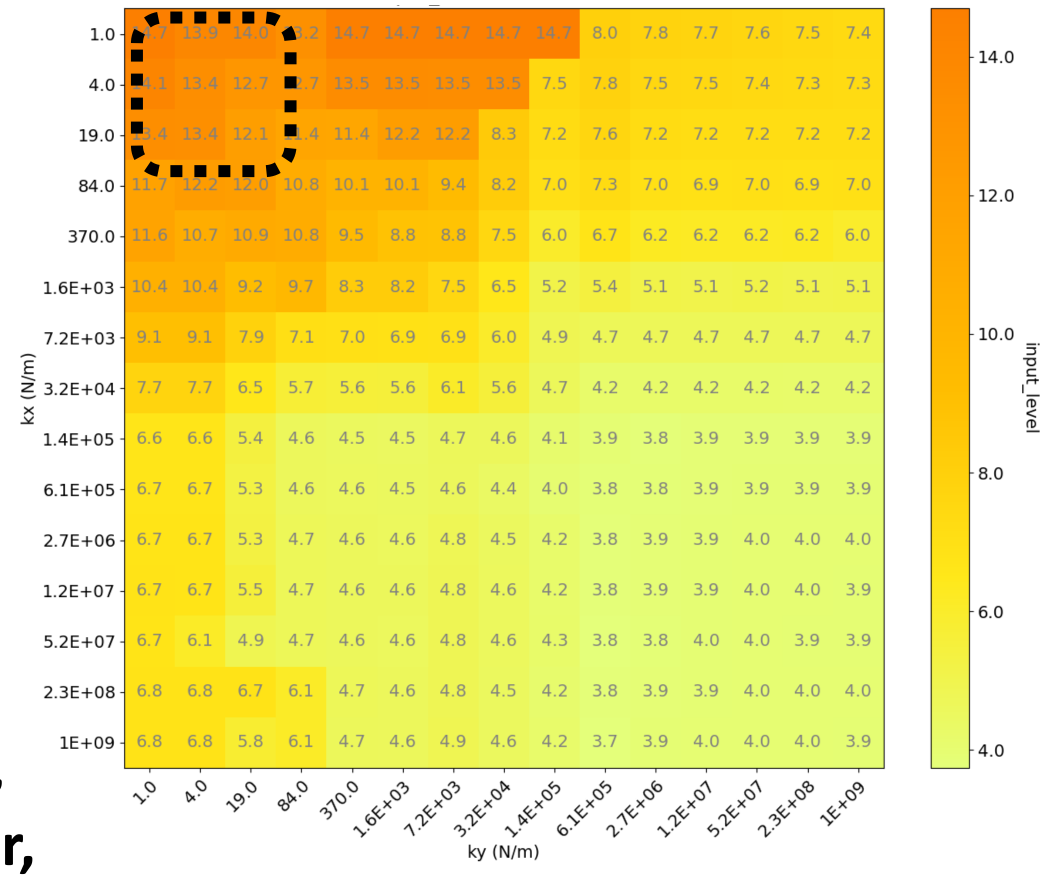
Stiff Fixture,
Low Error,
25-30 Degree Angle,
Small Excitation

Case Study 2 Input Angle & Excitation Level

Input Angle



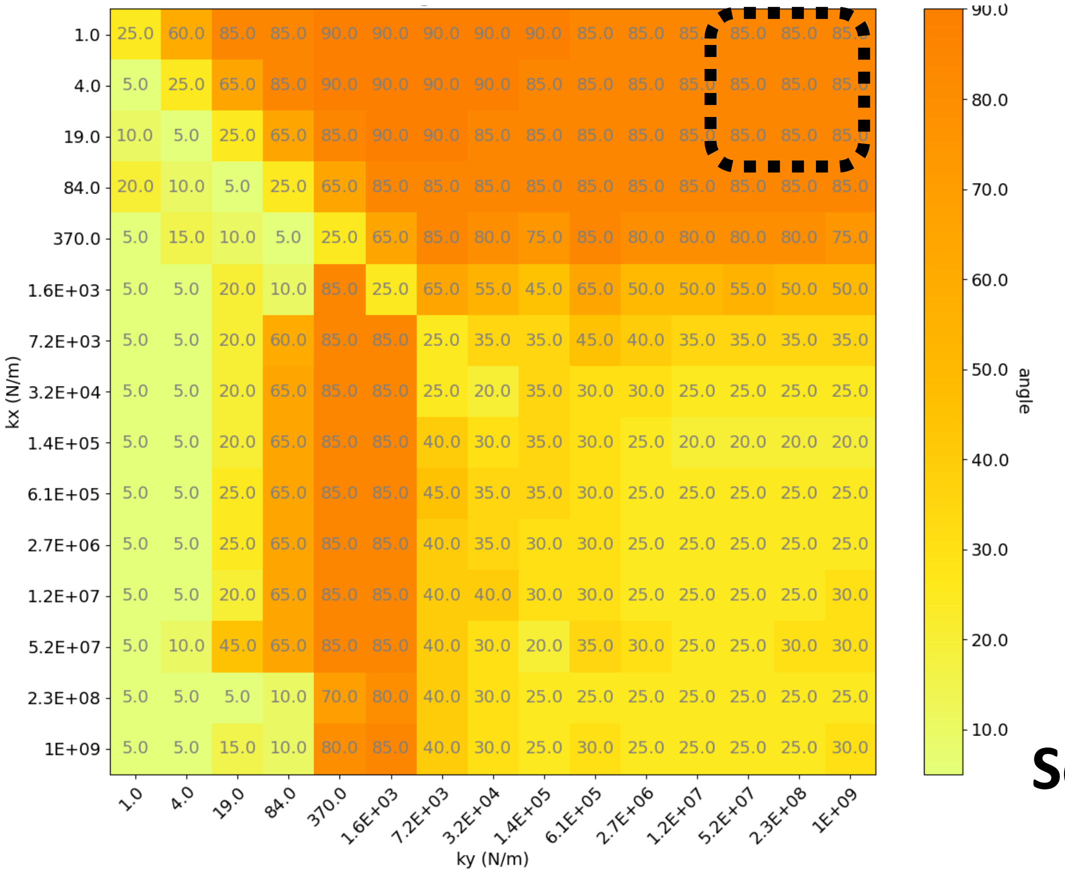
Input Excitation Level



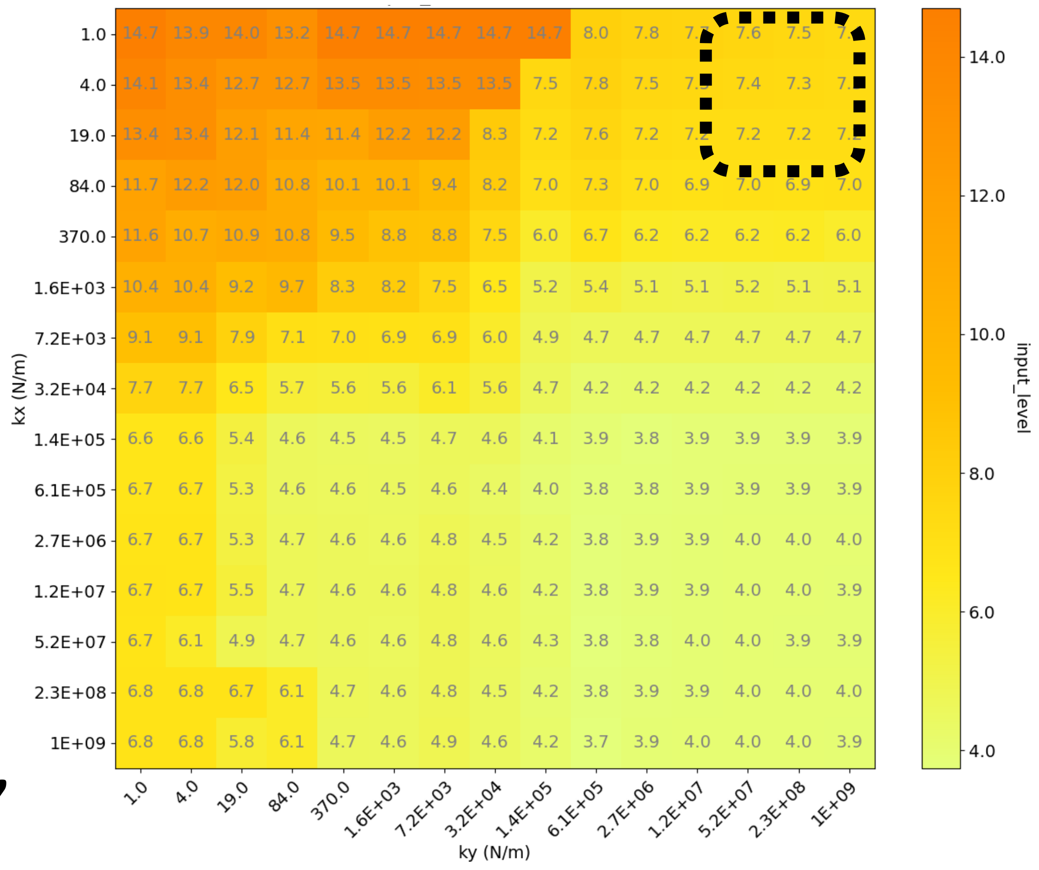
Soft Fixture, Medium Error, Variable Angle, Very Large Excitation

Case Study 2 Input Angle & Excitation Level

Input Angle



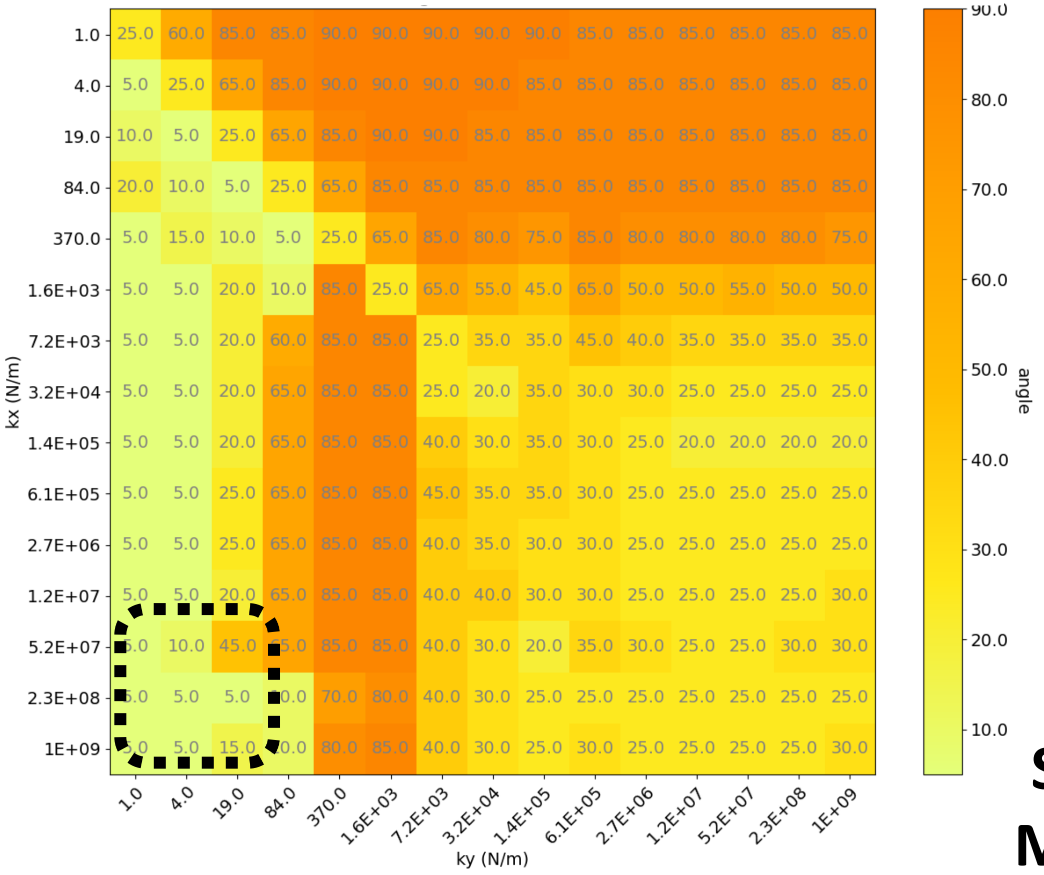
Input Excitation Level



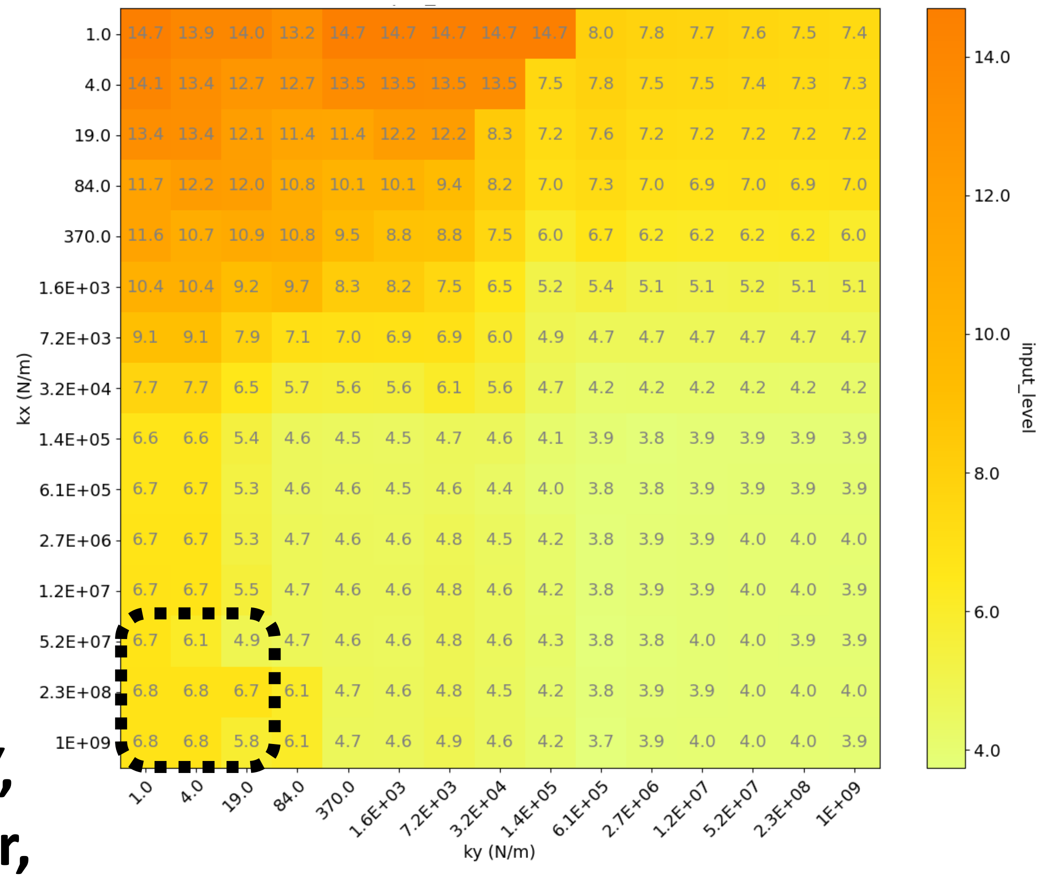
Soft X/Stiff Y,
High Error,
X-Axis Excitation Angle,
Medium Level Excitation

Case Study 2 Input Angle & Excitation Level

Input Angle



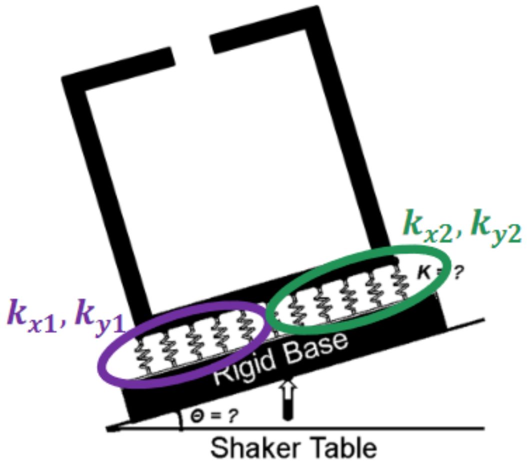
Input Excitation Level



Stiff X/Soft Y,
Medium Error,
Y-Axis Excitation Angle,
Medium Level Excitation

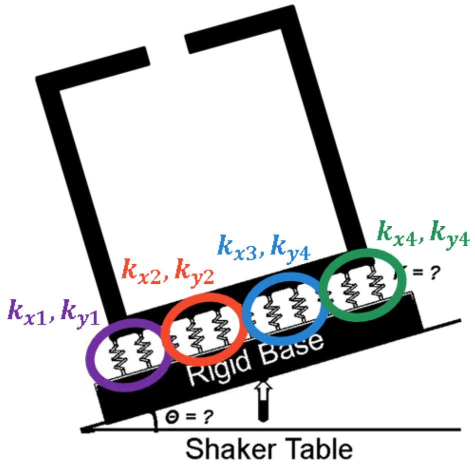
Case Study 3 (4 parameters)

	Mean Error	
	Sequential Single-Axis	SIMO Multi-Axis
RDBE	3.7 dB	4.5 dB
FTOL	80.0%	75.6%

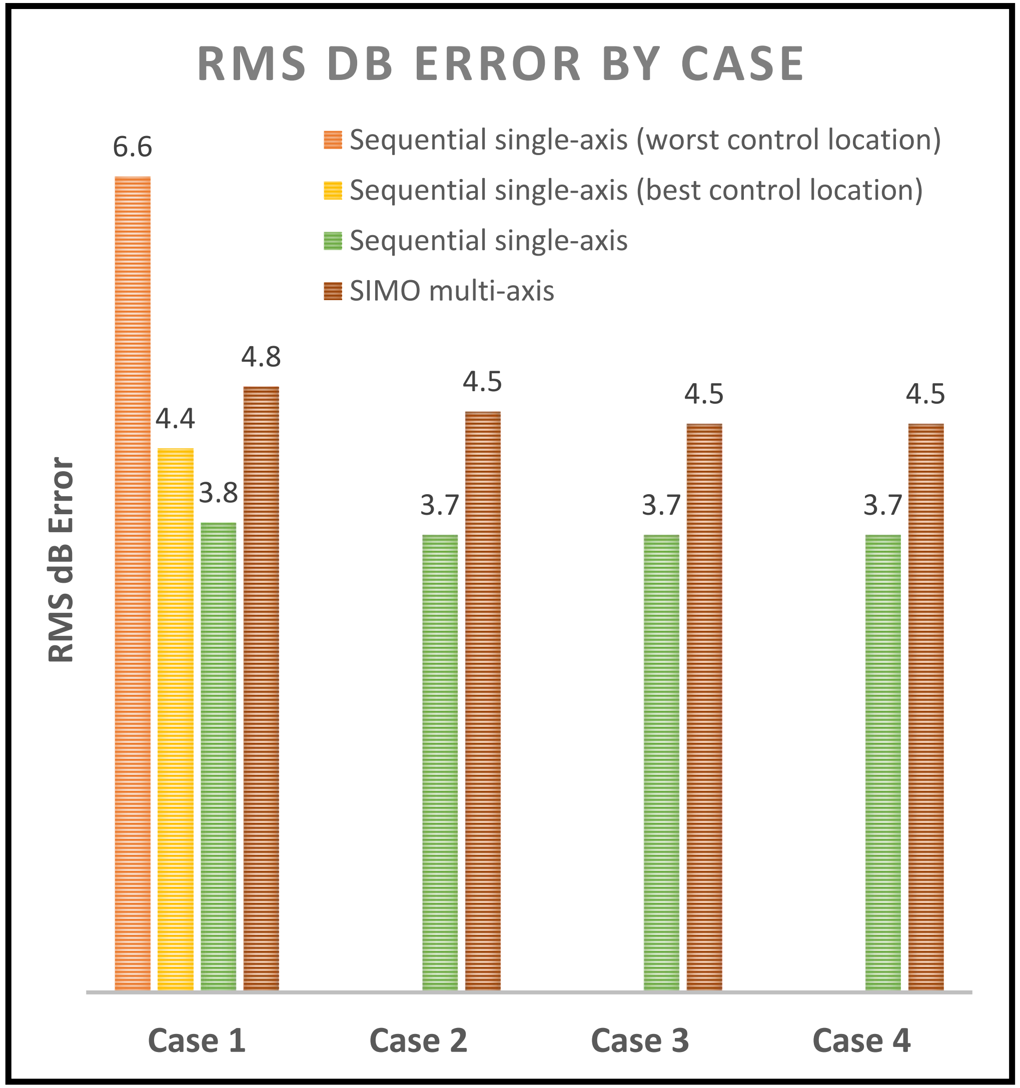


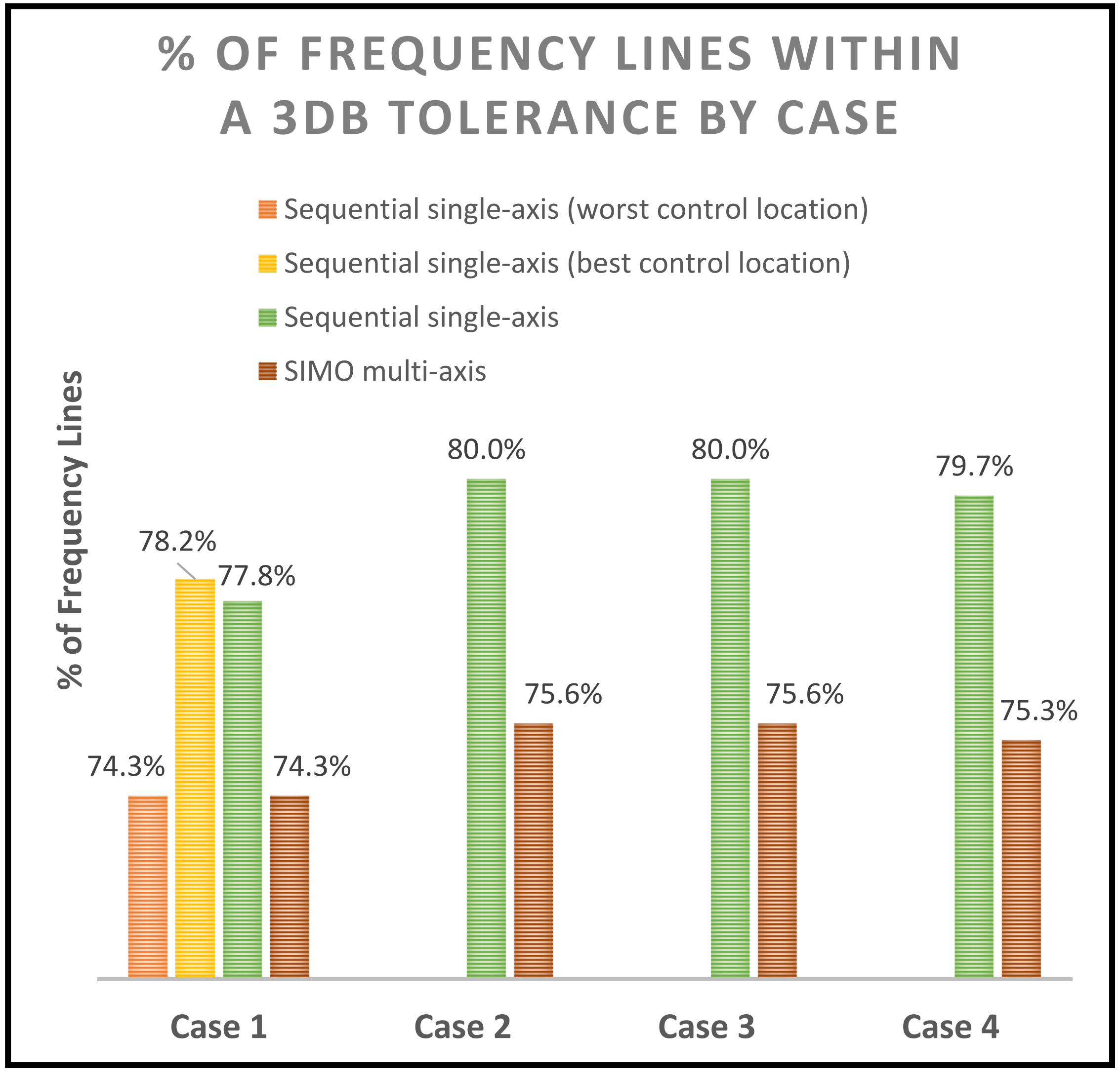
Case Study 4 (8 parameters)

	Mean Error	
	Sequential Single-Axis	SIMO Multi-Axis
RDBE	3.7 dB	4.5 dB
FTOL	79.6%	75.3%



Result Summary





Further Studies

The initial case studies showed the proposed method approximated a multi-axis test with on-axis errors only slightly worse than best-case sequential single-axis testing.

→ Would this result hold for different target test environments?

→ Repeated the study for a large population of target test environments to evaluate more general case.

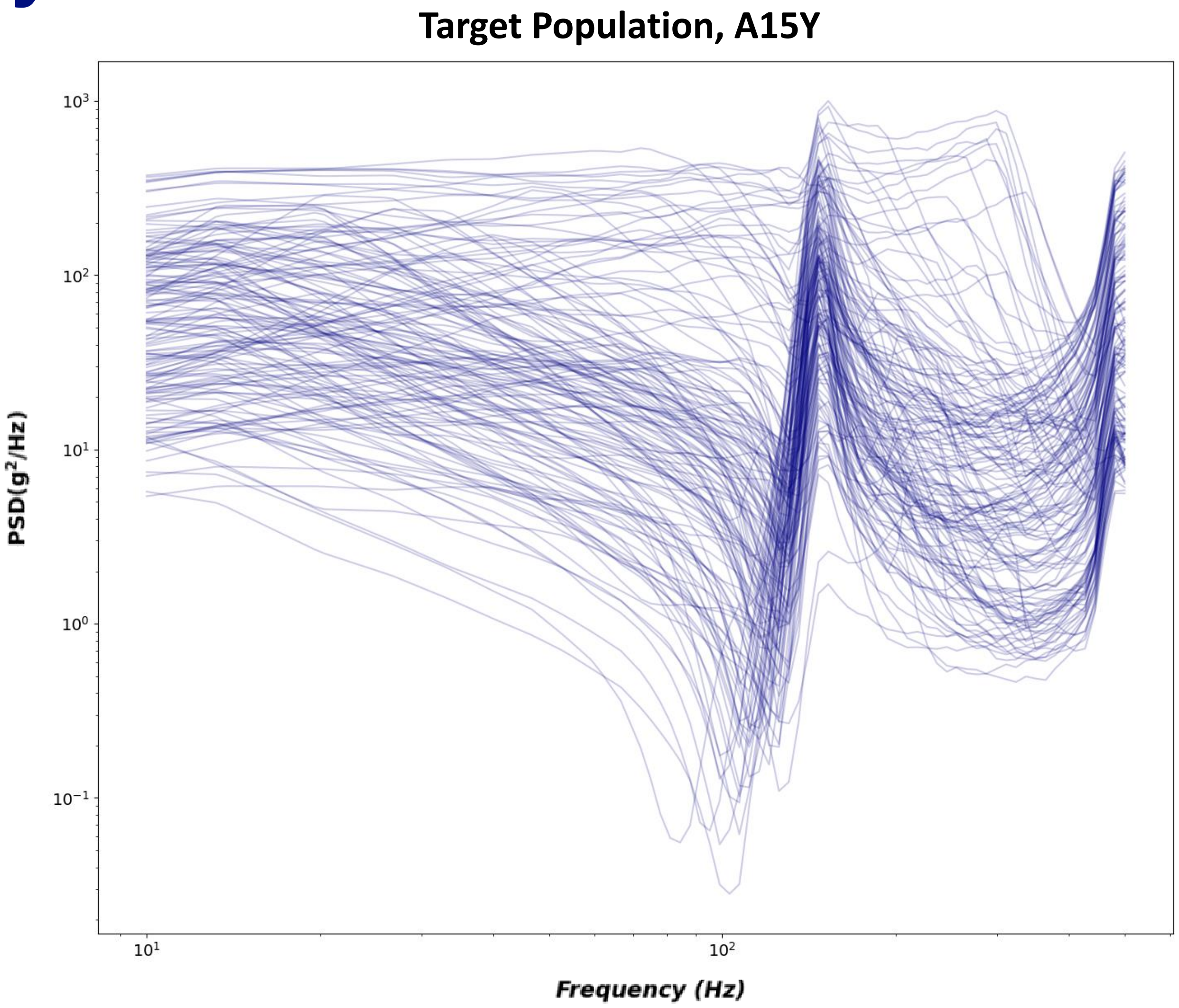
A dynamically optimized test fixture only slightly improved both the sequential test and SIMO test.

→ Can we achieve further improvements in SIMO test performance with more exotic test fixture designs?

→ Assessed four additional test fixture configurations with less similarity to the boundary condition imposed to generate the target test environment.

Target Population Study

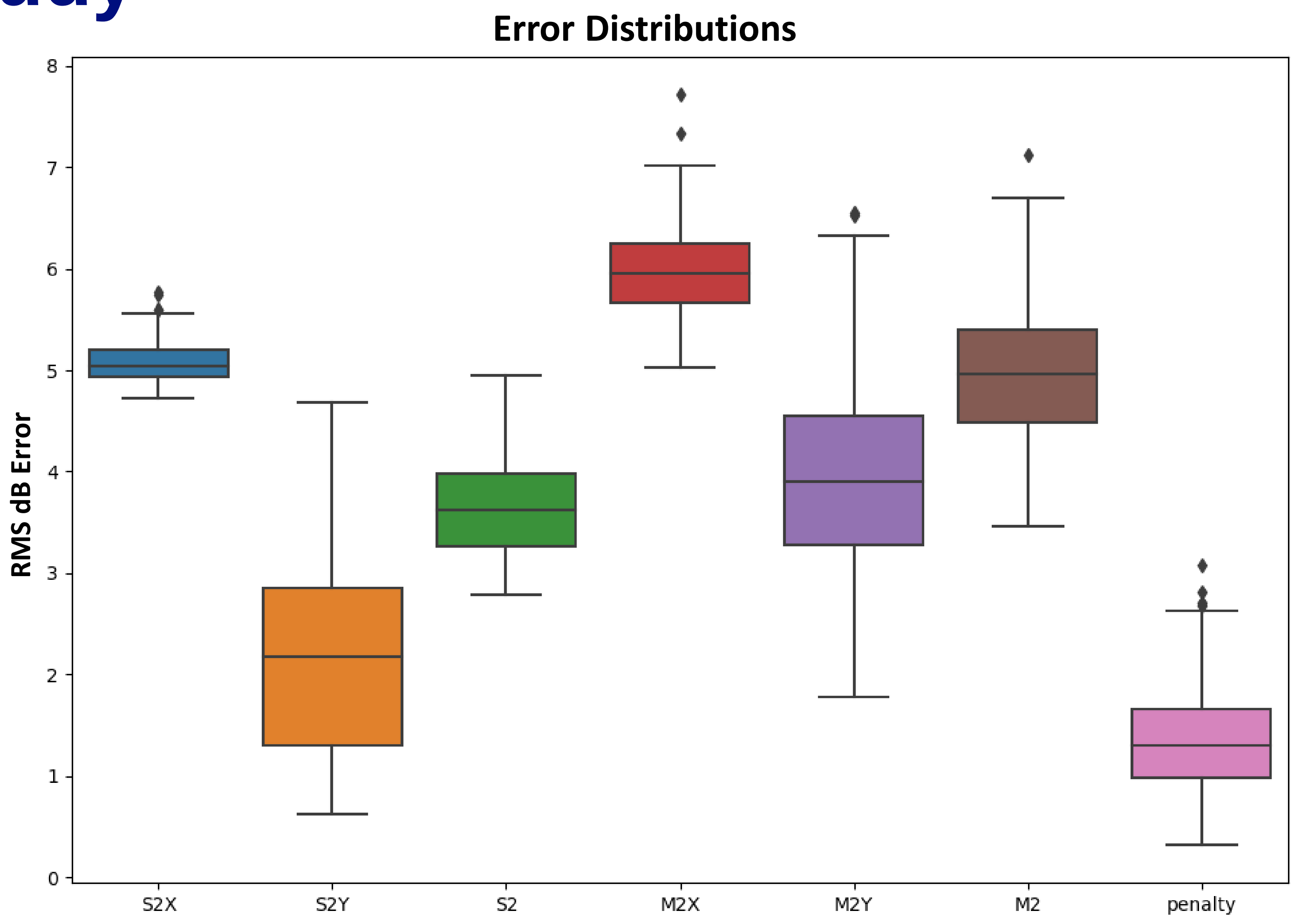
- 150 target test environment sets were generated by applying significant perturbations to the MIL-STD-810H base excitation environment and repeating the entire process.
- The resulting target test environment variation for one control location is shown.
- For each of the 150 target sets, the entire analysis was repeated for the rigid test fixture case only.



Target Population Study

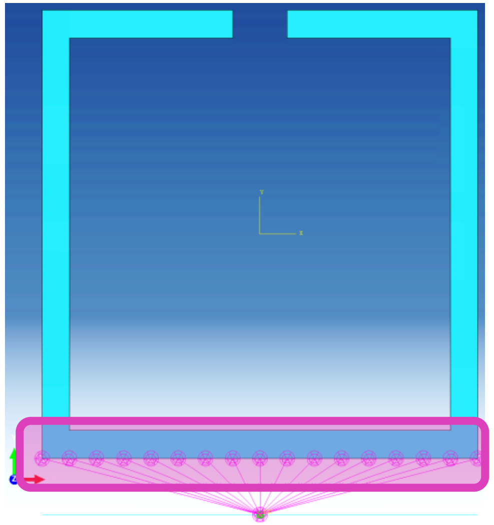
- Error distributions for target population study:
  - S2X: Sequential, X-test error
  - S2Y: Sequential, Y-test error
  - S2: Sequential, mean error
  - M2X: SIMO, X response error
  - M2Y: SIMO, Y response error
  - M2: SIMO, mean error
  - Penalty: Difference between S2 and M2

- The on-axis error penalty for a simultaneous SIMO test remains small for most of the target test environment population.



Is the increase in error acceptable for the SIMO multi-axis test to eliminate unavoidable cross-axis responses in the sequential test?
Can we do better with other test fixtures?

Test Fixture Attachment Points



Case Study 2

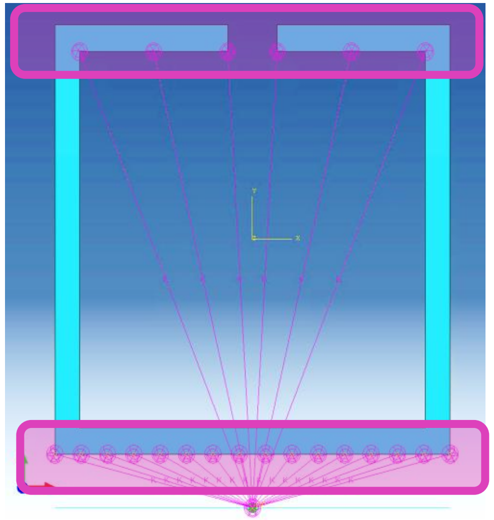
2 parameters of X and Y Stiffnesses Along Base

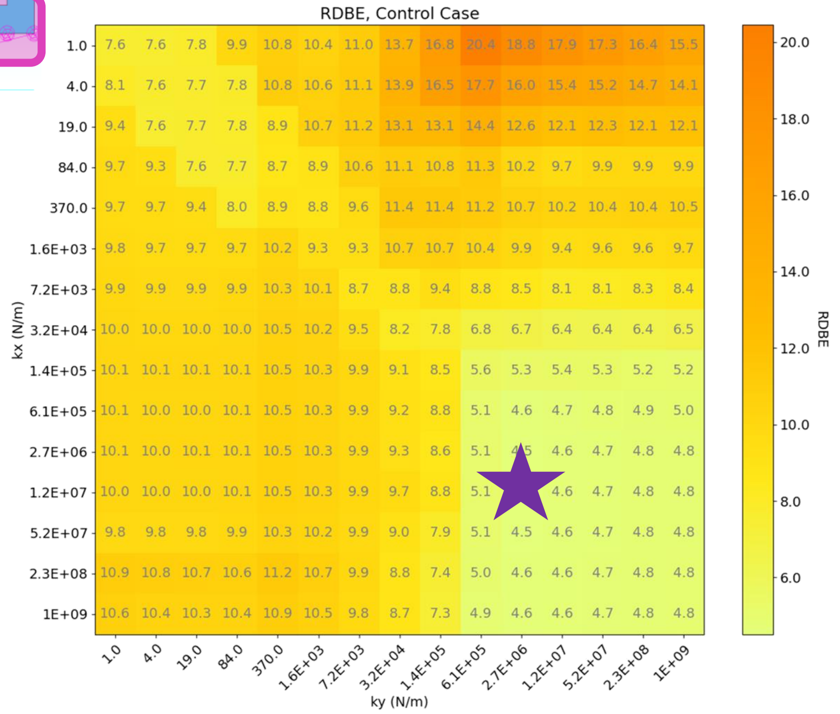
Minimum Error 4.5 dB

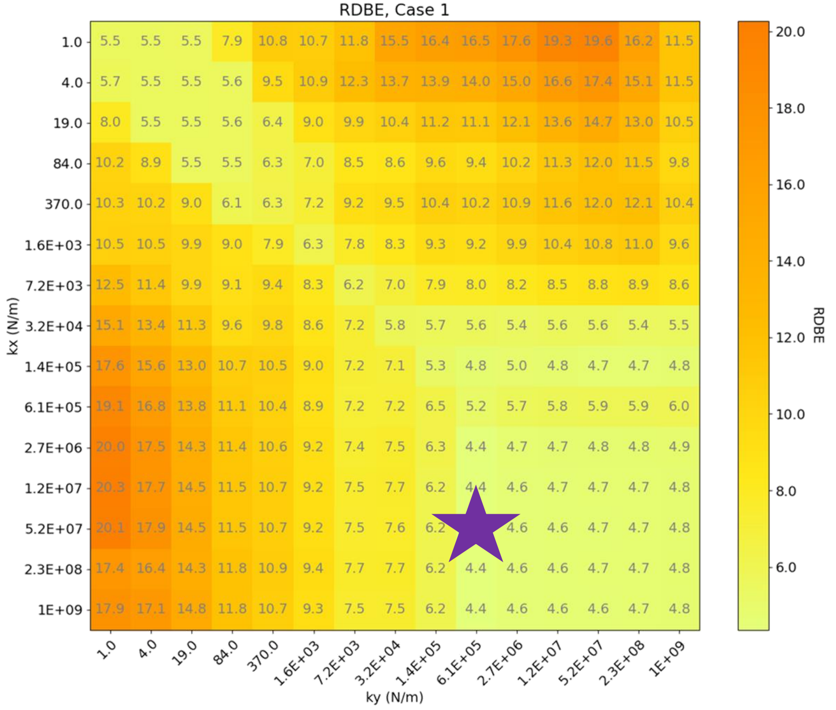
Added Top Springs

2 parameters of X and Y Stiffnesses Along Base and Top

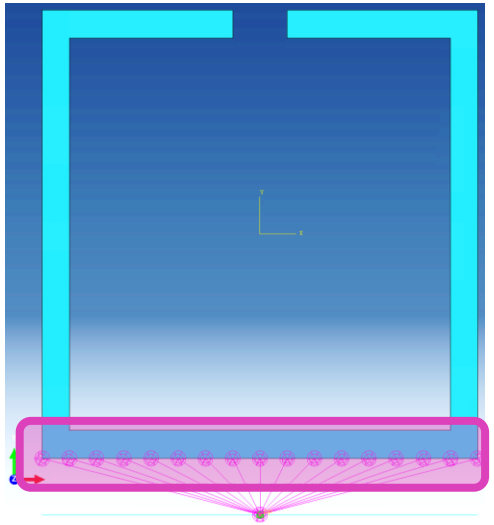
Minimum Error 4.3 dB







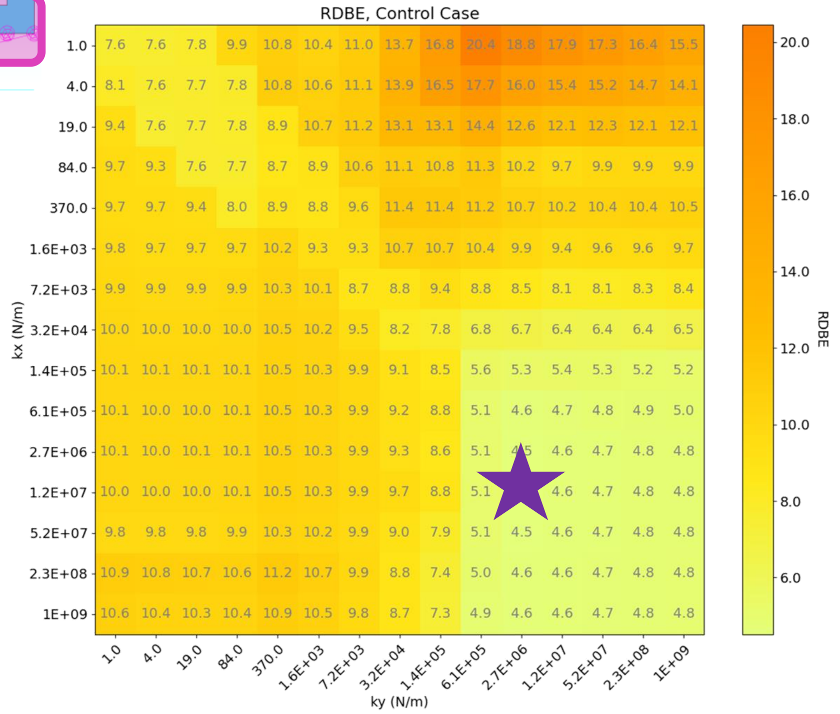
Test Fixture Attachment Points



Case Study 2

2 parameters of X and Y Stiffnesses Along Base

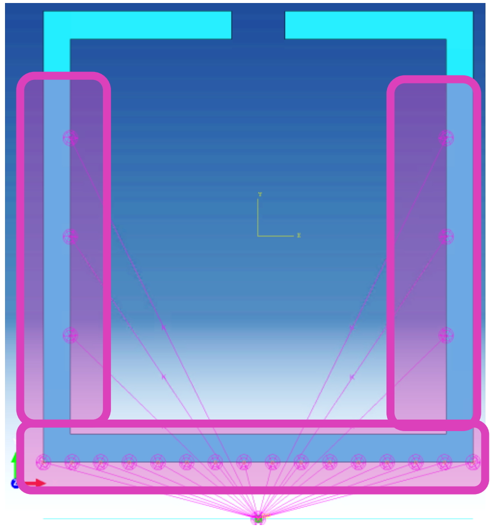
Minimum Error 4.5 dB

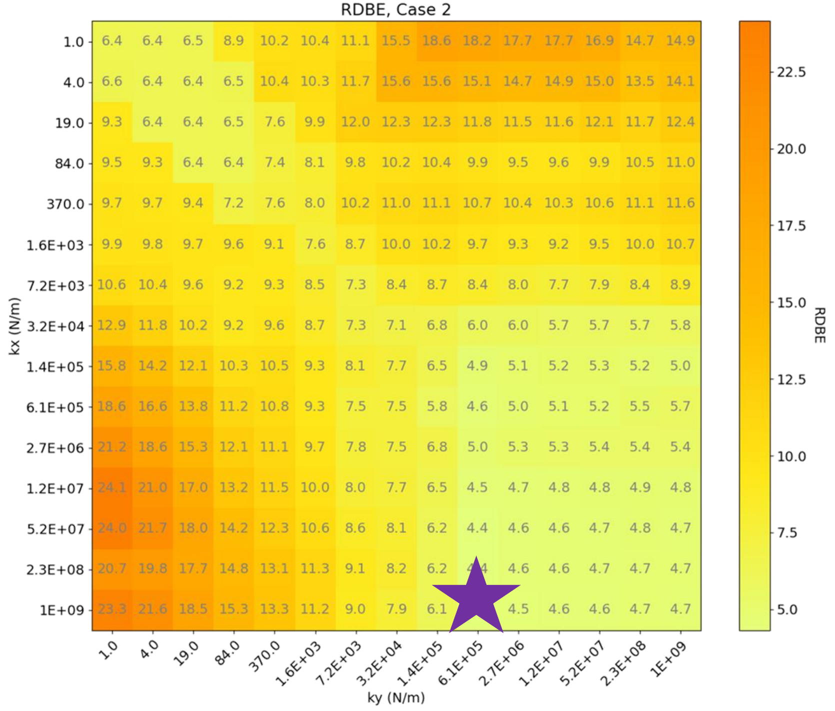


Added Side Springs

2 parameters of X and Y Stiffnesses Along Base and Sides

Minimum Error 4.3 dB





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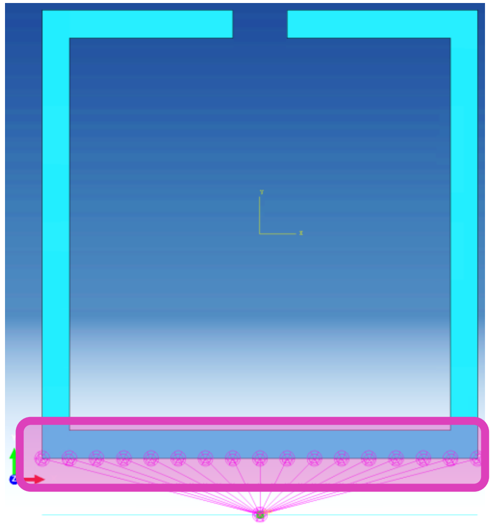
Test Fixture Attachment Points



Case Study 2

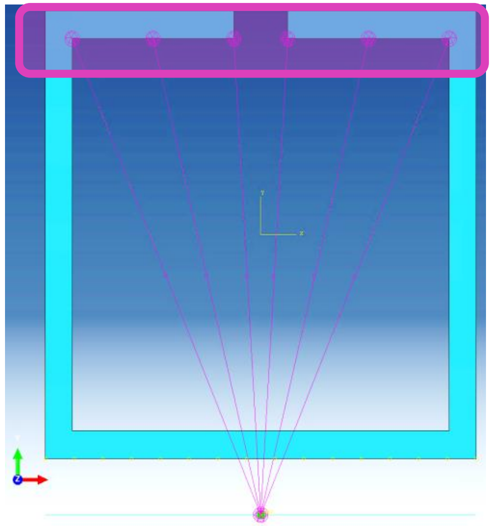
2 parameters of X and Y Stiffnesses Along Base

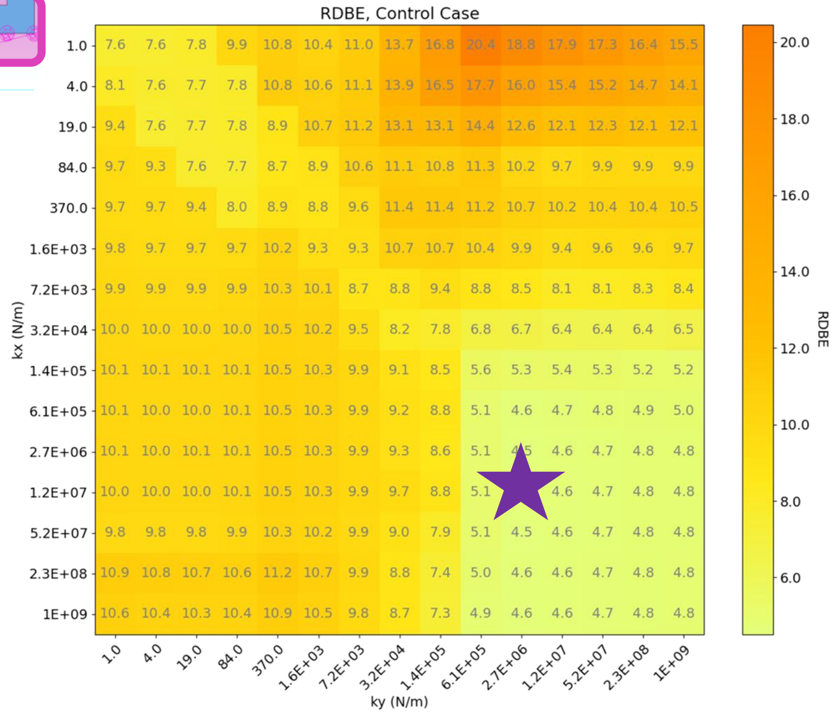
Minimum Error 4.5 dB

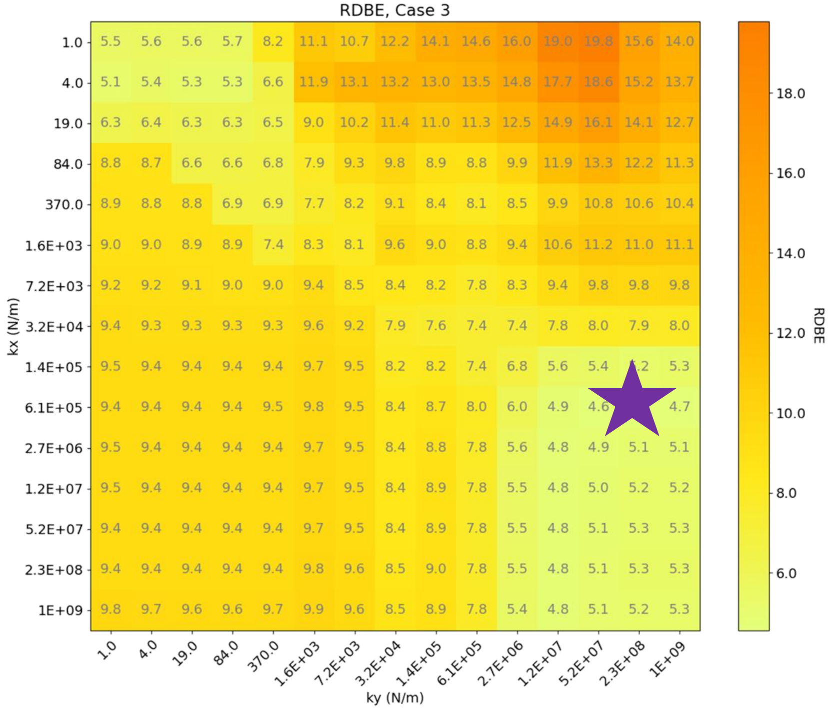
Only Top Springs

2 parameters of X and Y Stiffnesses Along Top

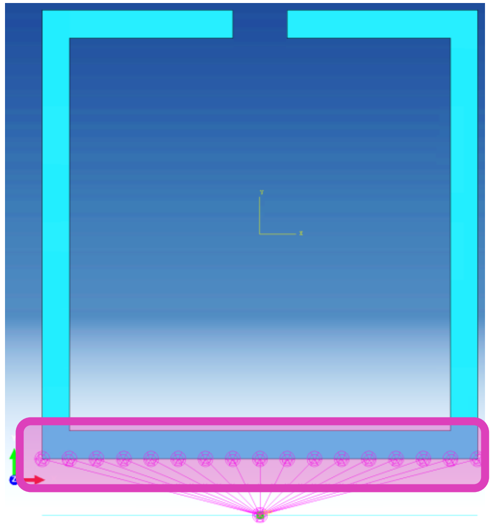
Minimum Error 4.5 dB







Test Fixture Attachment Points



Case Study 2

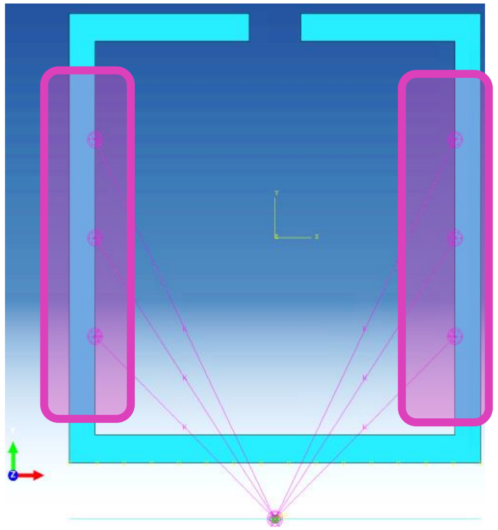
2 parameters of X and Y Stiffnesses Along Base

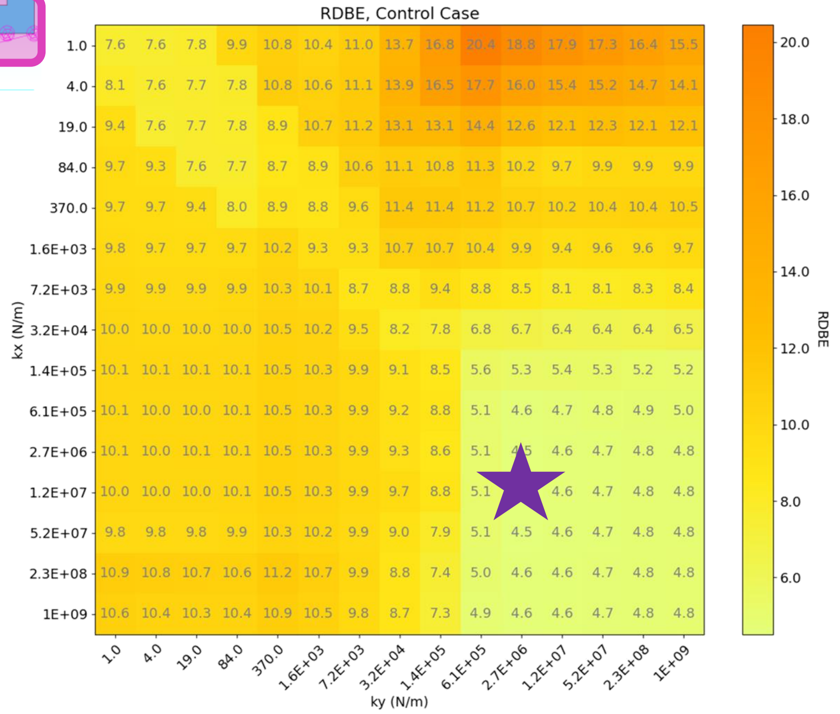
Minimum Error 4.5 dB

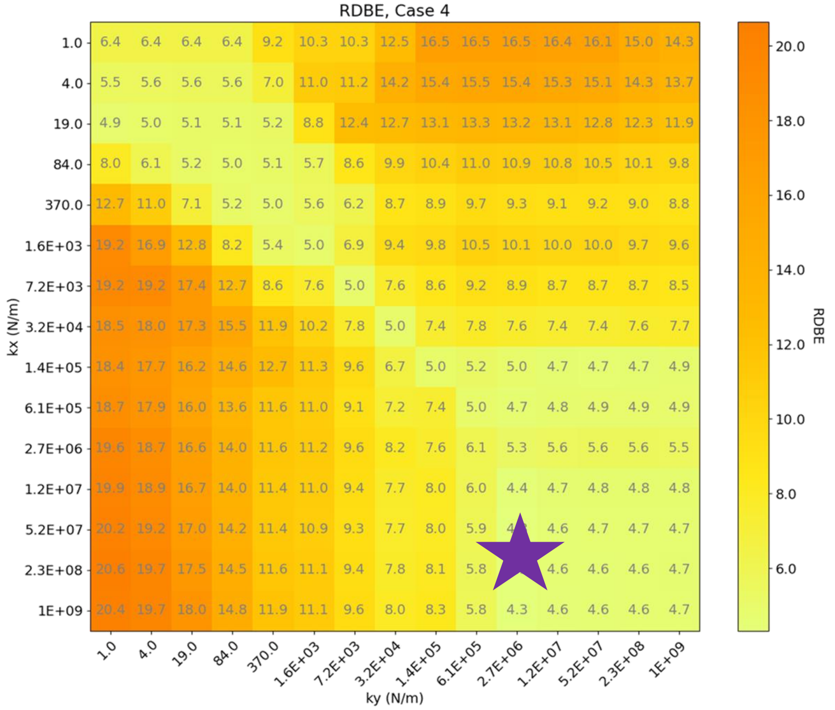
Only Side Springs

2 parameters of X and Y Stiffnesses Along Sides

Minimum Error 4.3 dB

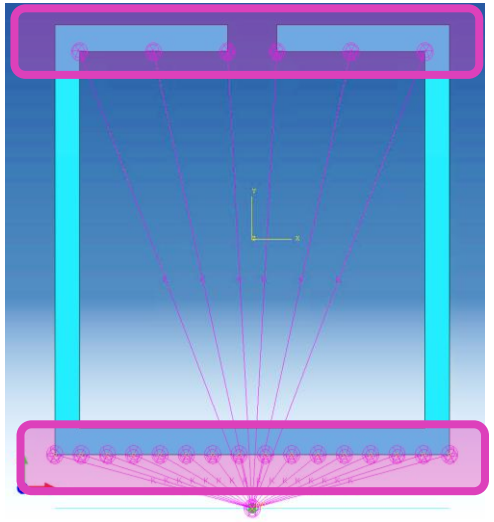
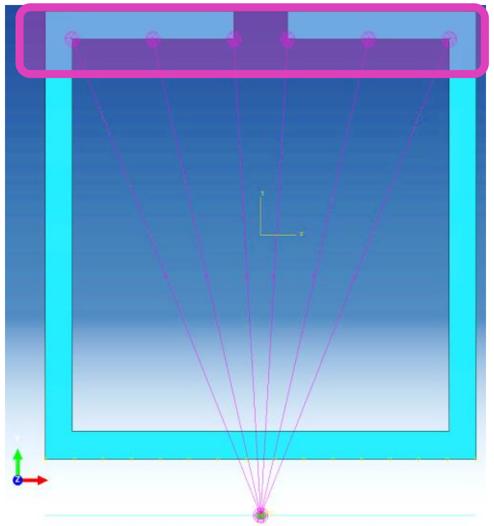
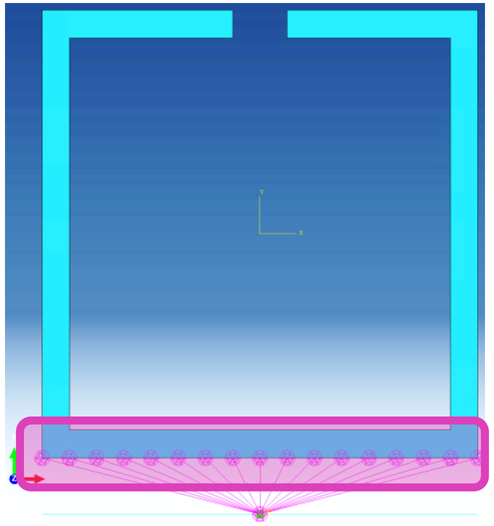
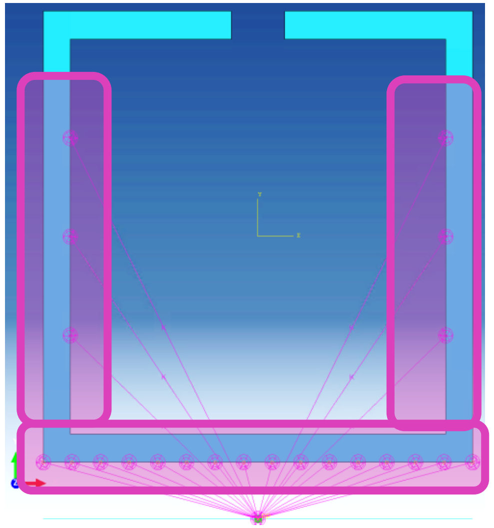
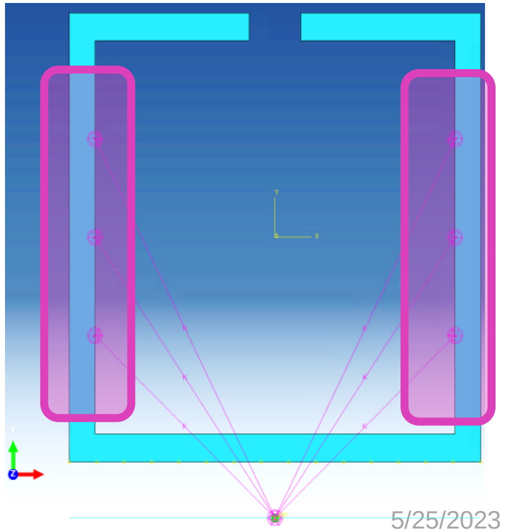






Test Fixture Attachment Points

- Unexpectedly, all of these possible fixture designs can result in RDBE of **4.3 - 4.5 dB**.
- With rigid fixtures, all of these fixture designs produce a test with RDBE of **4.7 - 5.3 dB**.
- More exotic, improved fixture designs may exist but are difficult to find and may not be intuitive.

Preliminary Study:

Can single-axis testing techniques provide a sufficient rapid approximation to a multi-axis test?

SIMO multi-axis test quality may be in family with traditional test strategies.

How much can we improve multi-axis test quality by optimizing passive test fixture hardware instead of adding active excitation sources?

Very good fixture designs are challenging while bad designs abound and need to be avoided.

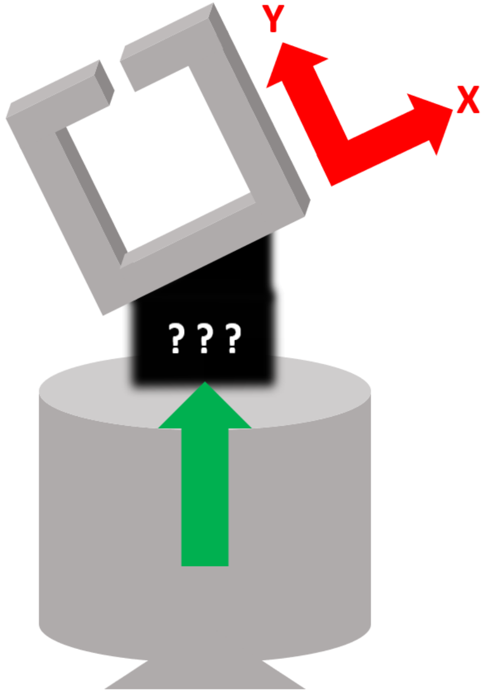
Question:

Is the simplest possible multi-axis test close to single-axis testing in test quality?

Preliminary study suggests yes.

How good do multi-axis tests need to be to replace single-axis testing in practice?

Unsettled



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Questions?

Single-Axis vs. Multi-Axis

- The field and lab environment's mismatch is exacerbated in sequential single-axis testing.

Compared to a 6DOF test, sequential single-axis testing produces different…				
Failure times	Failure distributions	Maximum Von Mises stress	Location of maximum Von Mises stress	Modal participations

French et al., 2006 (Failure times, Failure distributions)

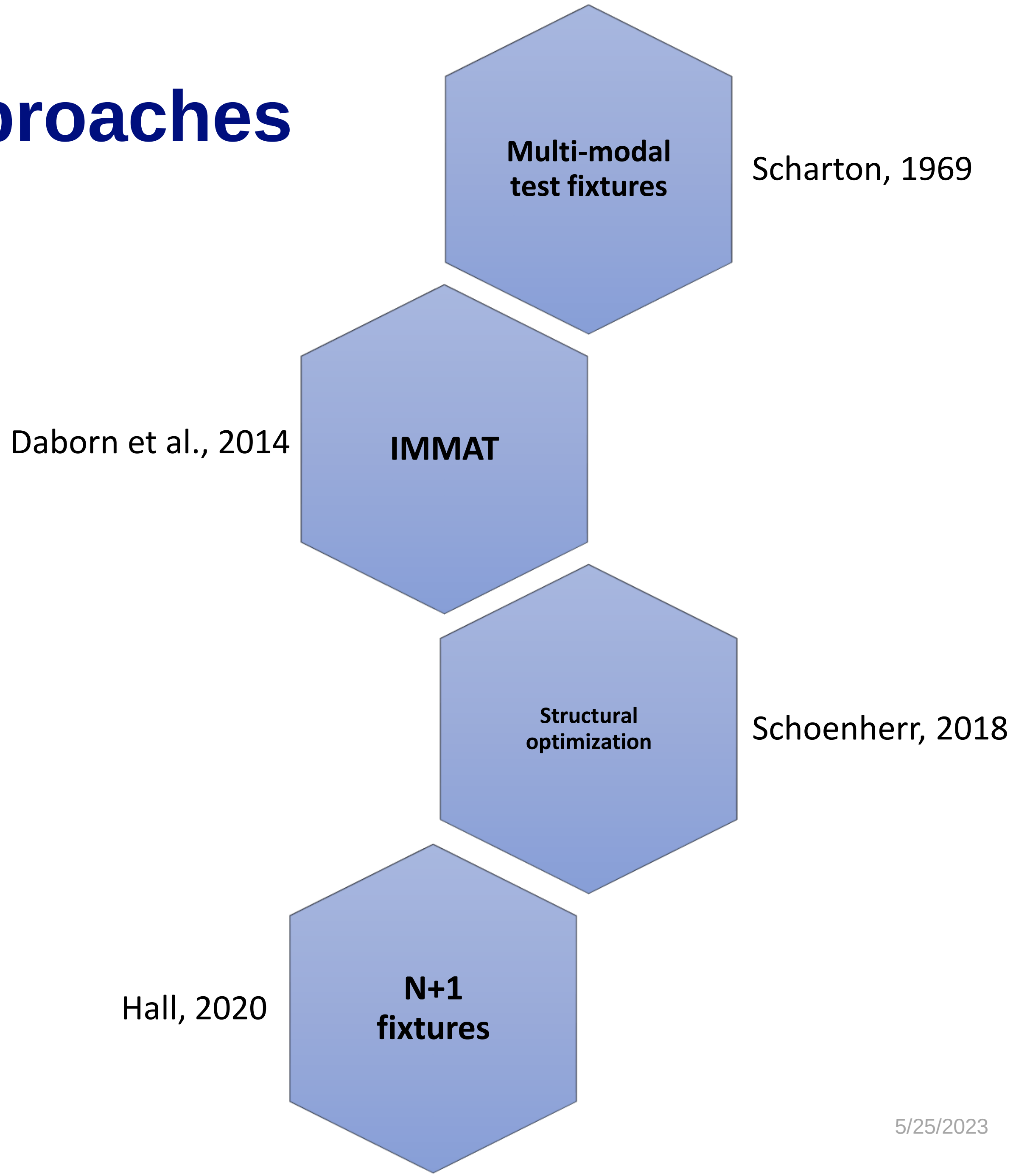
Gregory et al., 2009 (Maximum Von Mises stress, Location of maximum Von Mises stress, Modal participations)

Impedance Modification Approaches

- Two categories of approaches are trying to rectify the mismatch between field and lab environments:

  1. **Impedance modification**

  2. Input control

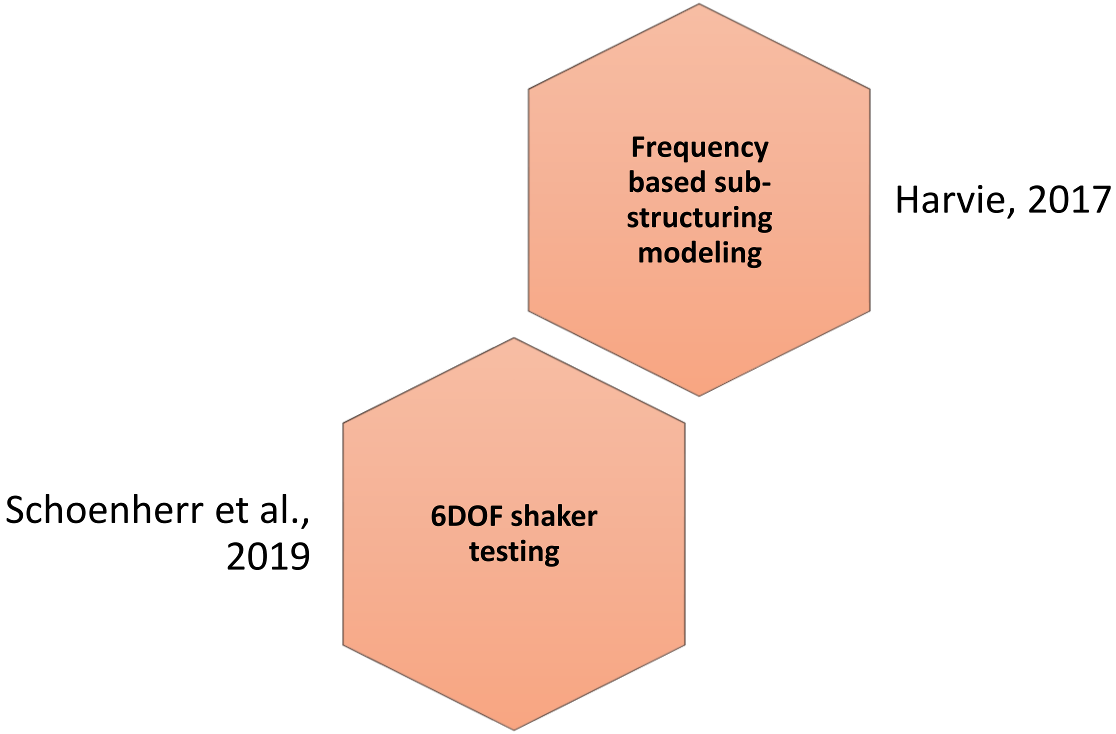


Input Control Approaches

- Two categories of approaches are trying to rectify the mismatch between field and lab environments:

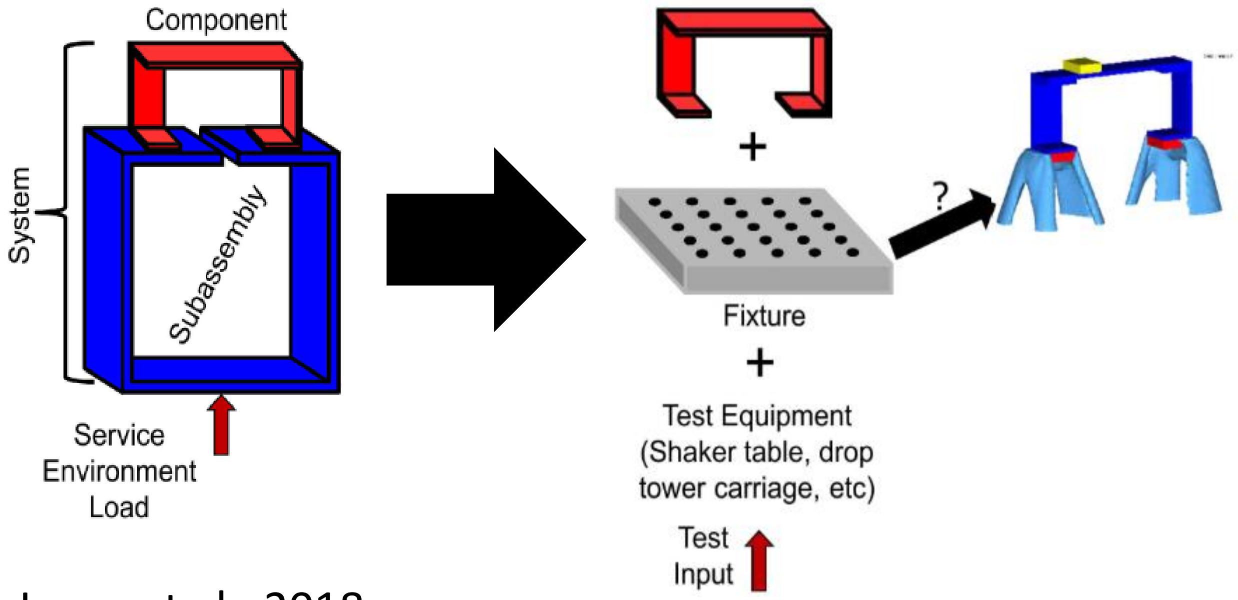
1. Impedance modification

2. **Input control**



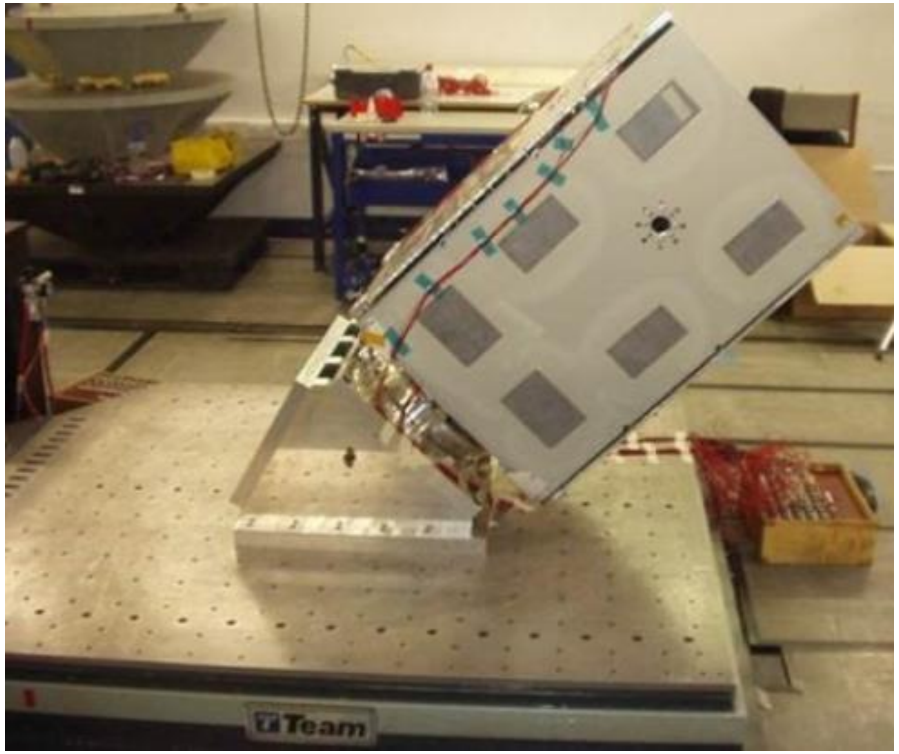
Structural Optimization

Topological Optimization



Jones et al., 2018

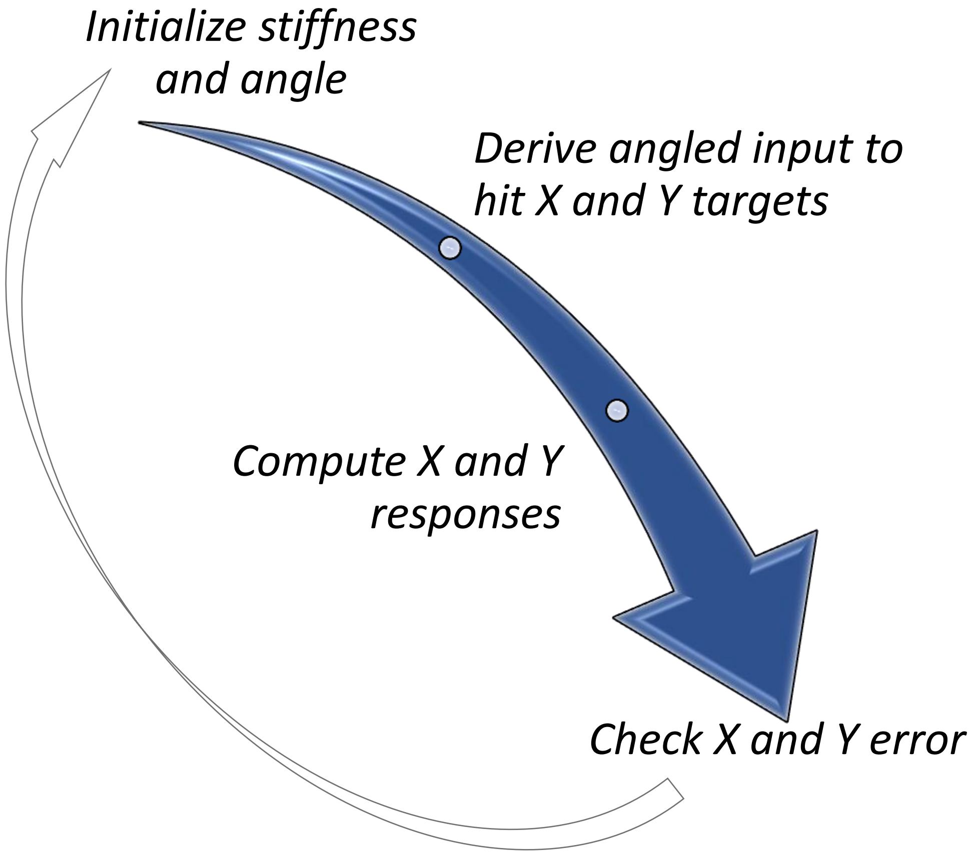
Angle Optimization



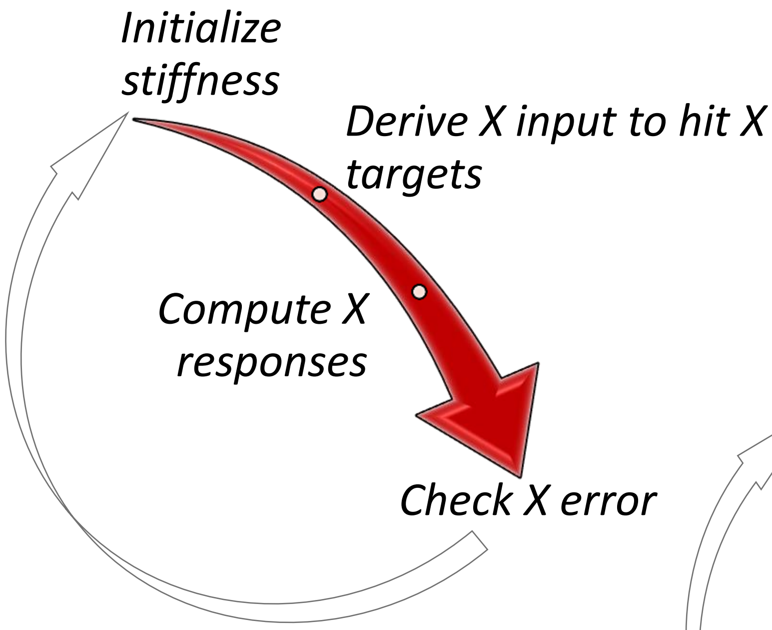
Knight et al., 2018

Simulation Approach

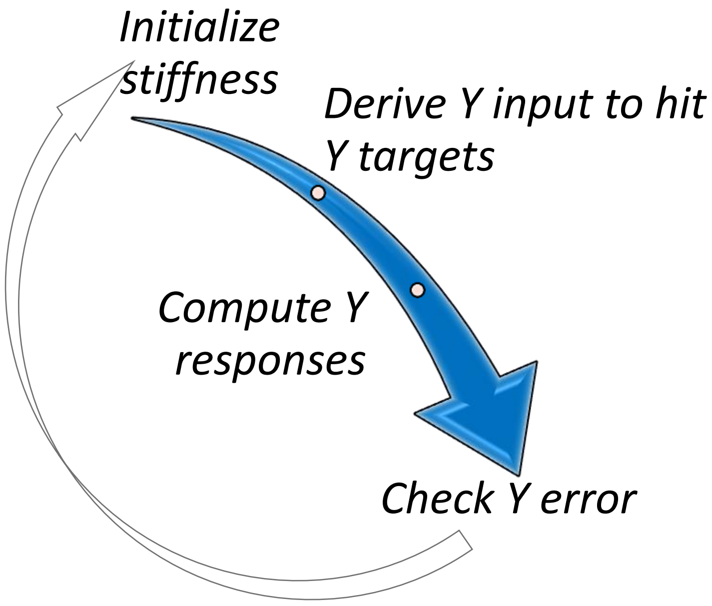
SIMO Multi-Axis Test



X-Axis Sequential Test



Y-Axis Sequential Test



Case Studies

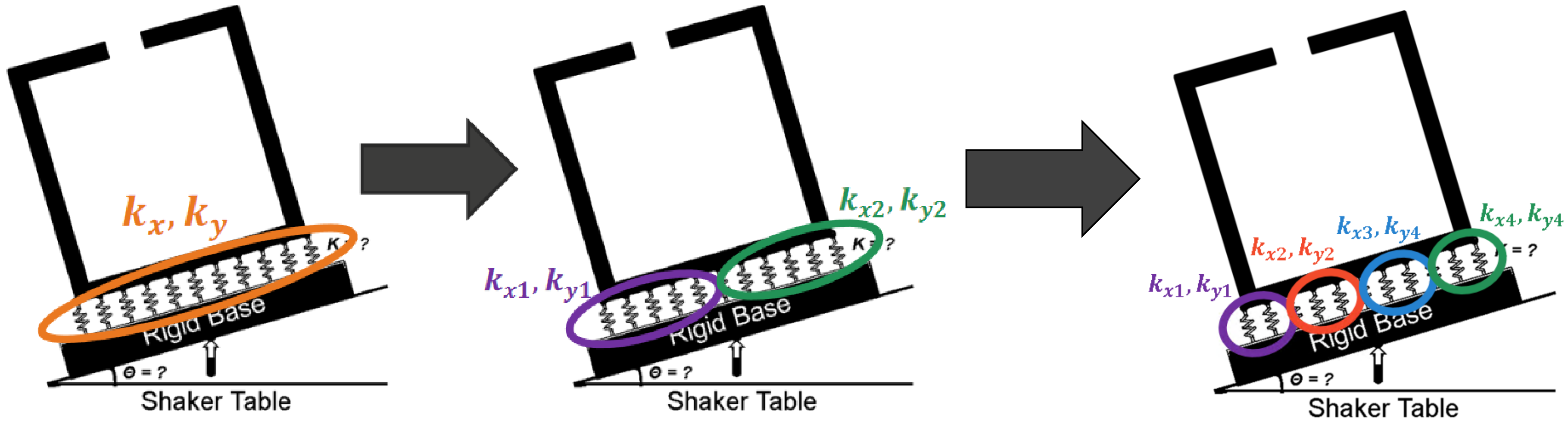
Sequential, single-axis testing and the proposed method are compared with increasing levels of test fixture complexity and design effort.

Case	Test Fixture Design	Comparisons
1	Rigid	1. Sequential single-axis (single control location) 2. Sequential single-axis (all control locations) 3. SIMO multi-axis (all control locations)
2	Optimized (2 parameters)	1. Sequential single-axis 2. SIMO multi-axis
3	Optimized (4 parameters)	1. Sequential single-axis 2. SIMO multi-axis
4	Optimized (8 parameters)	1. Sequential single-axis 2. SIMO multi-axis

Case Studies

- In our model, the stiffness of the springs providing the boundary condition for the BARC test article is varied to change the test fixture.
- In Case 1, the boundary condition is rigid.
- In Cases 2, 3, and 4, the boundary condition is optimized using an increasing number of parameters to determine how much test fixture complexity contributes to improving the possible solutions.

Case 2 **Case 3** **Case 4**



Case Study 2 (2 parameters)

The solution found for each test was:

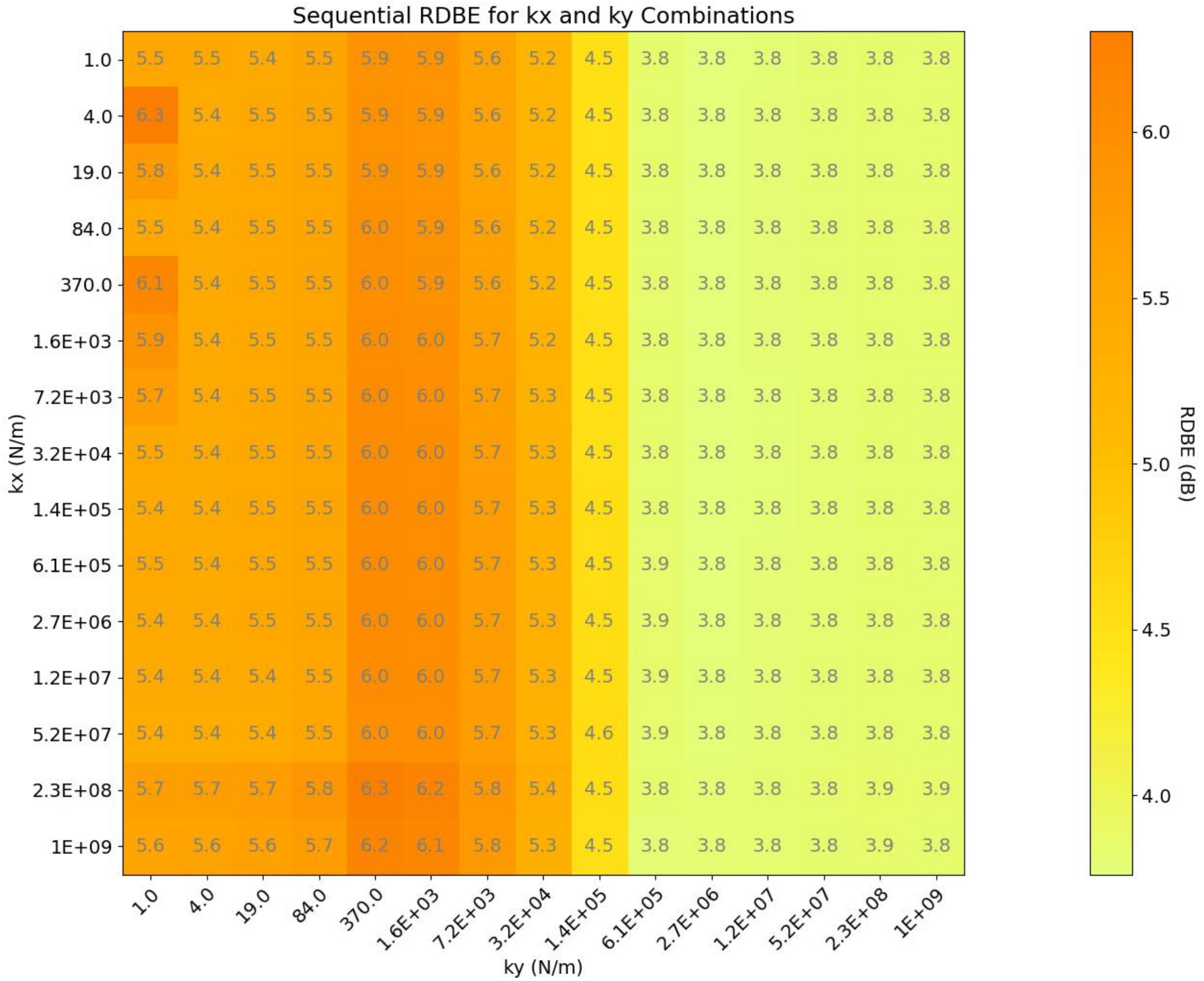
1. For the sequential test, $k_x = 3.2 * 10^4$ and $k_y = 2.7 * 10^6$ N/m.

2. For the SIMO test, $k_x = 1.2 * 10^7$, $k_y = 2.7 * 10^6$ N/m, and $\theta = 27°$.

	Mean Error	
	Sequential Single-Axis	**SIMO Multi-Axis**
RDBE	3.7 dB	4.5 dB
FTOL	80.0%	75.6%

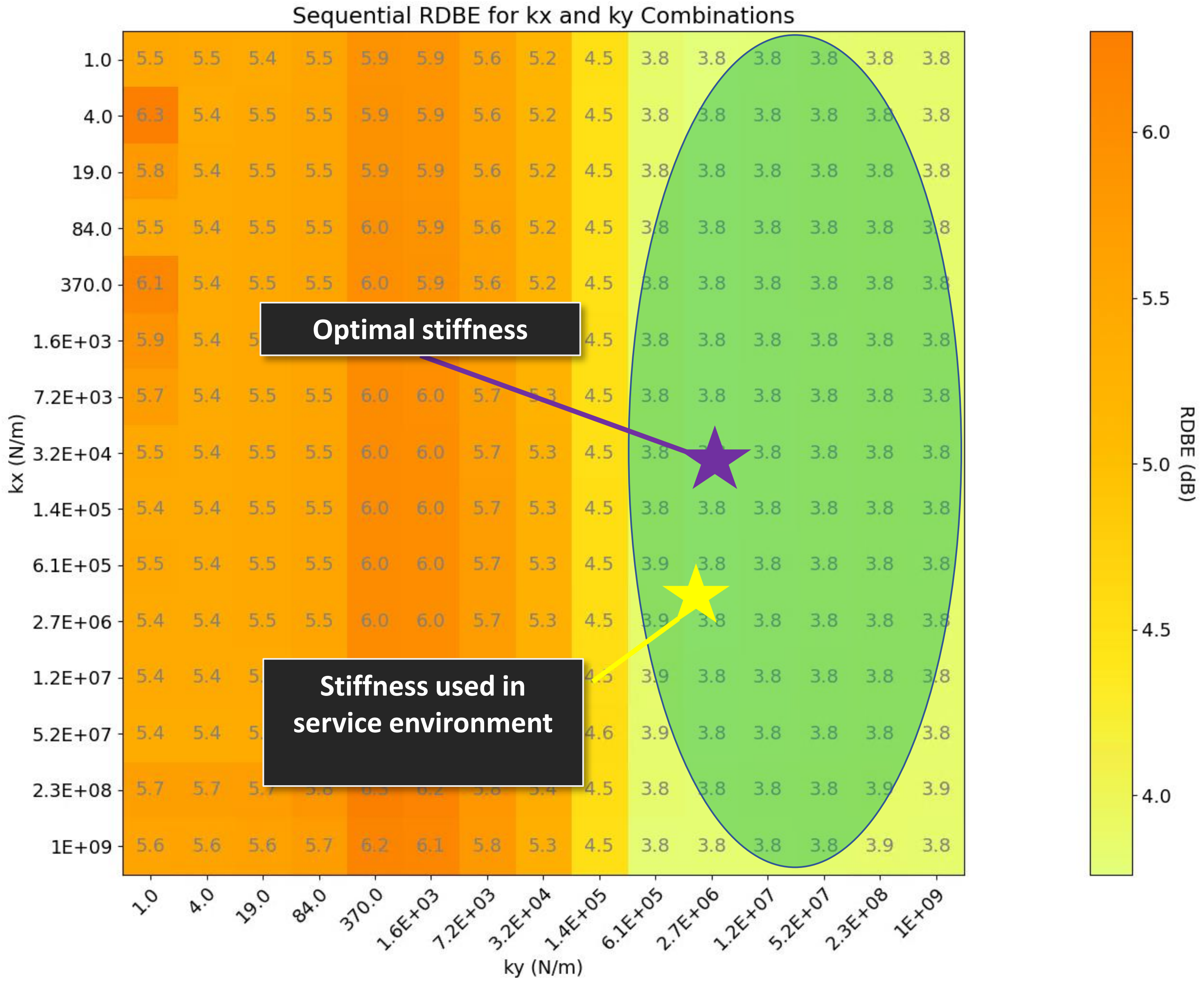
Case Study 2

- The sequential test's stiffness optimization found the X-stiffness had little impact while the Y-stiffness needed to be above $1.4 * 10^5\ N/m$ to produce good error.



Case Study 2

- The sequential test's stiffness optimization found the X-stiffness had little impact while the Y-stiffness needed to be above $1.4 * 10^5\ N/m$ to produce good error.



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Case Study 3

The solution found for each test was:

1. For the sequential test, $k_{x1} = 3.2 * 10^4$, $k_{x2} = 1$, $k_{y1} = 2.7 * 10^6$, $k_{y2} = 2.7 * 10^6$ N/m.

2. For the SIMO test, $k_{x1} = 19$, $k_{x2} = 2.3 * 10^8$, $k_{y1} = 2.7 * 10^6$, $k_{y2} = 2.7 * 10^6$ N/m, $\theta = 27°$.

	Mean Error	
	Sequential Single-Axis	**SIMO Multi-Axis**
RDBE	3.7 dB	4.5 dB
FTOL	80.0%	75.6%

Case Study 4

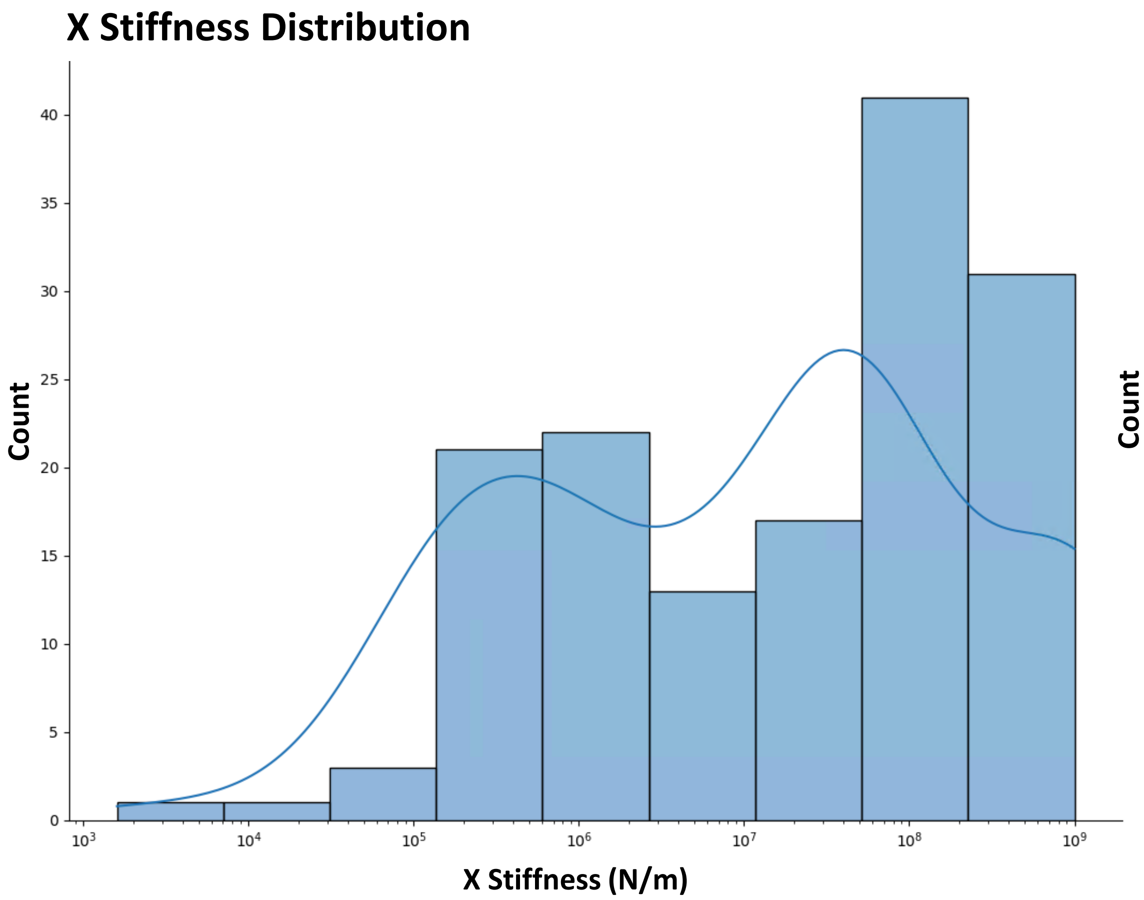
The solution found for each test was:

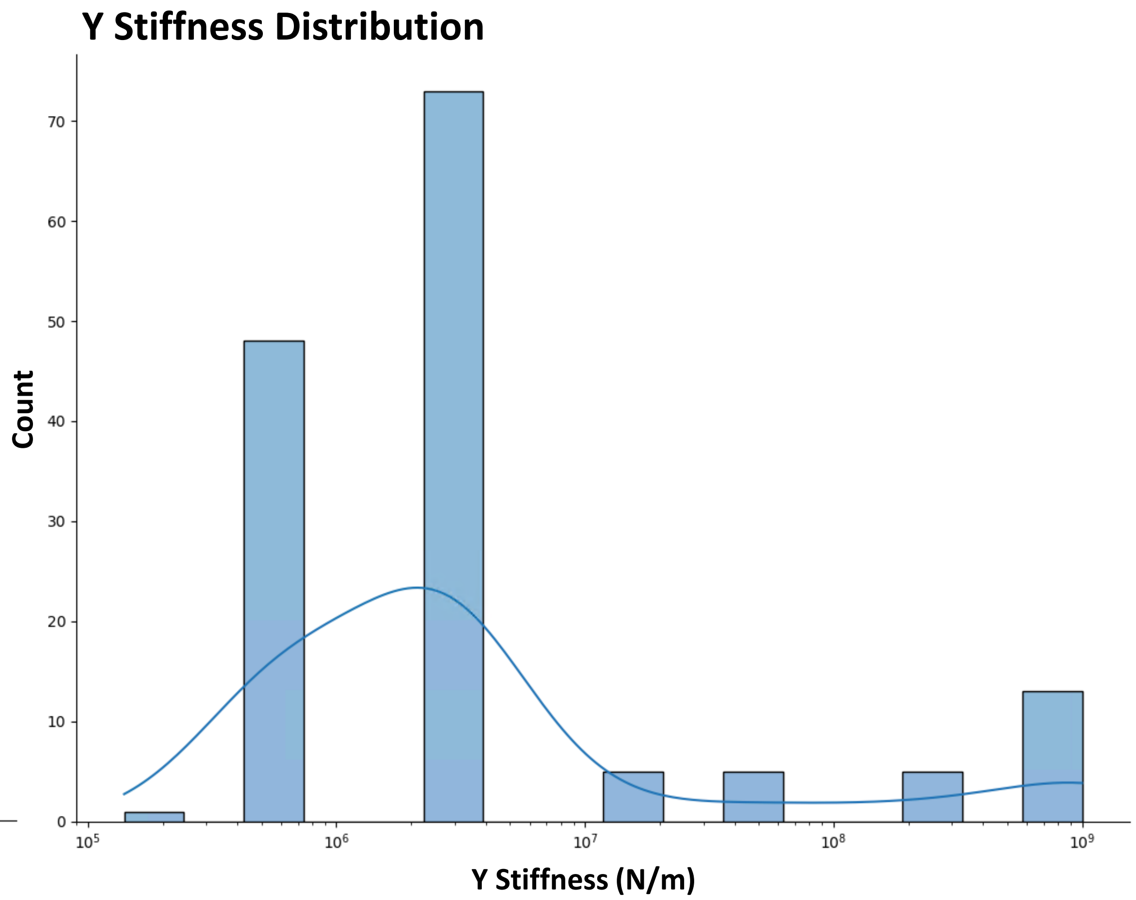
1. For the sequential test, $\mathrm{k_{x1}} = 1, \mathrm{k_{x2}} = 1, \mathrm{k_{x3}} = 1, \mathrm{k}_{x4} = 1, \mathrm{k_{y1}} = 1, \mathrm{k_{y2}} = 10^9, \mathrm{k_{y3}} = 10^9, \mathrm{k}_{y4} = 1\ \mathrm{N/m}.$

2. For the SIMO test, $\mathrm{k_{x1}} = 10^9, \mathrm{k_{x2}} = 3.2 * 10^4, \mathrm{k_{x3}} = 2.7 * 10^6, \mathrm{k}_{x4} = 2.7 * 10^6, \mathrm{k_{y1}} = 2.7 * 10^6, \mathrm{k_{y2}} = 2.7 * 10^6,$ $\mathrm{k_{y3}} = 10^9, \ \mathrm{k}_{y4} = 2.7 * 10^6\ \mathrm{N/m}, \ \theta = 27°.$

	Mean Error	
	Sequential Single-Axis	**SIMO Multi-Axis**
RDBE	3.7 dB	4.5 dB
FTOL	79.6%	75.3%

Target Population Study

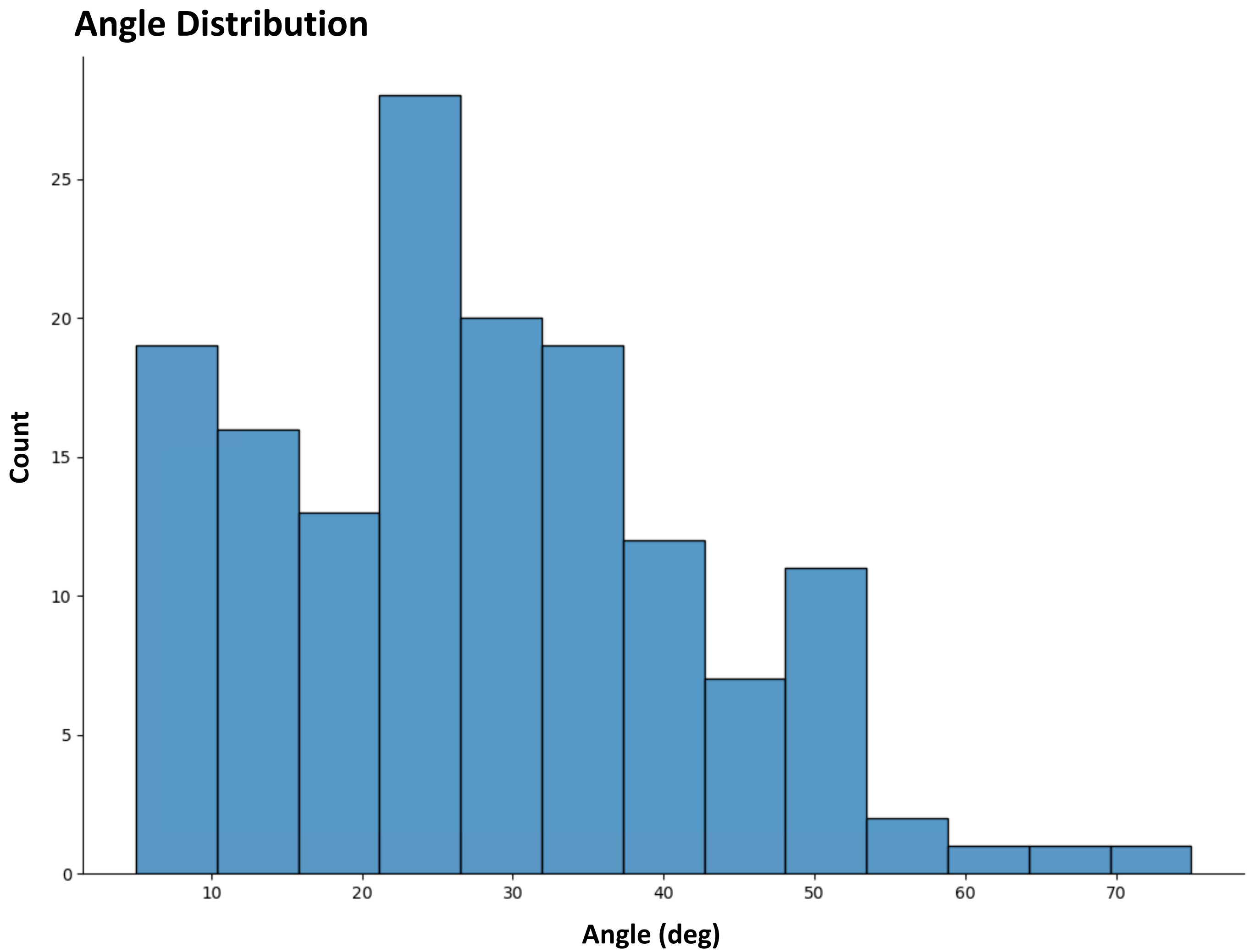




Target Population Study

- For the population of targets, the distribution of optimal excitation SIMO test excitation angles are shown.

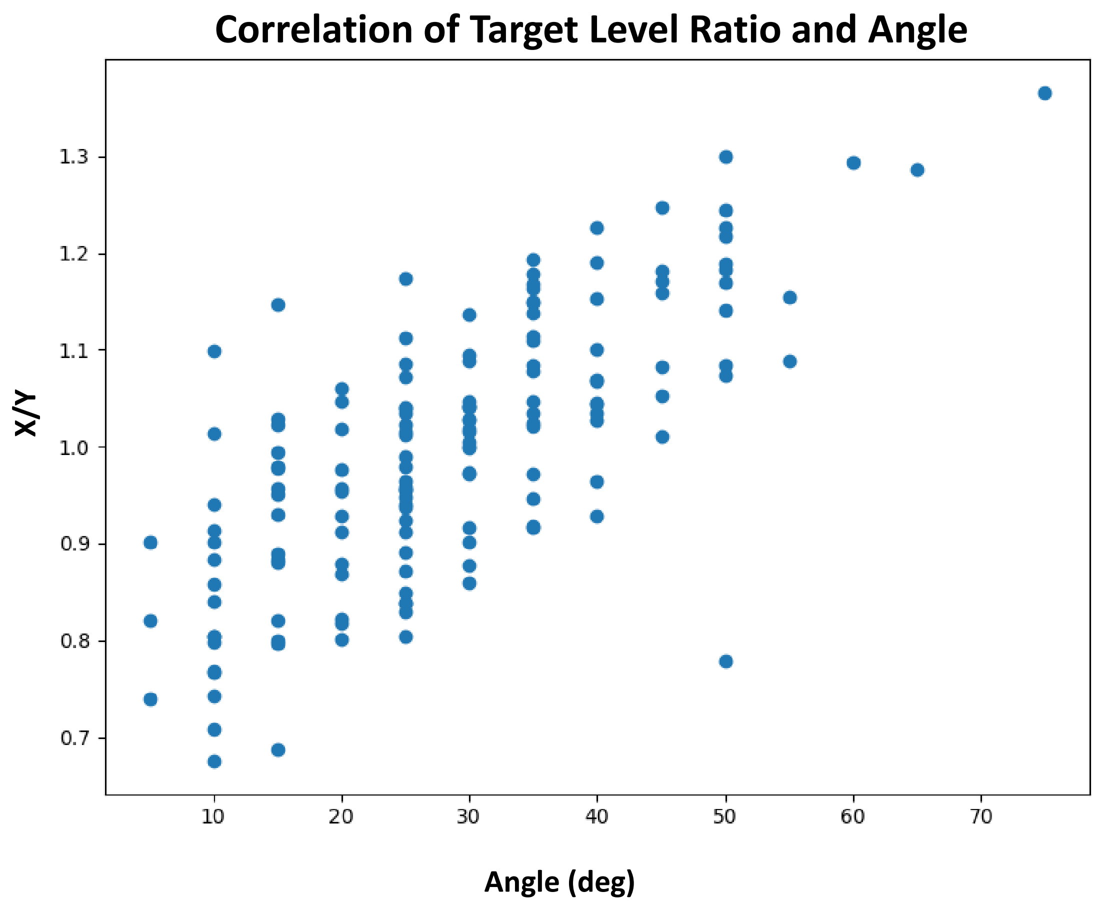
- The angle most commonly fell between 20 and 40 degrees



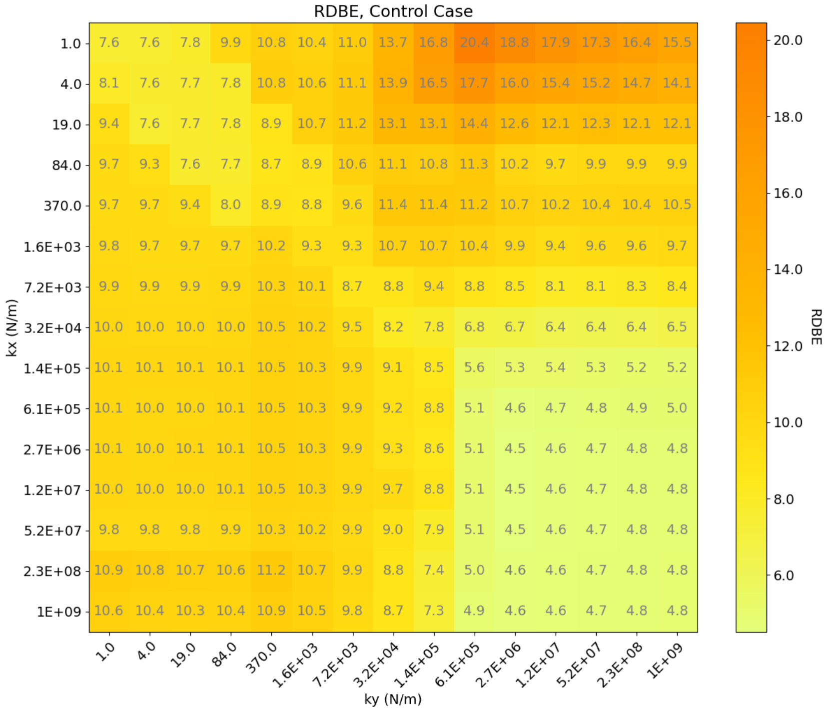
Target Population Study

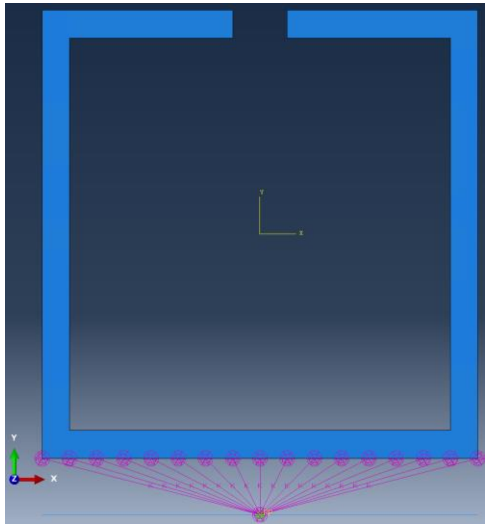
- Evaluated possible predictive metrics for optimal excitation angle based on target environment alone.

- A ratio of energy between X-axis and Y-axis targets (X/Y) has a correlation coefficient with optimal angle of 0.728.

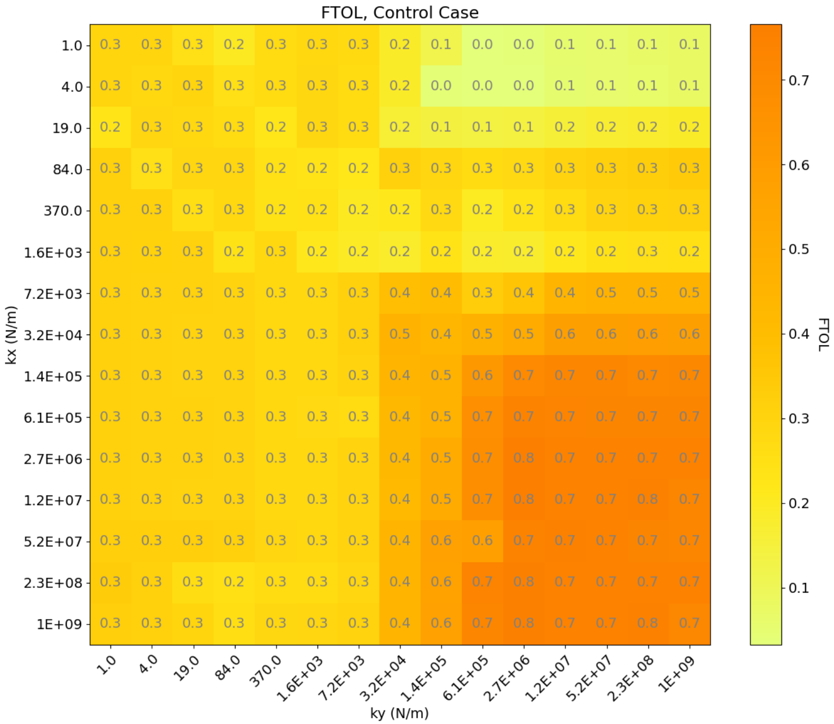


Test Fixture Attachment Points



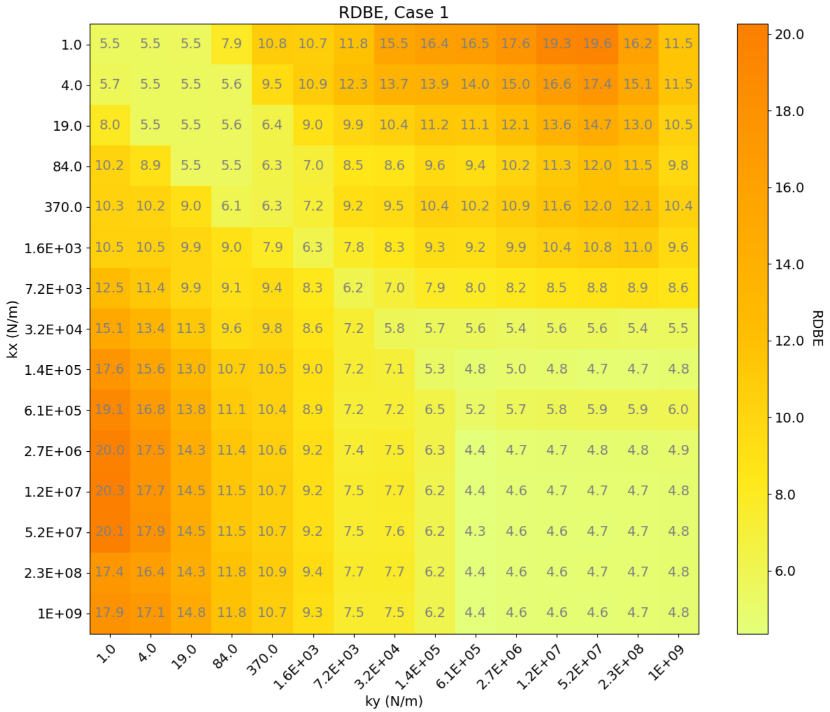


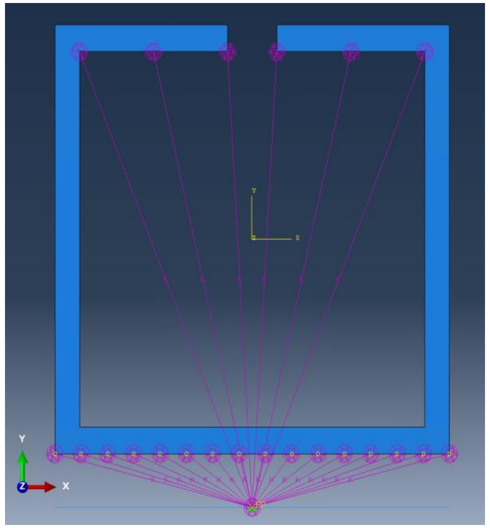
Control Case



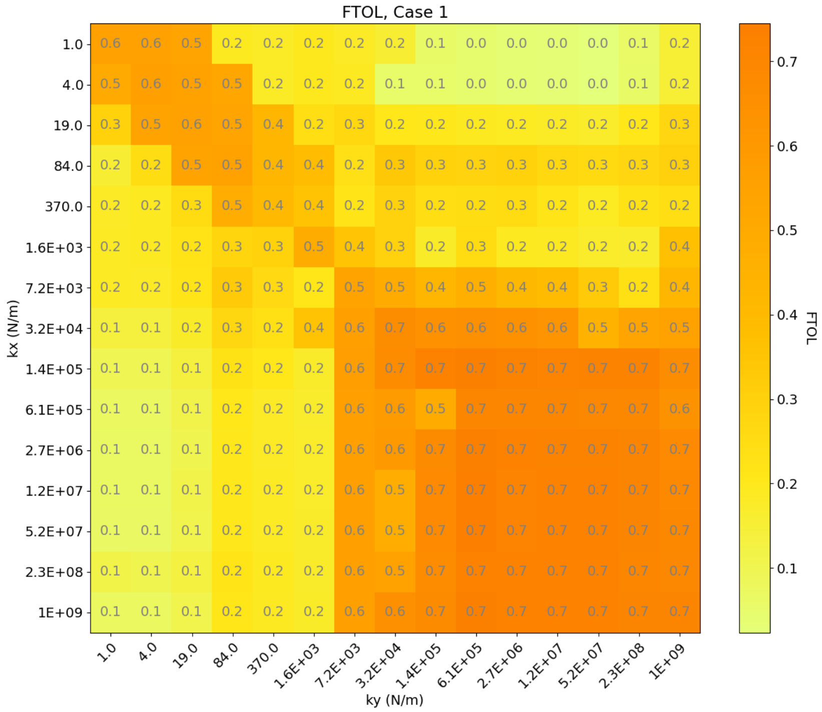
- To assess potential improvements via varied test fixture attachment point, we assign the default target's test fixture optimization as the control case.

Test Fixture Attachment Points



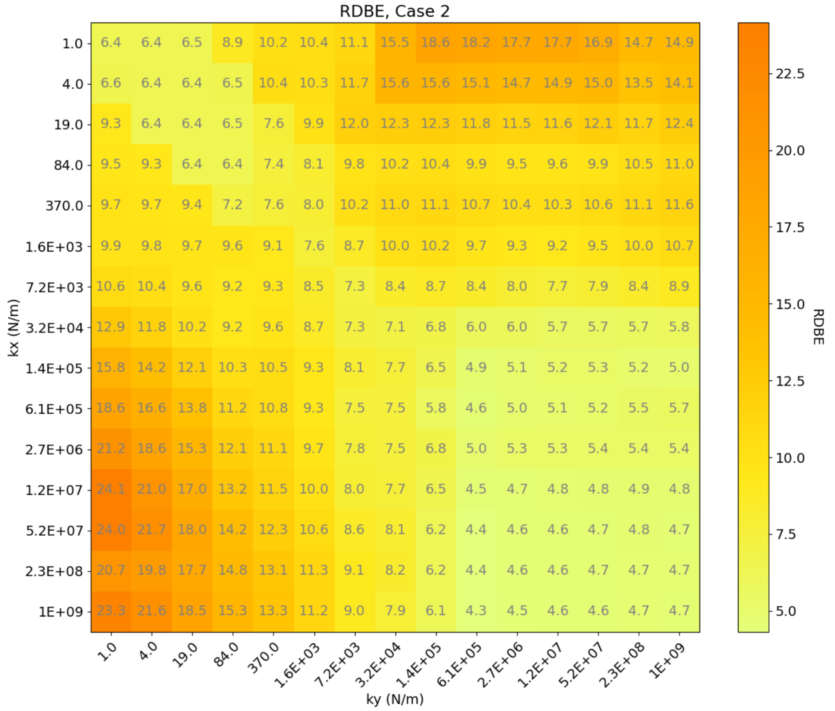


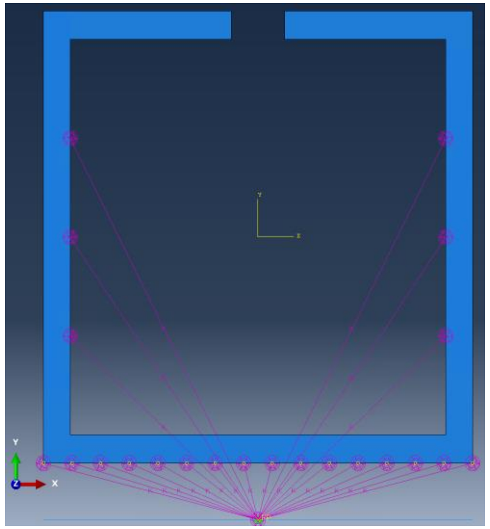
Case 1



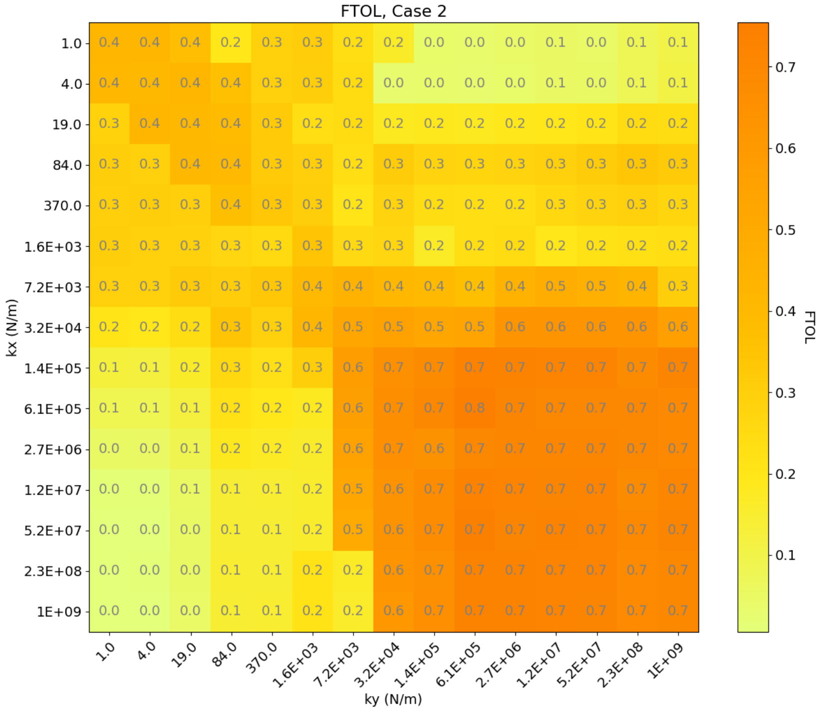
- The first assessed case includes additional springs attached to the top of the BARC. This setup found an improved RMS dB error of 4.3 dB.

Test Fixture Attachment Points



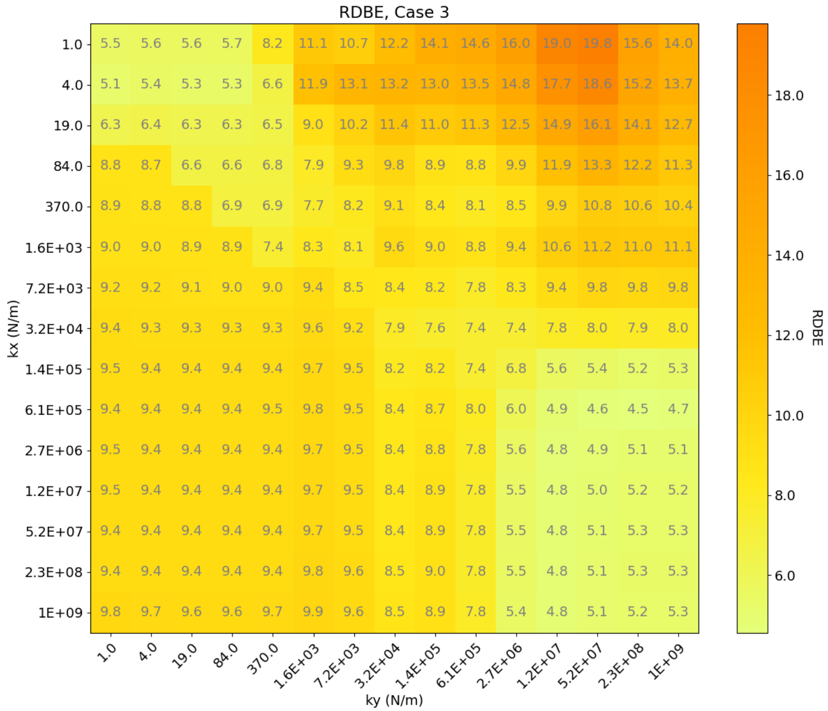


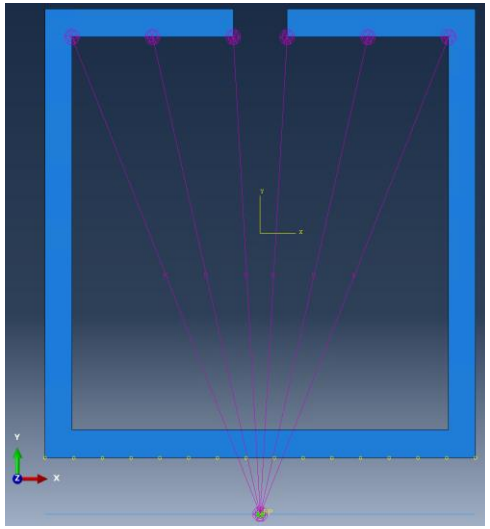
Case 2



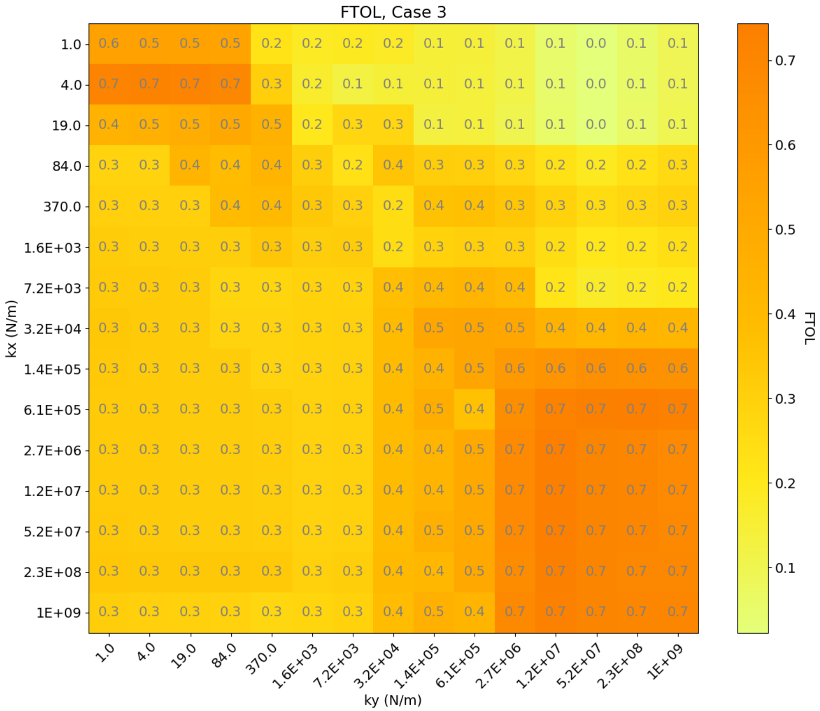
- The second assessed case includes additional springs attached to the side of the BARC. This setup found an improved RMS dB error of 4.3 dB.

Test Fixture Attachment Points



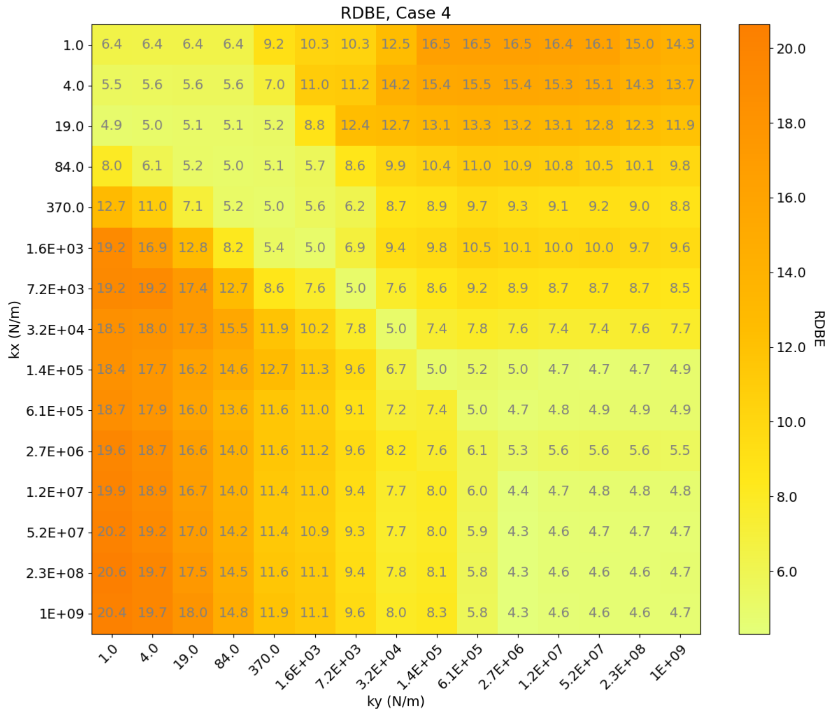


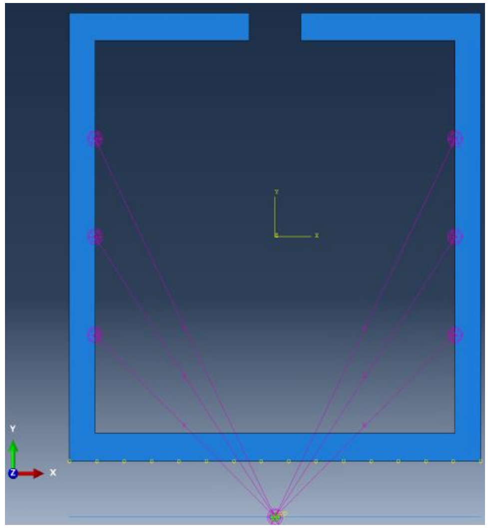
Case 3



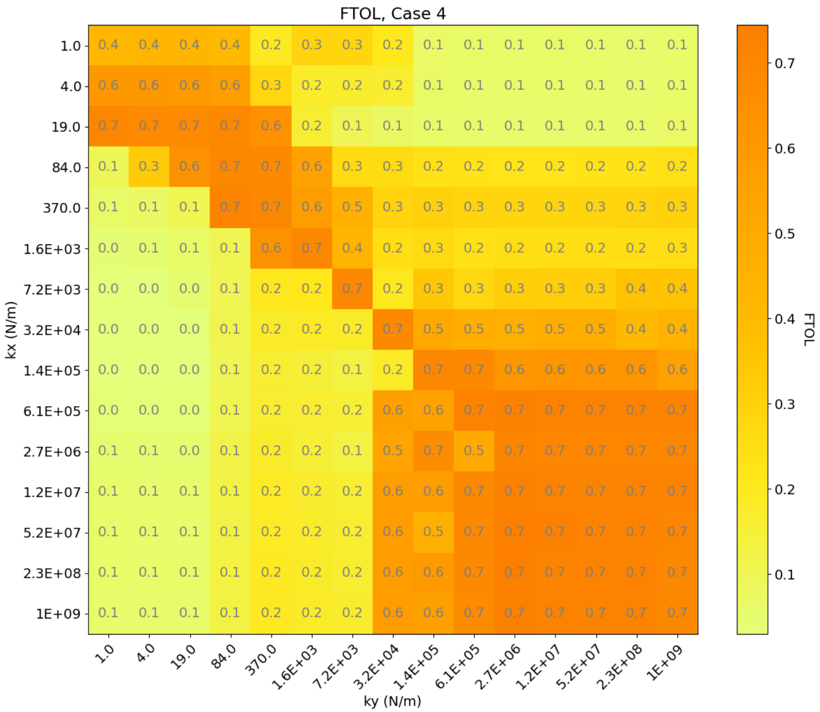
- The third assessed case has springs attached only to the top of the BARC. This case failed to improve upon the control case.

Test Fixture Attachment Points





Case 4



- The fourth assessed case has springs attached only to the sides of the BARC. This setup found an improved RMS dB error of 4.3 dB.

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