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# Boundary Condition Compensation Map (From Field to Laboratory Response)

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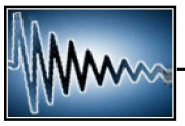
# Motivation

- *Laboratory vibration tests typically mimic field environment dynamics*
- *<u>Any</u> difference between the boundary conditions change the dynamic characteristics of the device under test*



# Motivation

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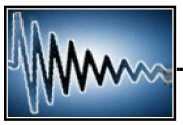
## Field Environment

https://share-ng.sandia.gov/news/resources/news_releases/images/2017/TTR_FlyBy.jpg



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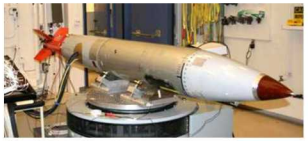

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## Laboratory Test

https://www.sandia.gov/news/publications/lab_accomplishments/articles/2016/nuclear-weapons-engineering.html

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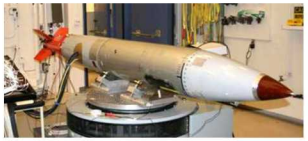

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**Airplane ≠ Shaker Fixture**

# Motivation

- *Two beam assembly used to demonstrate the problem*

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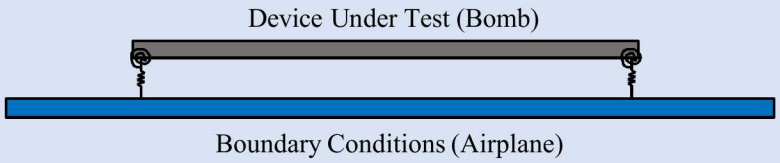

# Motivation

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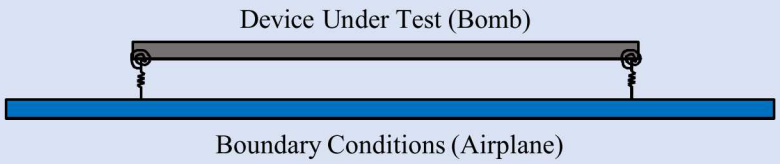


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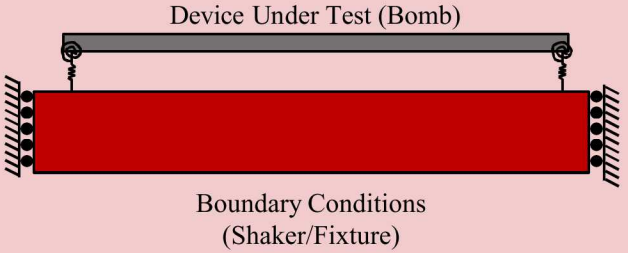
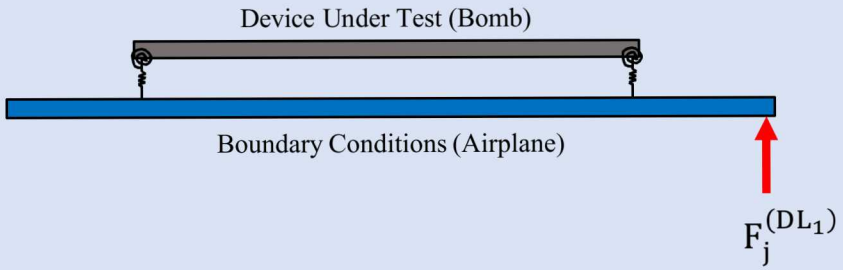


# Motivation

## Reference Excitation Location

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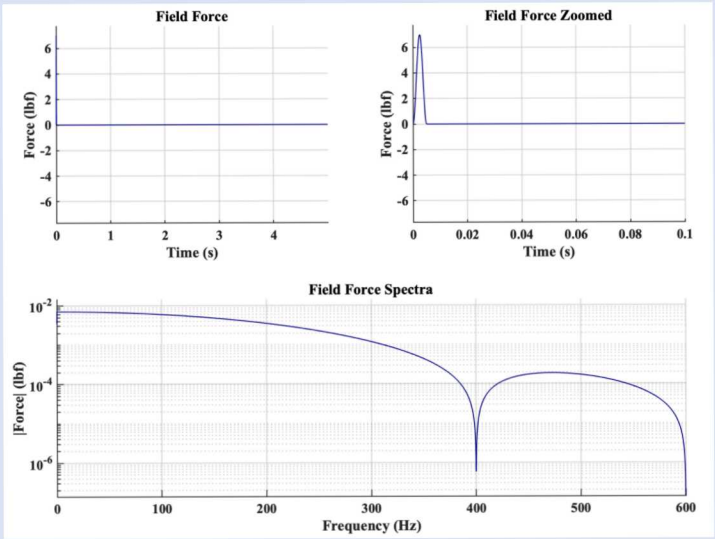

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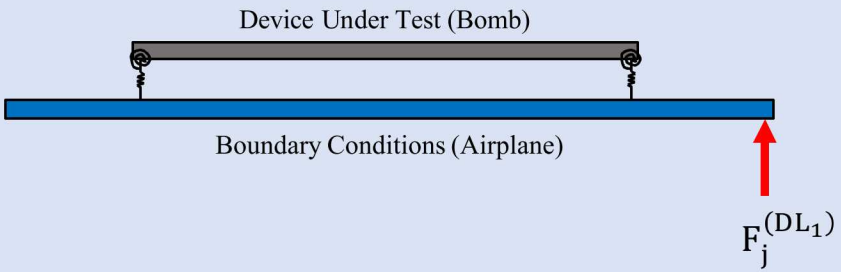


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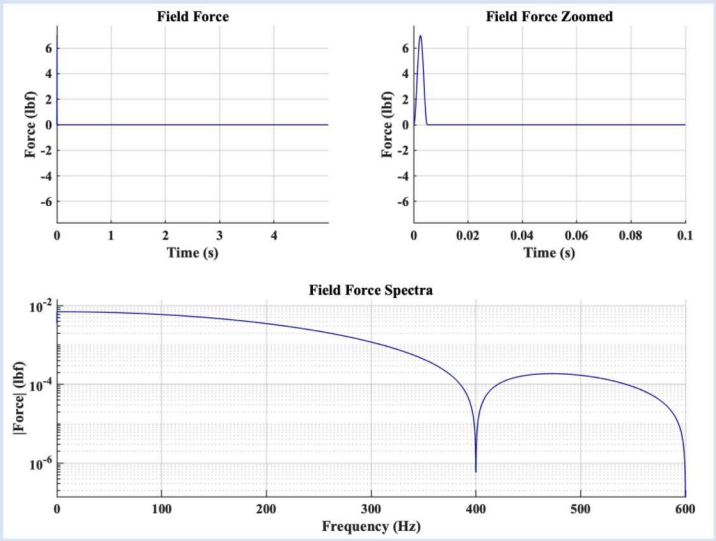


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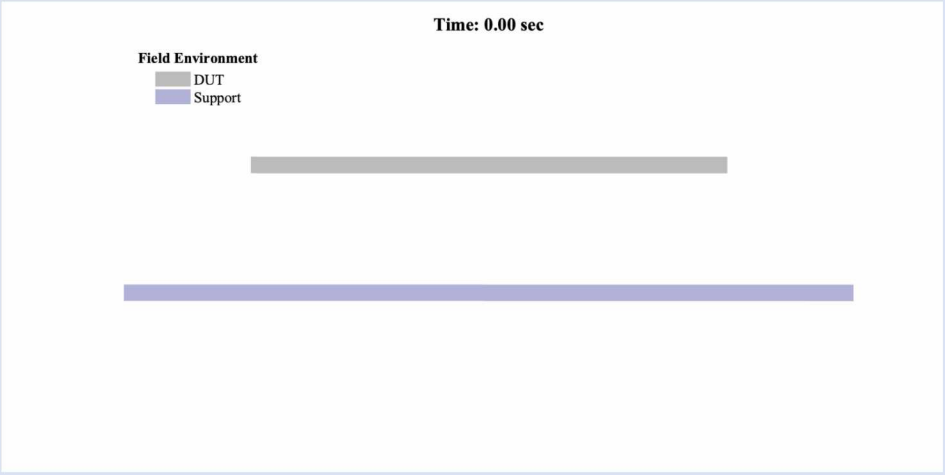
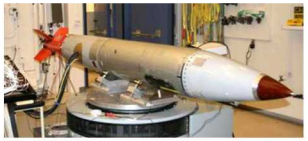



**Reference response, try to match in laboratory**

# Motivation



***How can the laboratory test system be excited to replicate the DUT field environment dynamics?***

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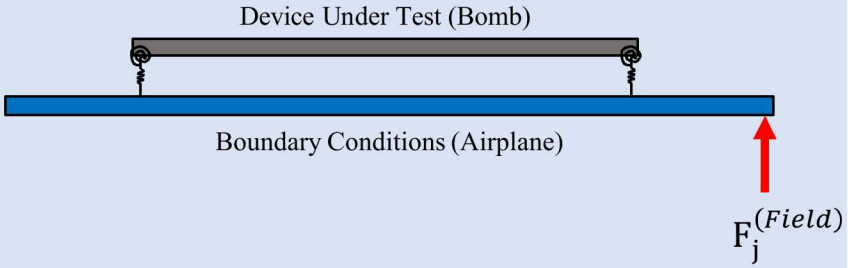


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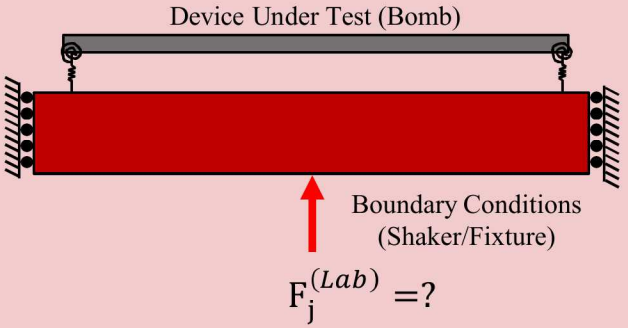

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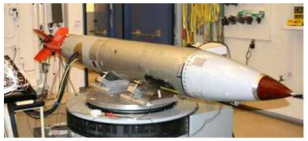

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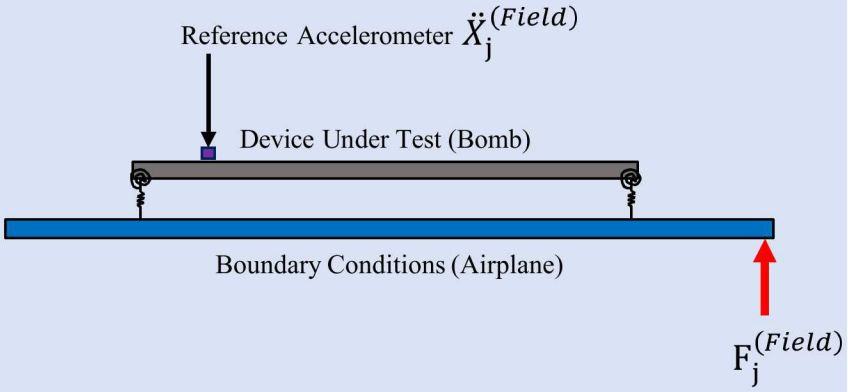


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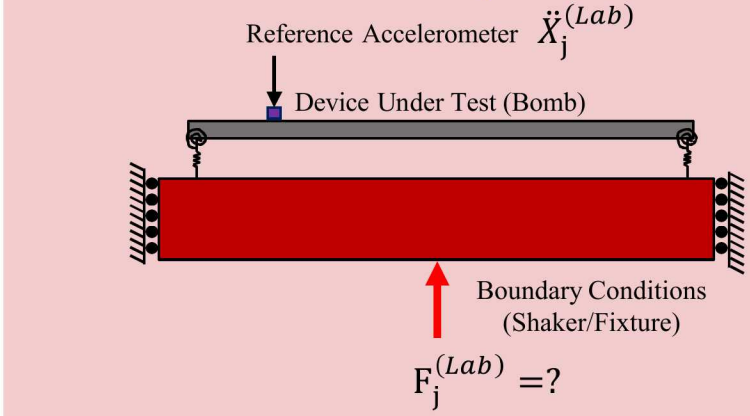


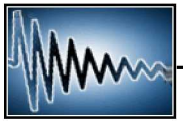

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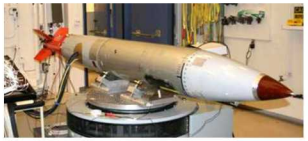

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$$\mathrm{F}_{\mathrm{j}}^{(Lab)} = H_{ij}^{(Lab)^{g}} \ddot{X}_{\mathrm{j}}^{(Lab)}$$

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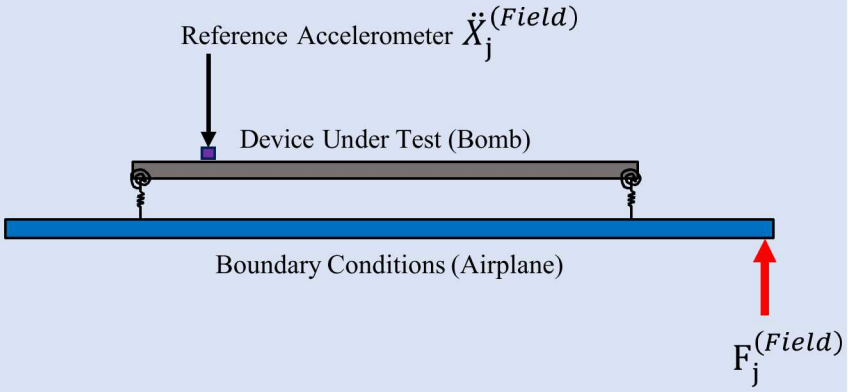


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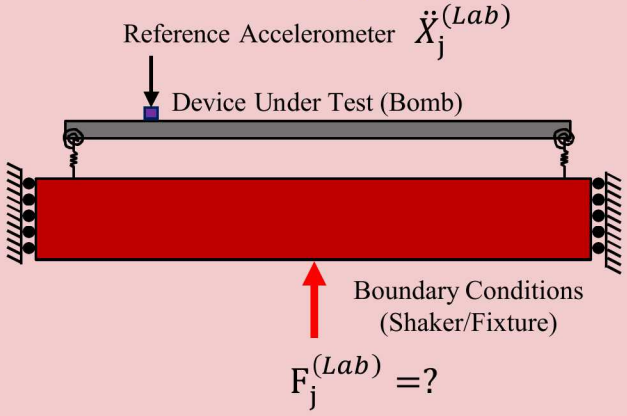

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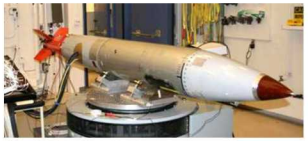

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$$F_j^{(Lab)} = H_{ij}^{(Lab)} {}^{g}\ddot{X}_j^{(Lab)}$$

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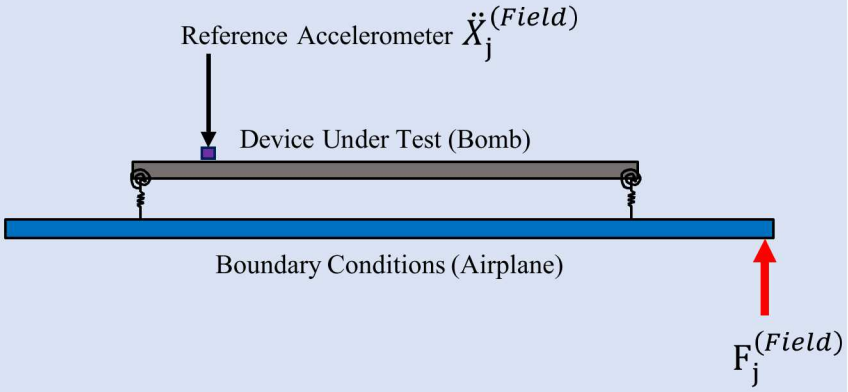


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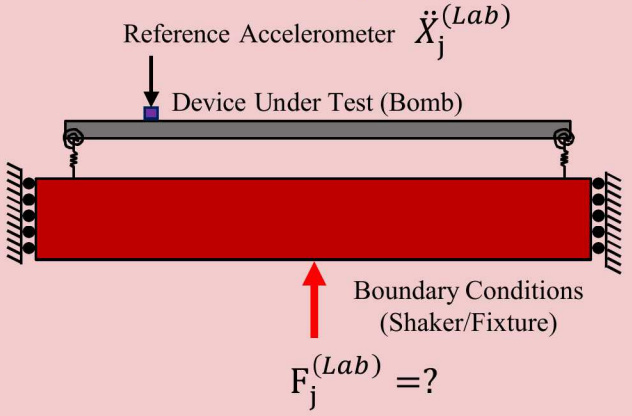


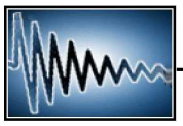

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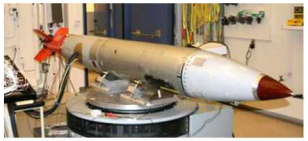

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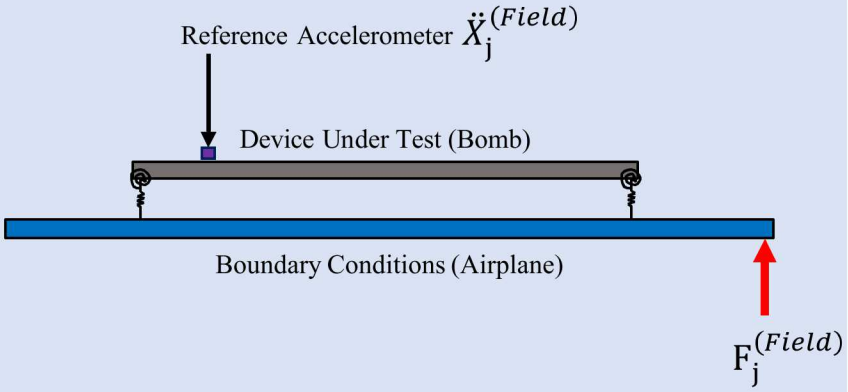


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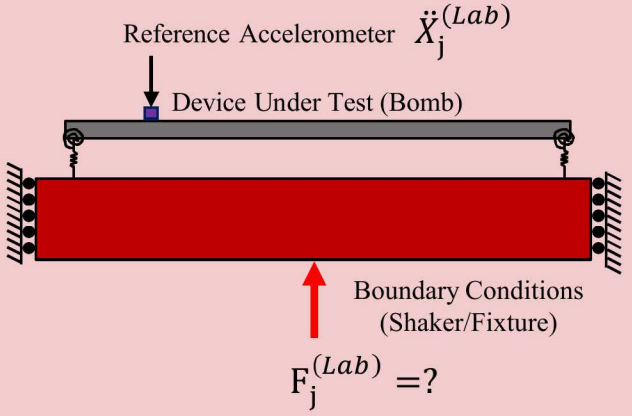

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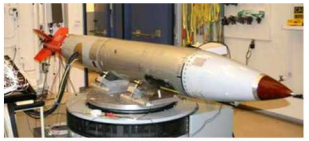

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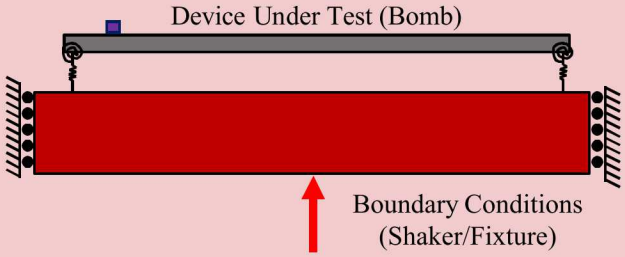


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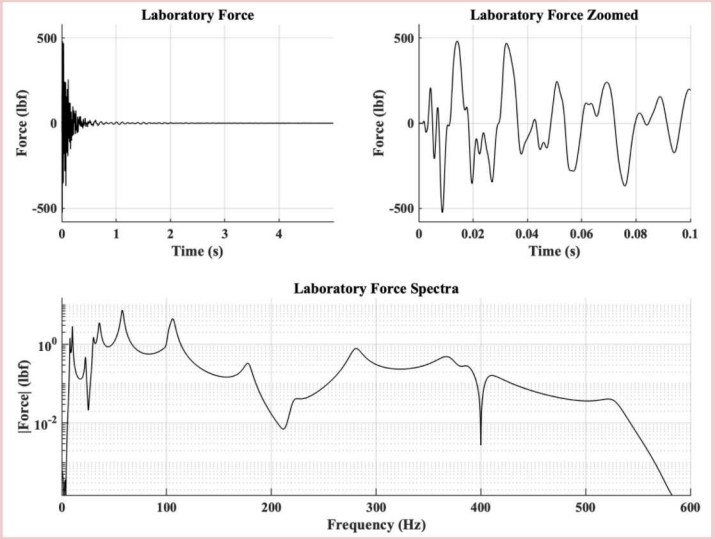


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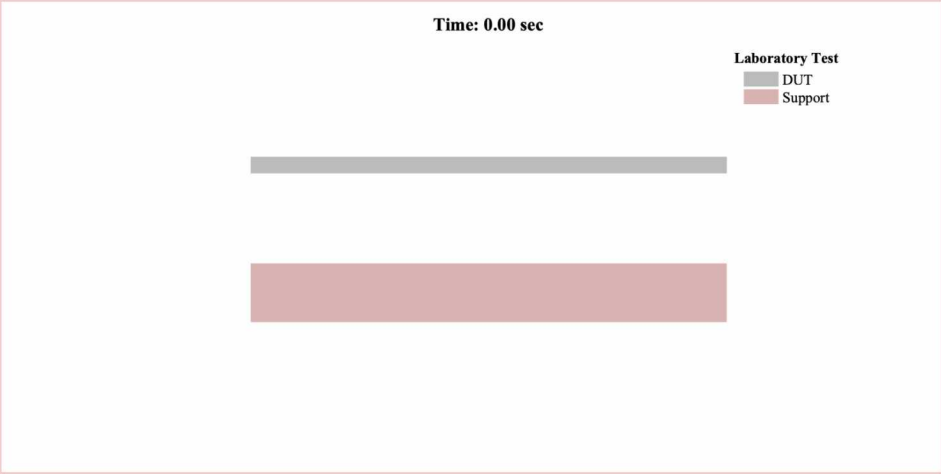

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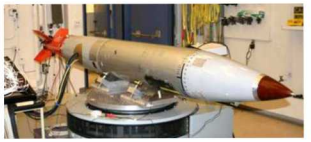
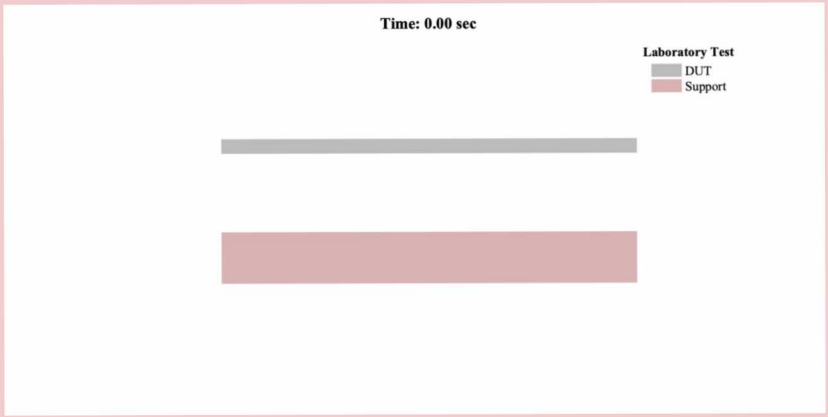


## Field Environment Response


## Matched Laboratory Test Response



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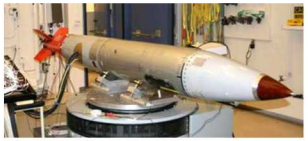

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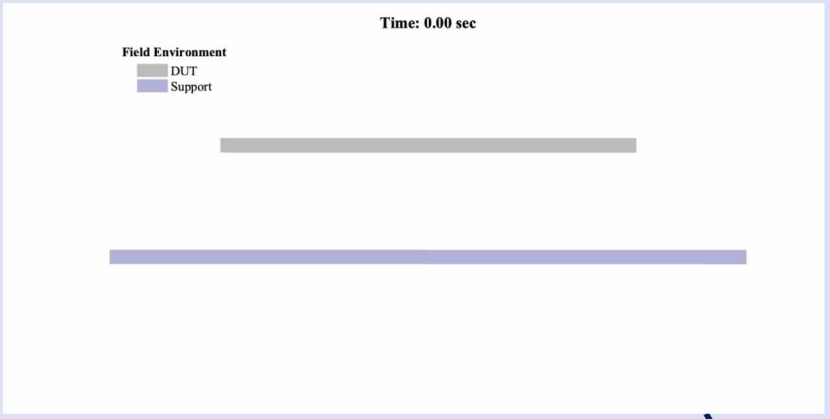


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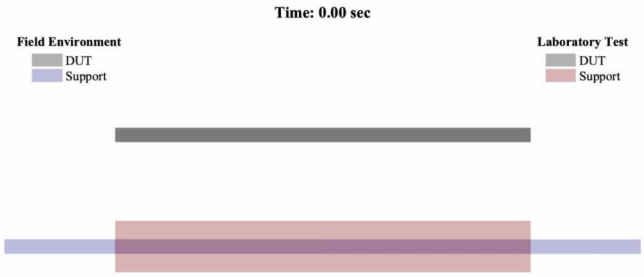

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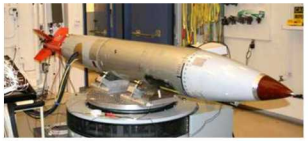

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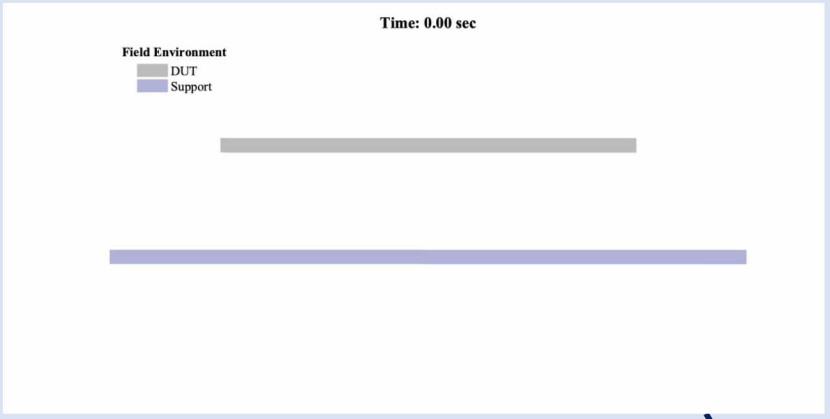


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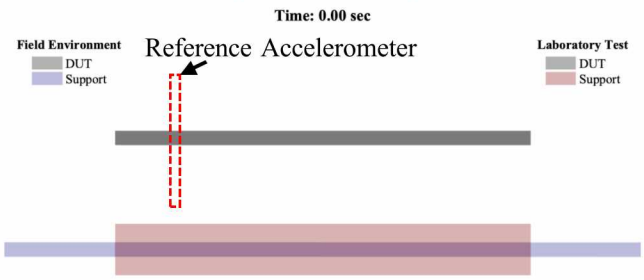


**Field and Laboratory DUT Response Only Match at Reference DOF!**

# Motivation

- *We need to allow and account for laboratory fixture flexibility*

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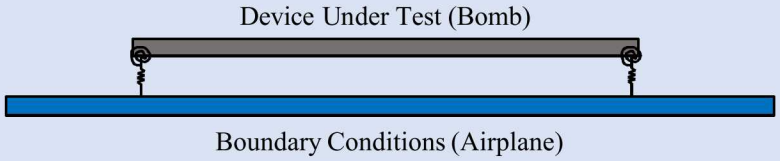


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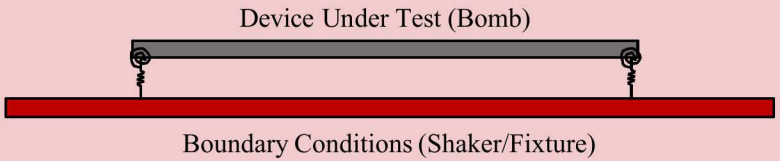

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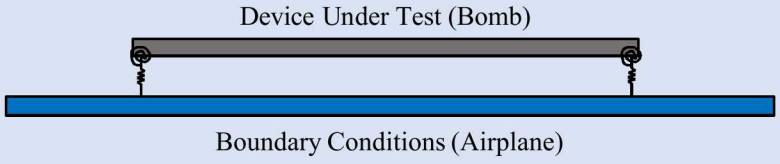


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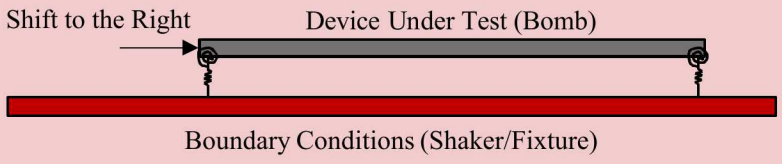

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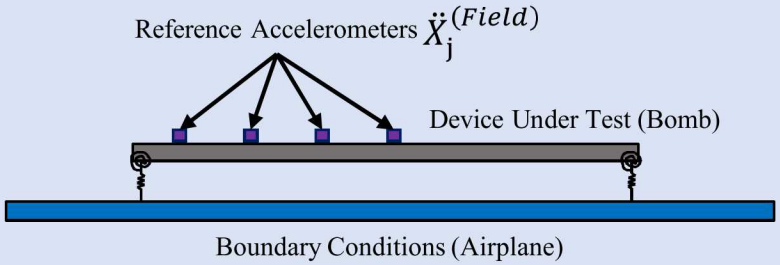


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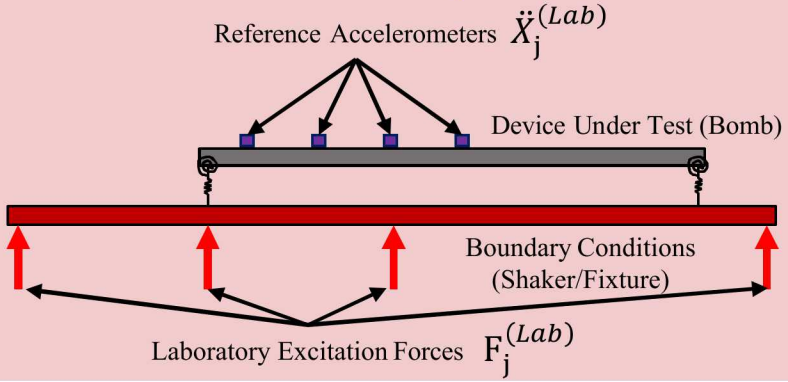

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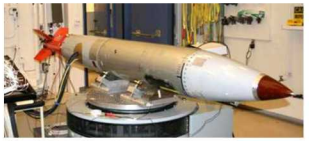

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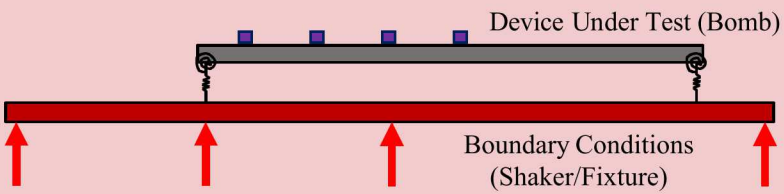


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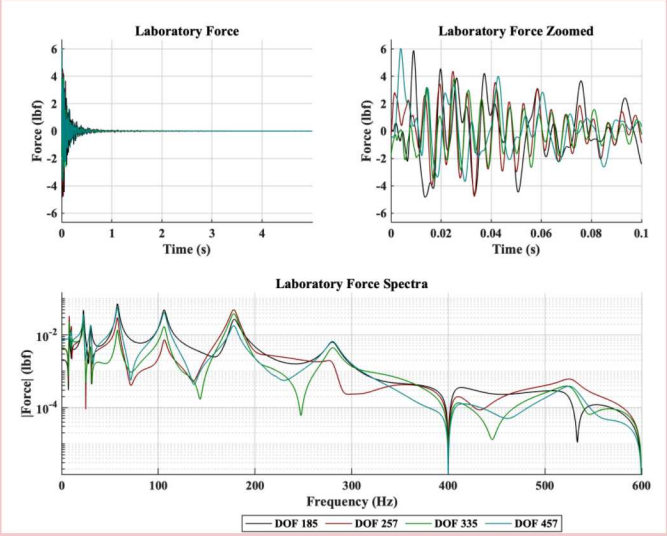


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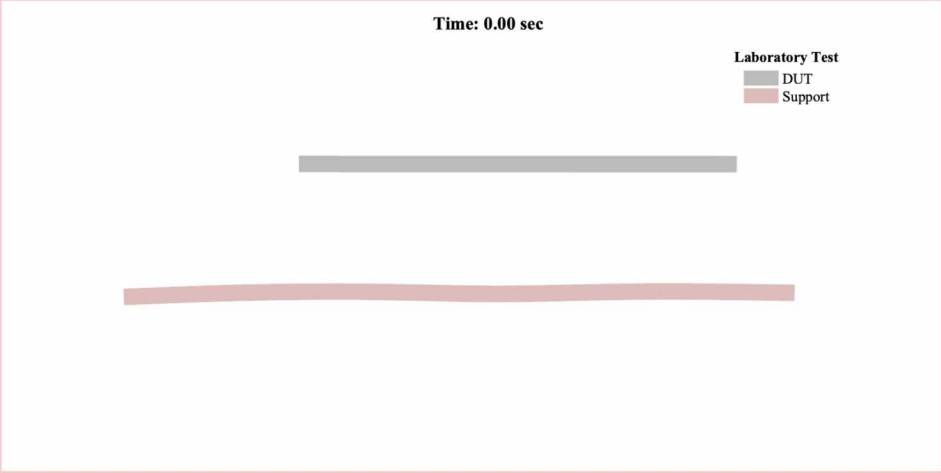

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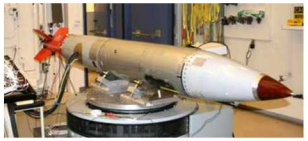

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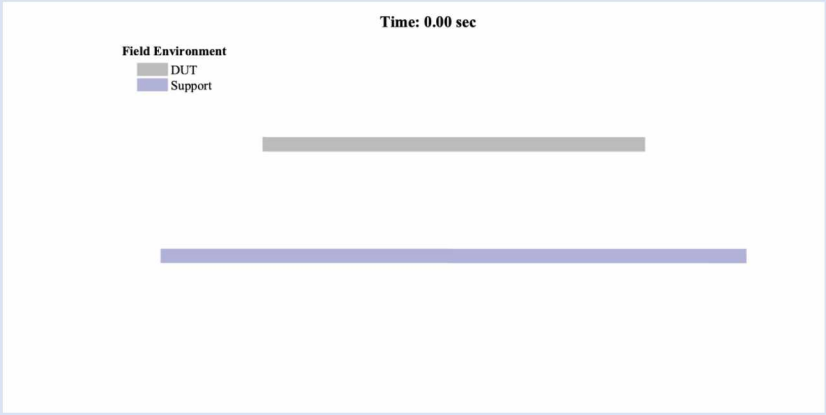


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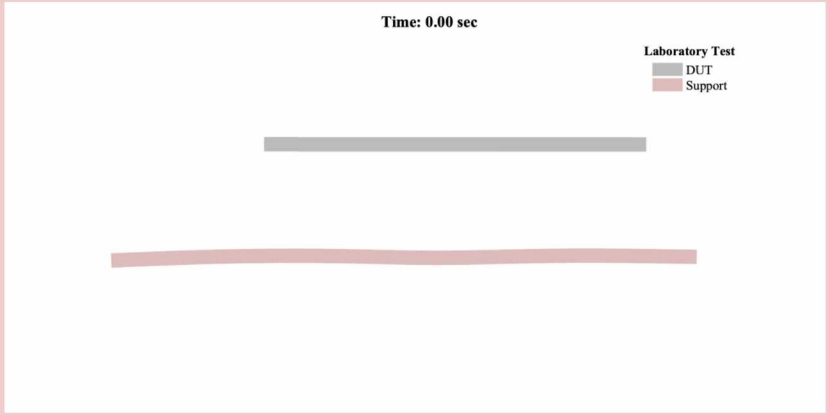

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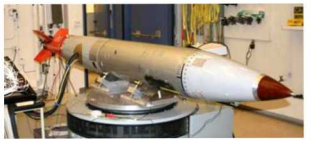
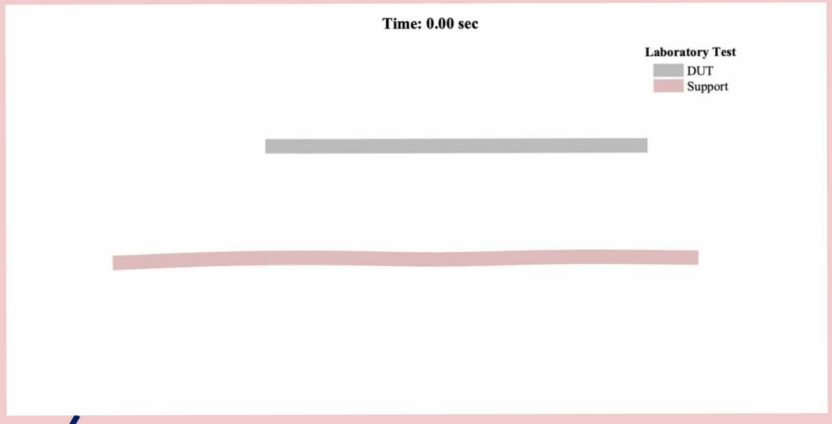
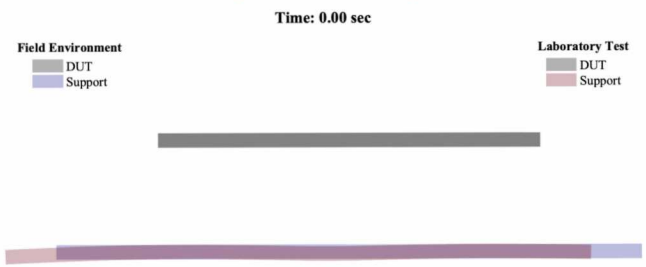


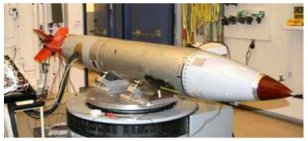
## Field Environment Response


## Matched Laboratory Test Response



# Motivation



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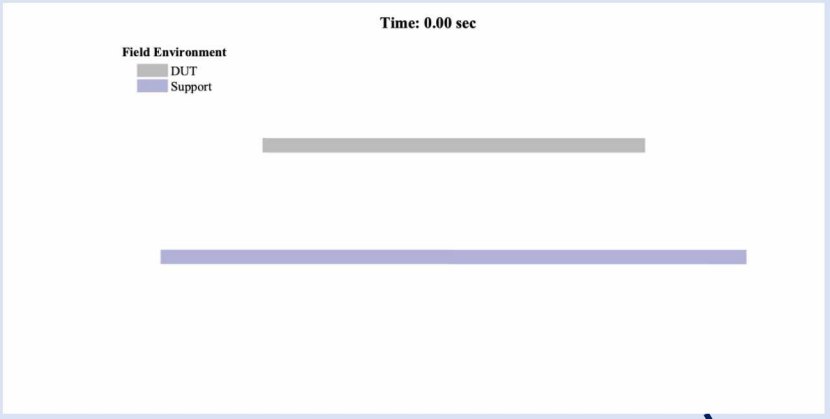


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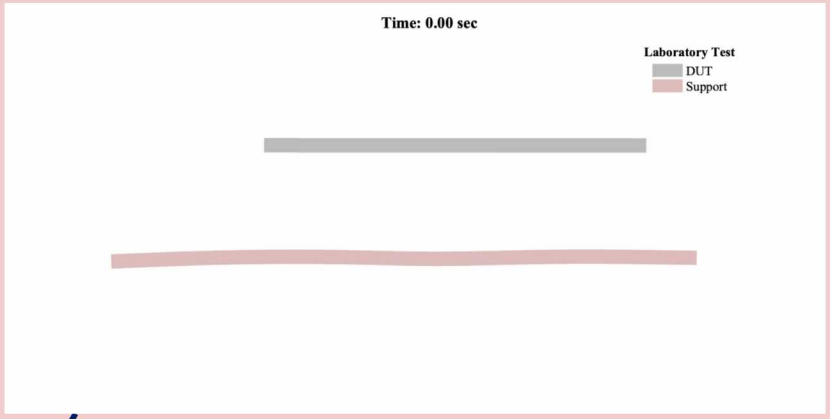
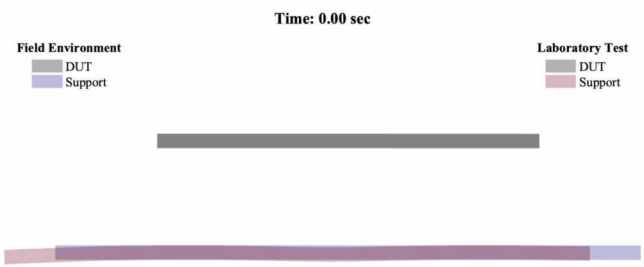
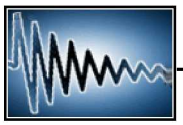



**Field and Laboratory DUT Response Match Perfectly at all DUT DOFs!**

# Motivation

***How are the laboratory test system modes used to create the field environment motion?***



# Motivation

*How are the laboratory test system modes used to create the field environment motion?*

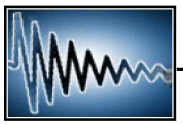
*Specifically, which laboratory test system modes are used to create each field environment modal response?*

Laboratory Test System Modal Responses

Field Environment System Modal Responses

$$\left\{\ddot{P}^{(Lab)}\right\} = \left[\overline{T}^{(Field)\rightarrow(Lab)}\right]\left\{\ddot{P}^{(Field)}\right\}$$

Modal Transformation Matrix from Field to Laboratory



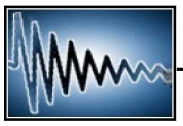
# Theory

**Desired Relationship:**

$$\left\{\ddot{P}^{(Lab)}\right\} = \left[\overline{T}^{(Field)\rightarrow(Lab)}\right]\left\{\ddot{P}^{(Field)}\right\}$$

**Form of Solution:**

$$\left\{F_j^{(Lab)}\right\} = \left[H_{ij}^{(Lab)}\right]^g \left\{\ddot{X}_i^{(Field)}\right\}$$



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$$\downarrow$$

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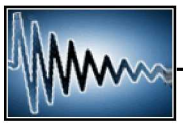

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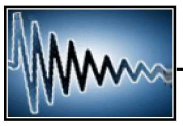

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$$\left\{\ddot{X}_i^{(Lab)}\right\} = \left[H_{ij}^{(Lab)}\right]\left[H_{ij}^{(Lab)}\right]^g \left\{\ddot{X}_i^{(Field)}\right\}$$

$$\downarrow \text{ Modal transformation}$$

$$\left\{\ddot{P}^{(Lab)}\right\} = \left[\overline{H}^{(Lab)}\right]\left[U_j^{(Lab)}\right]^T \left[\left[U_i^{(Lab)}\right]\left[\overline{H}^{(Lab)}\right]\left[U_j^{(Lab)}\right]^T\right]^g \left[U_i^{(Field)}\right]\left\{\ddot{P}^{(Field)}\right\}$$

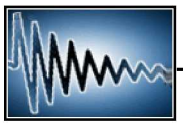
$$\left[\overline{T}^{(Field)\rightarrow(Lab)}\right]$$

# Theory

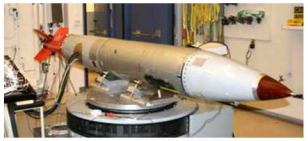
The Modal Amplitude Contribution Matrix (MACM) is then formed by multiplying each field environment transformation by the field environment modal response.

$$\left[M\ddot{A}CM\right] = \left[\bar{T}^{(Field)\rightarrow(Lab)}\right] \cdot \left\{\ddot{P}^{(Field)}\right\}^{T}$$

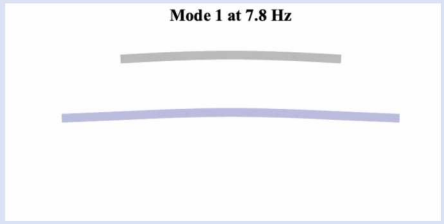
The MACM matrix gives us physical insight into how modes of the laboratory test are utilized to create the field environment DUT response for a set of excitation locations.

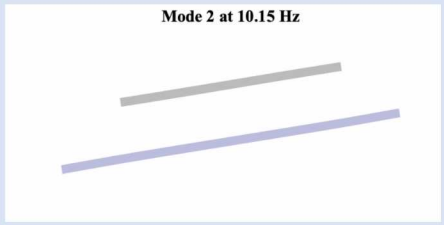


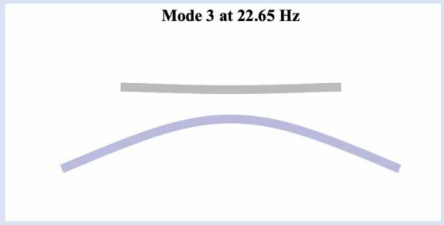
# Theory

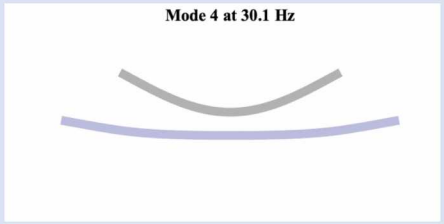


## Field Environment Modes



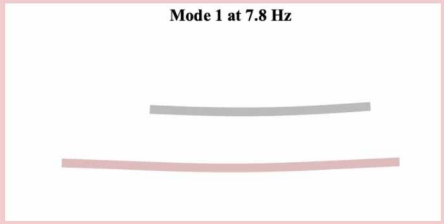



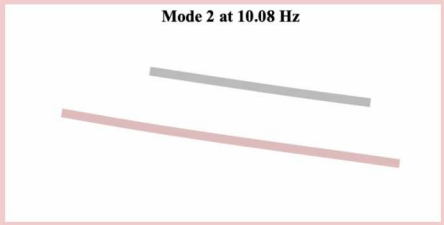



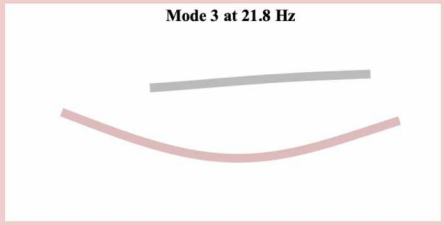

$$\left[\overline{T}(Field)\rightarrow(Lab)\right]$$

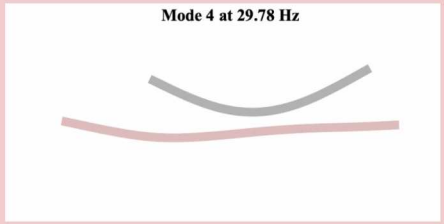
The transformation matrix describes how linear combinations of laboratory test modes are used to create the field environment response

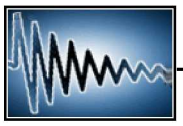
## Laboratory Test Modes



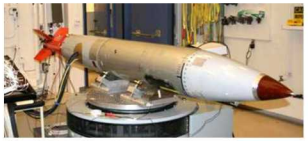



# Theory



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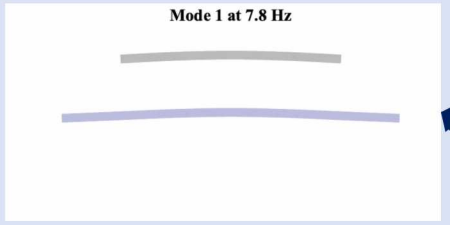
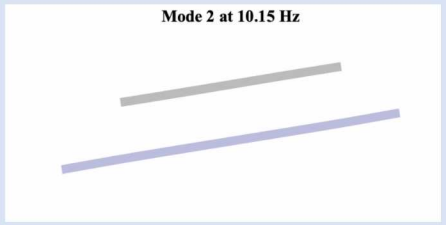
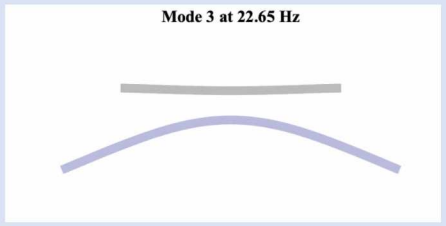
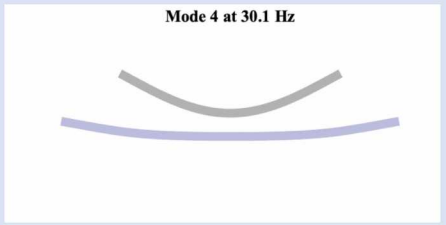



0.99

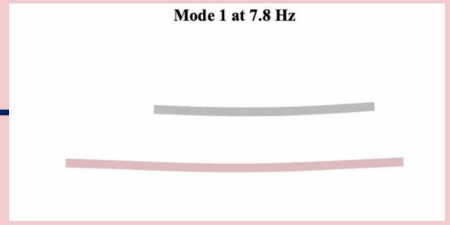
-0.04

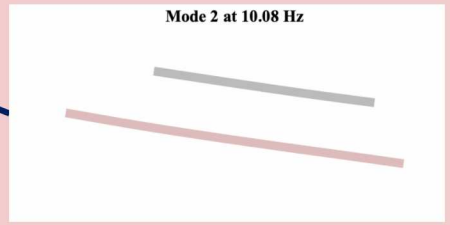
0.01

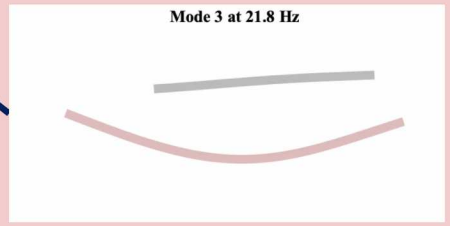
0.00

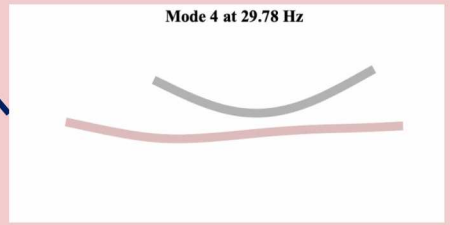
$\left[\overline{T}^{(DL_1)\rightarrow(DL_2)}\right]$

## Laboratory Test Modes



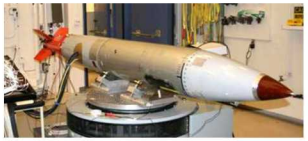




*The transformation matrix described how linear combinations of laboratory test modes are used to create the field environment response*

# Theory



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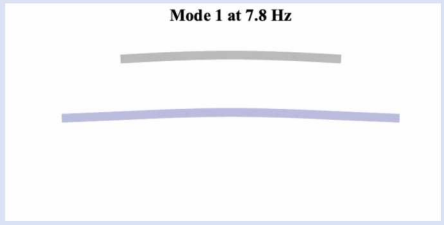
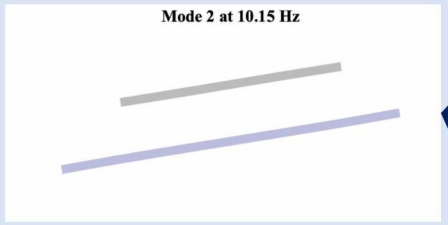
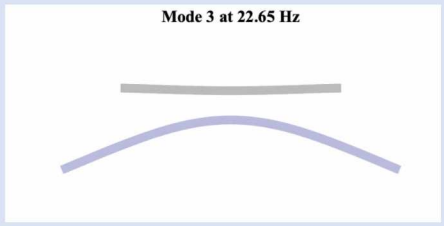
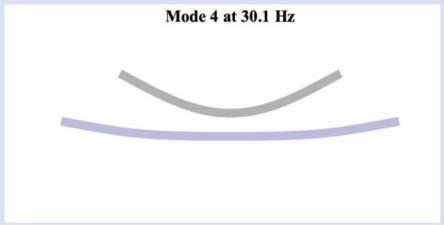



0.21

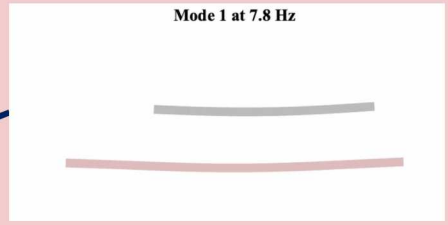
-1.02

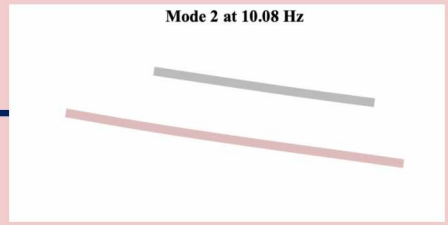
-0.00

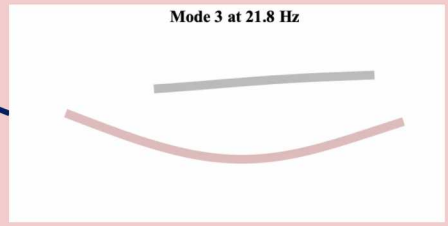
0.01

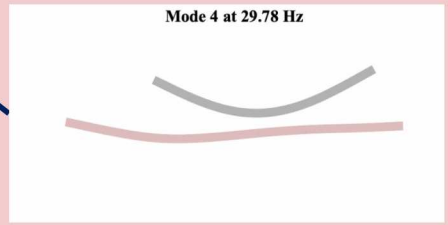
$\left[\overline{T}^{(DL_1)\rightarrow(DL_2)}\right]$

## Laboratory Test Modes

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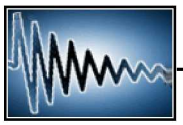
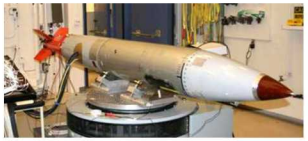


# Theory



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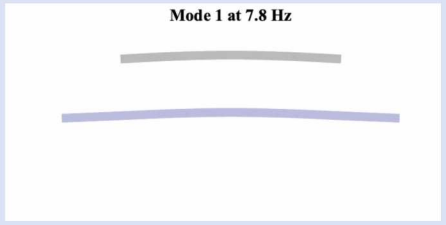
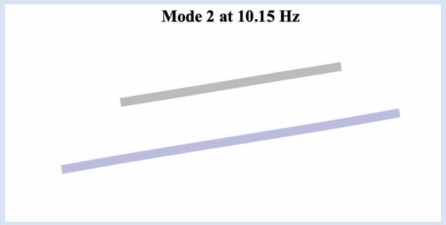
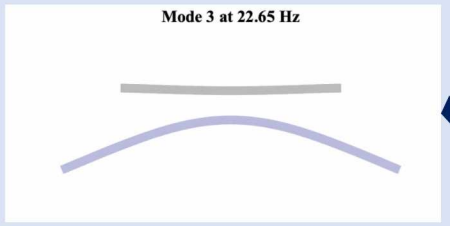
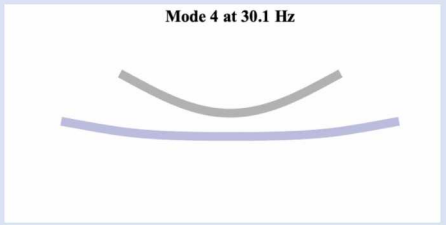
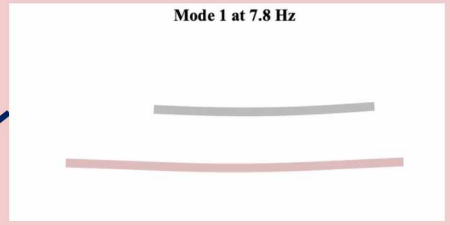


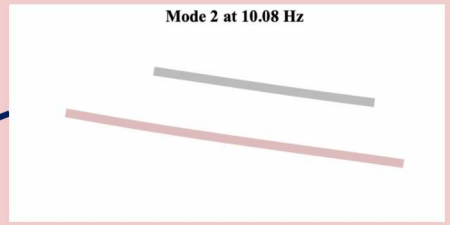



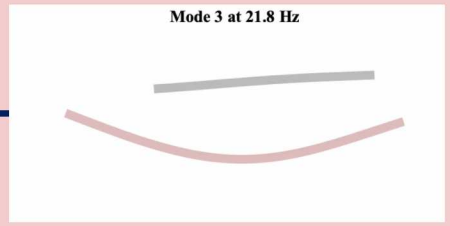



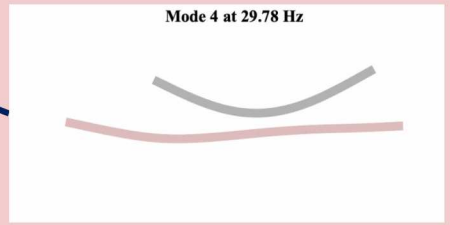




## Laboratory Test Modes




0.26

-0.09

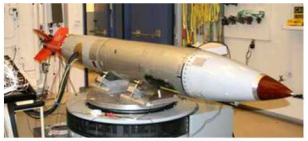
-0.22

$[T^{(DL_1)\rightarrow(DL_2)}]$

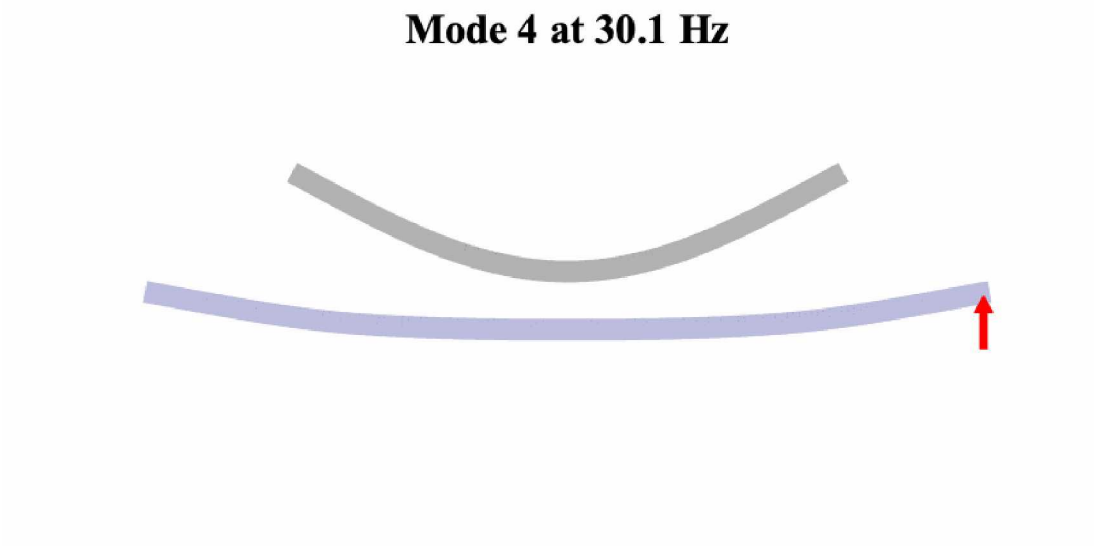
0.06

*The transformation matrix described how linear combinations of laboratory test modes are used to create the field environment response*

# Sine Excitation

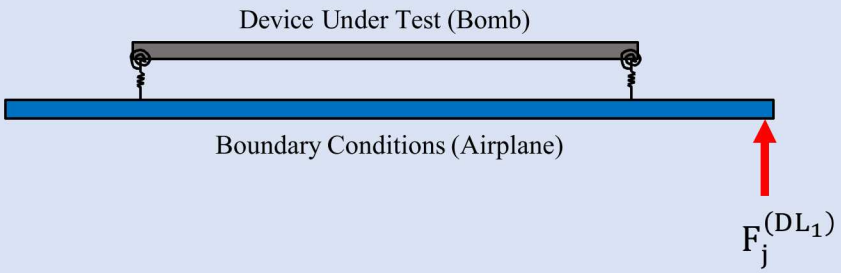


## Simple Example: Sine excitation at field mode #4

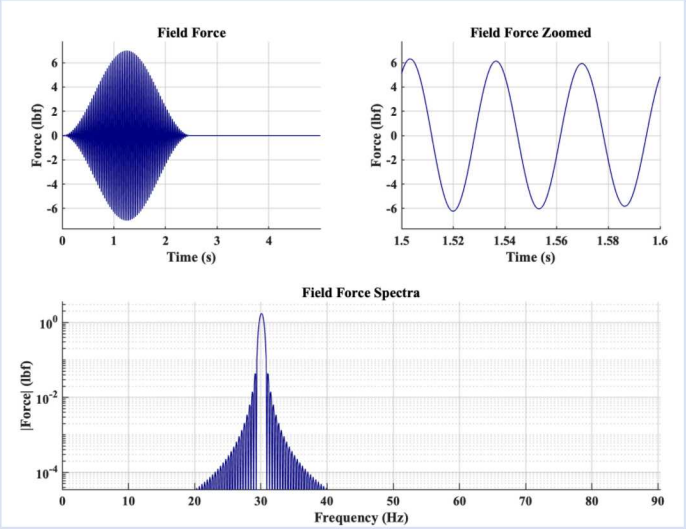


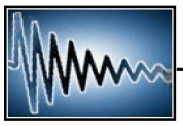
# Sine Excitation

## Reference Excitation Location



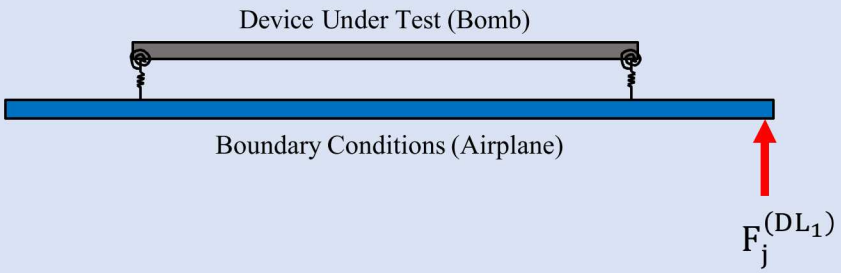

## Reference Excitation Force



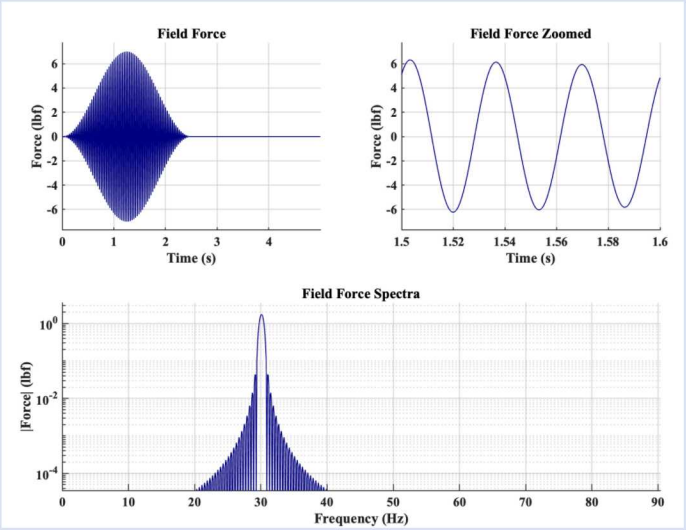



# Sine Excitation

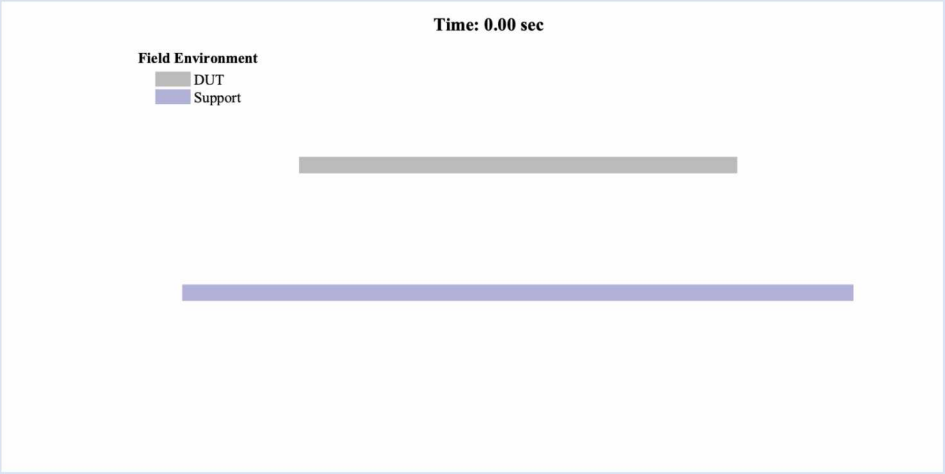
## Reference Excitation Location




## Reference Excitation Force

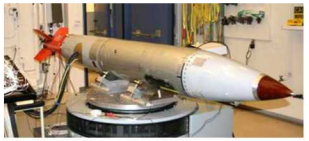



## Reference Response

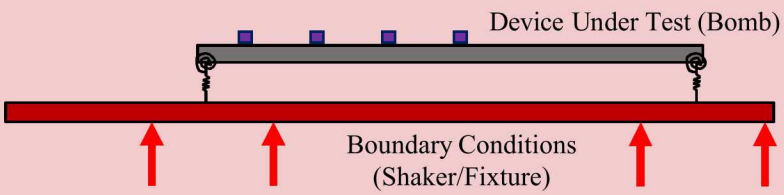



**Reference response, try to match in laboratory**

# Sine Excitation



## Reference Excitation Location

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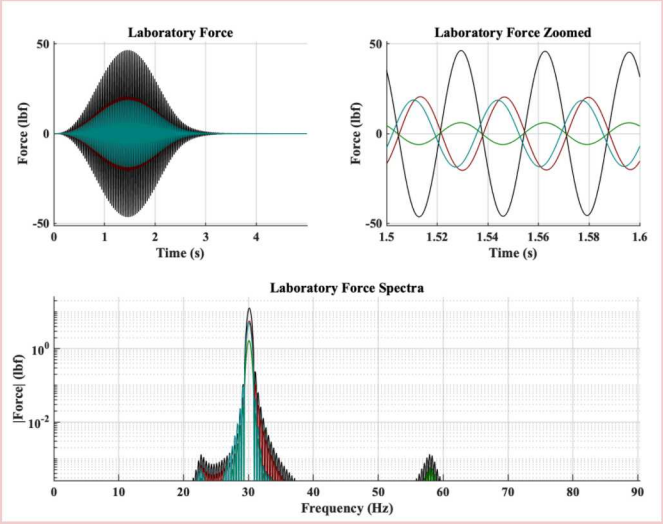


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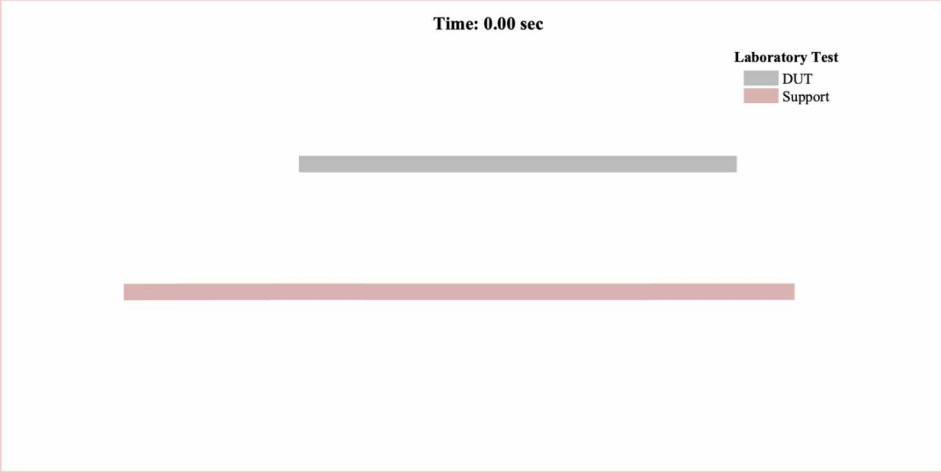
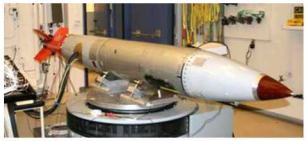
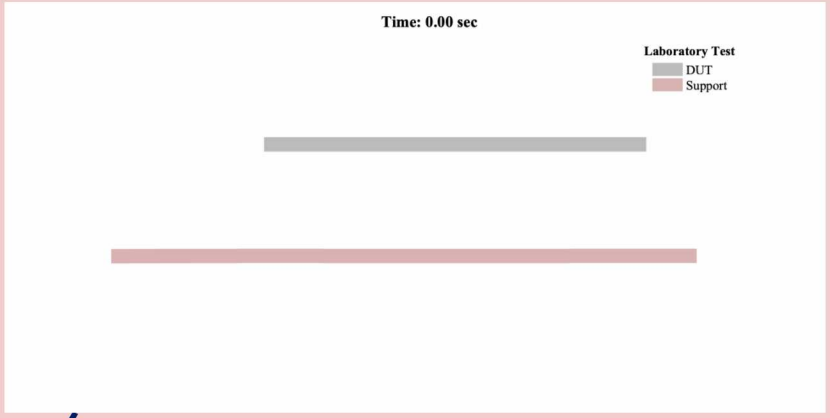


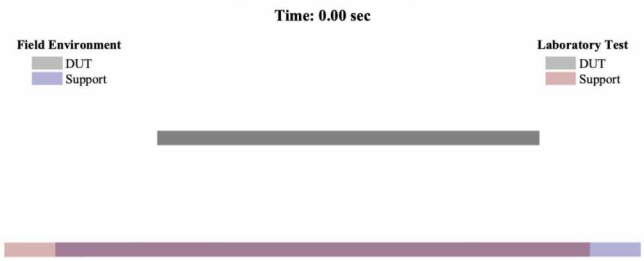
# Sine Excitation



## Field Environment Response

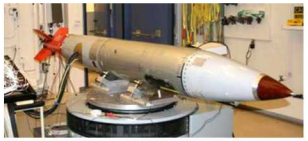

## Matched Laboratory Test Response



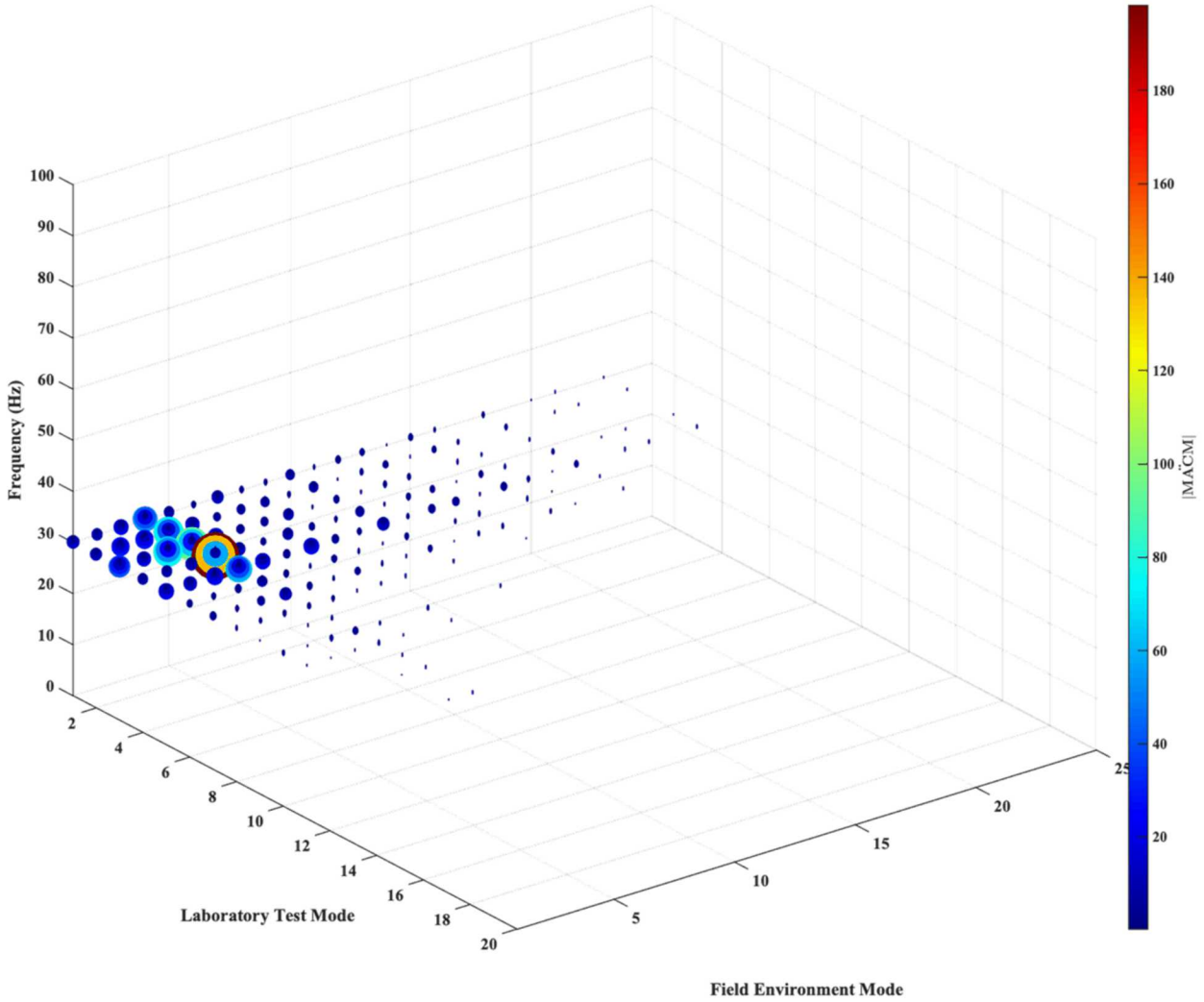




**Field and Laboratory DUT Response Match Perfectly at all DUT DOFs!**

# Sine Excitation



$$[M\ddot{A}CM]$$



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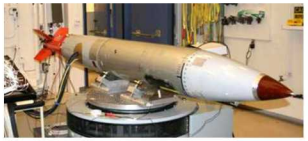
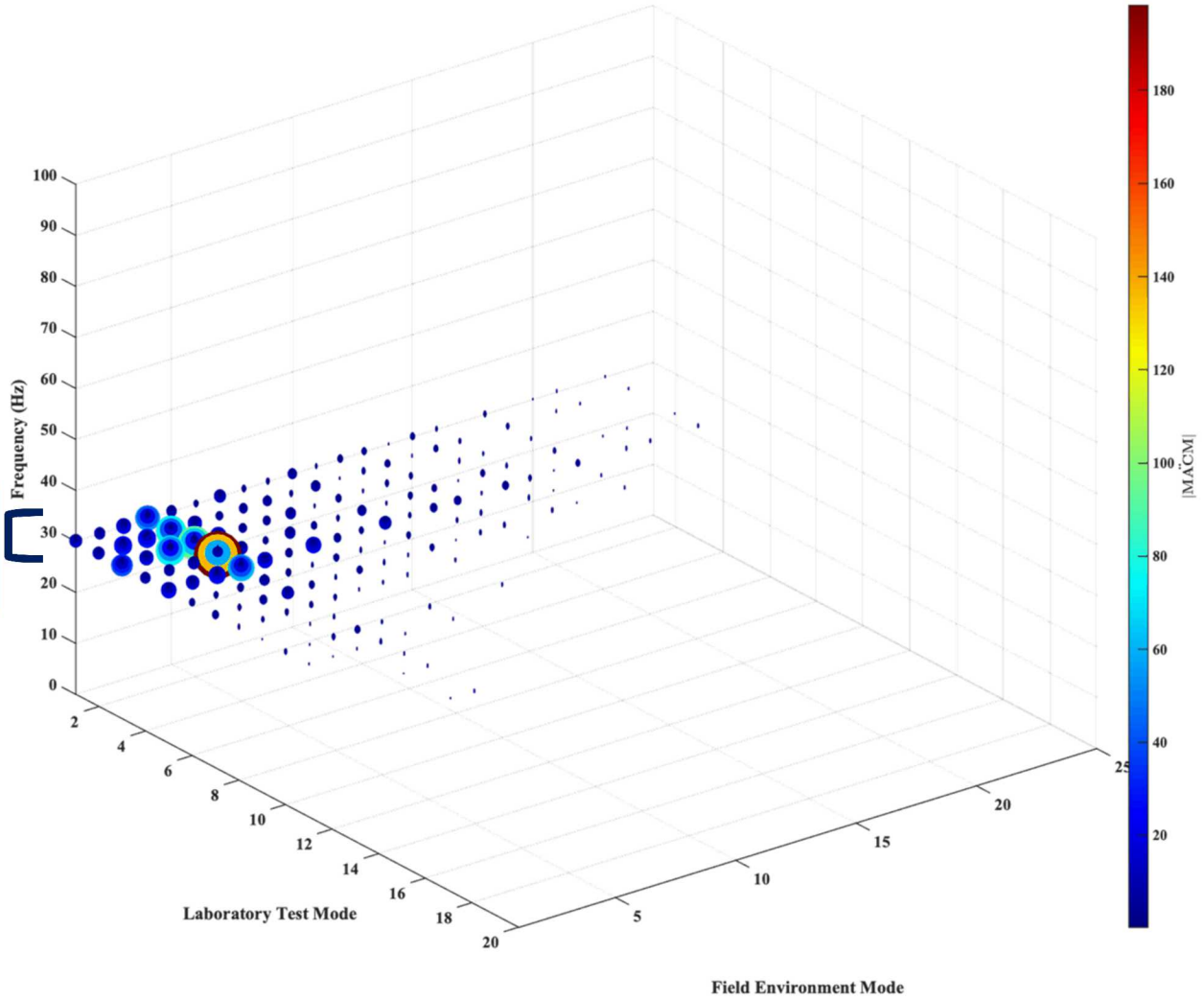
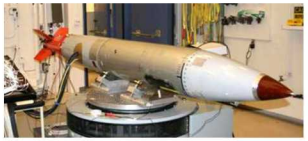


$$[M\ddot{A}CM]$$

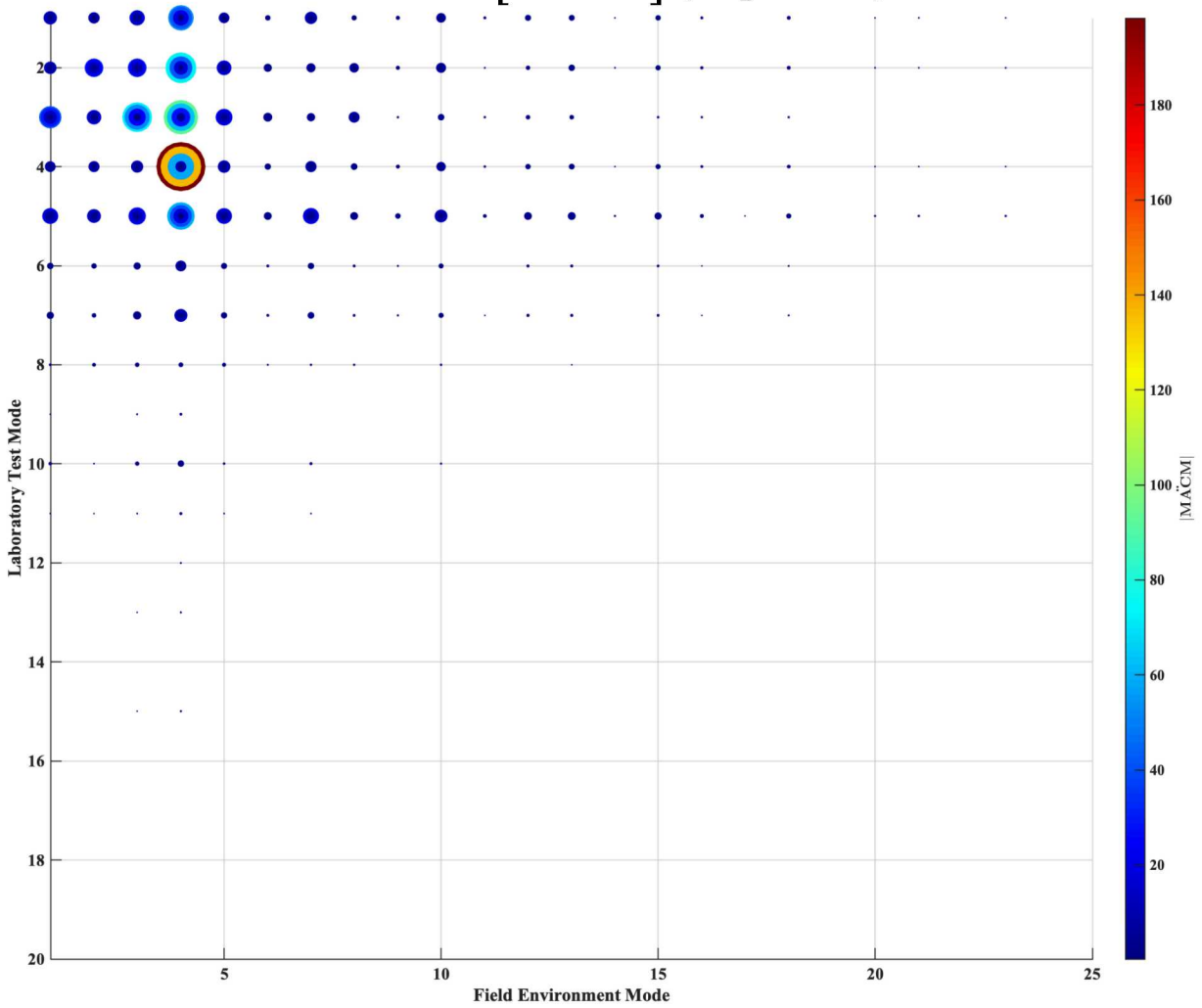



Most of the response is around 30 Hz

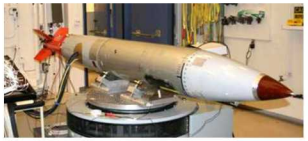
# Sine Excitation



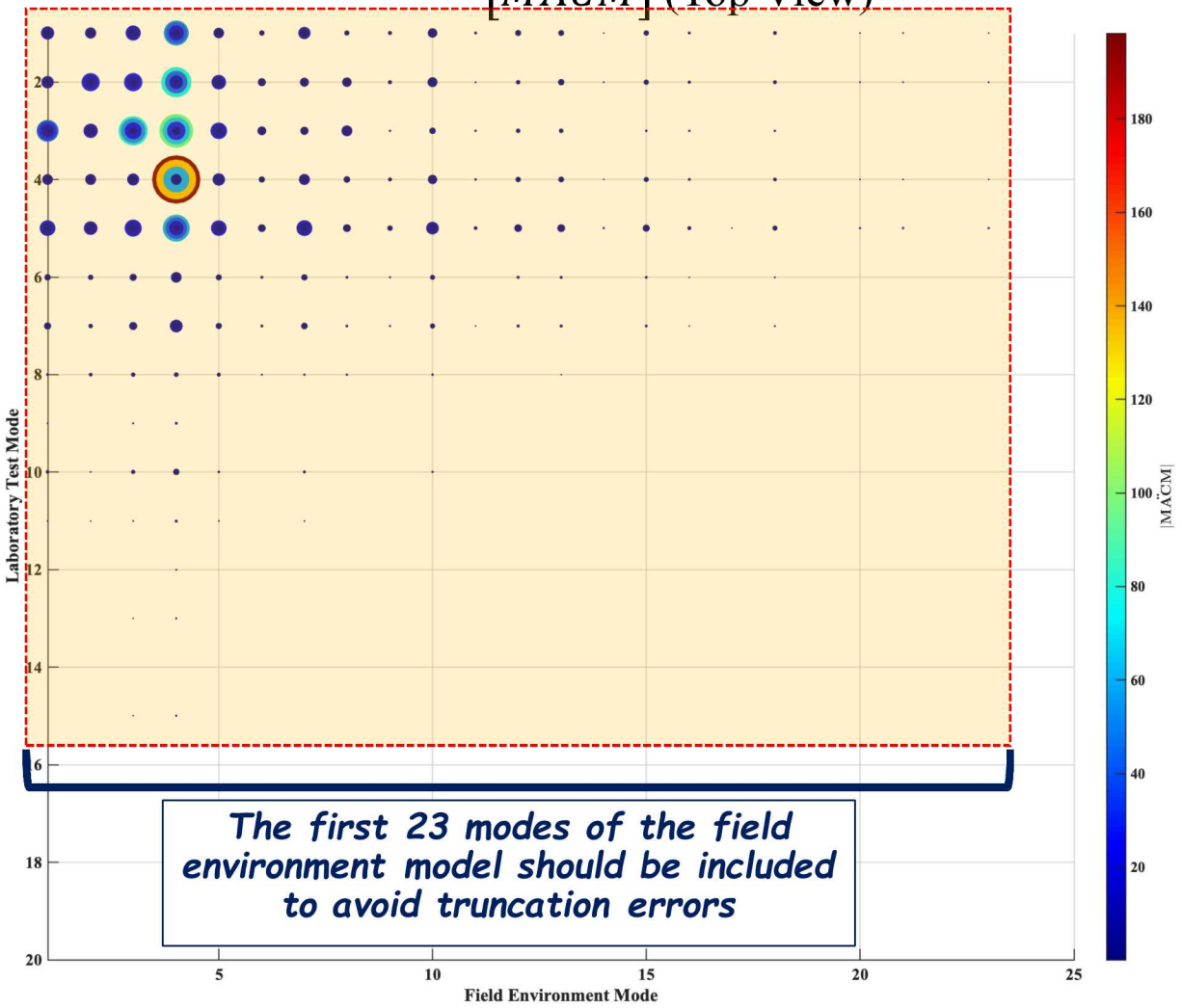
$[M\ddot{A}CM]$ (Top View)



# Sine Excitation

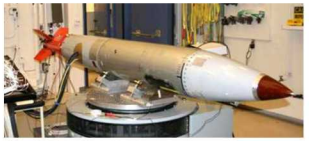


$[MÄCM]$ (Top View)

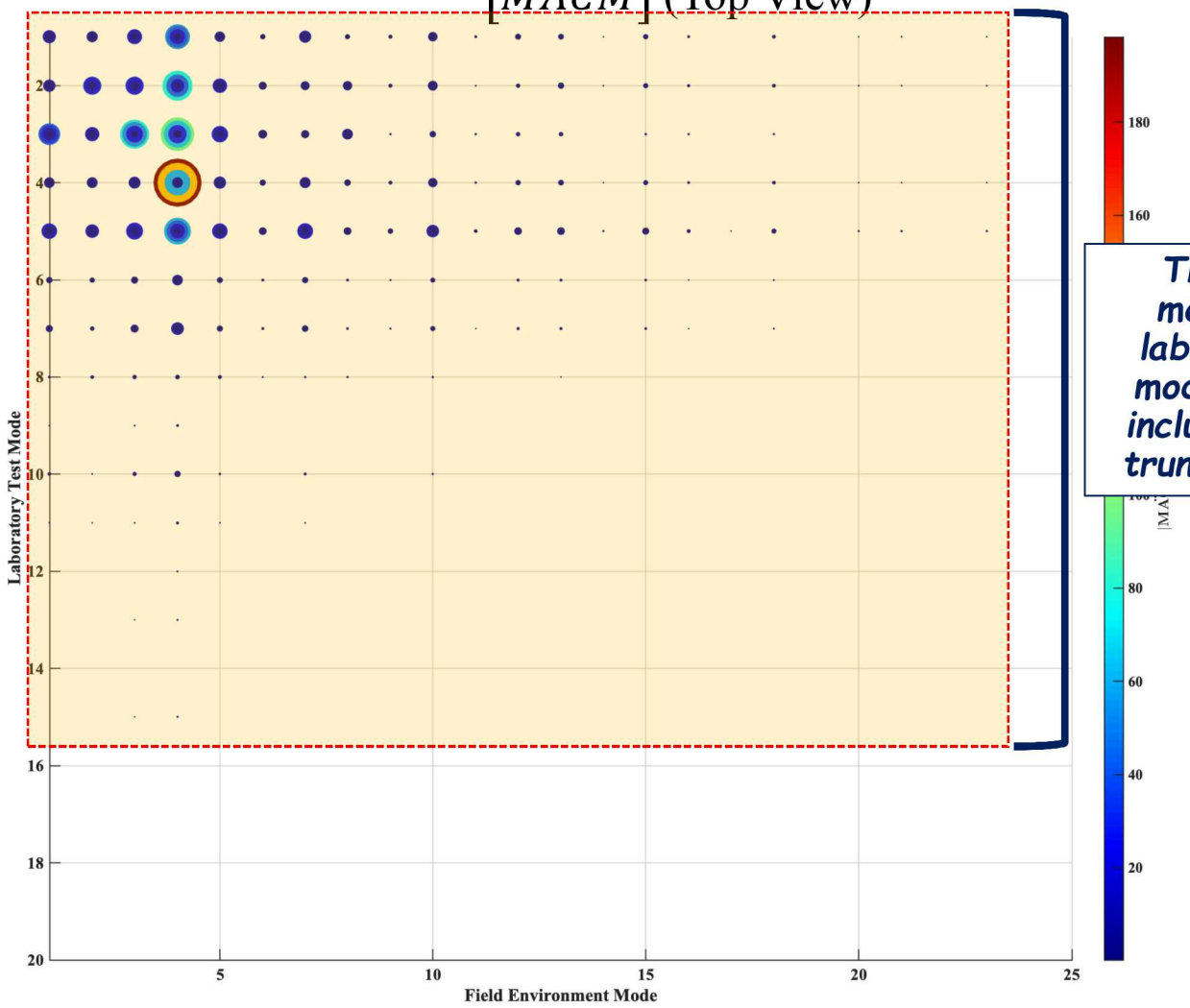



**The first 23 modes of the field environment model should be included to avoid truncation errors**

# Sine Excitation

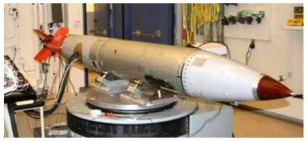


$[M\ddot{A}CM]$ (Top View)

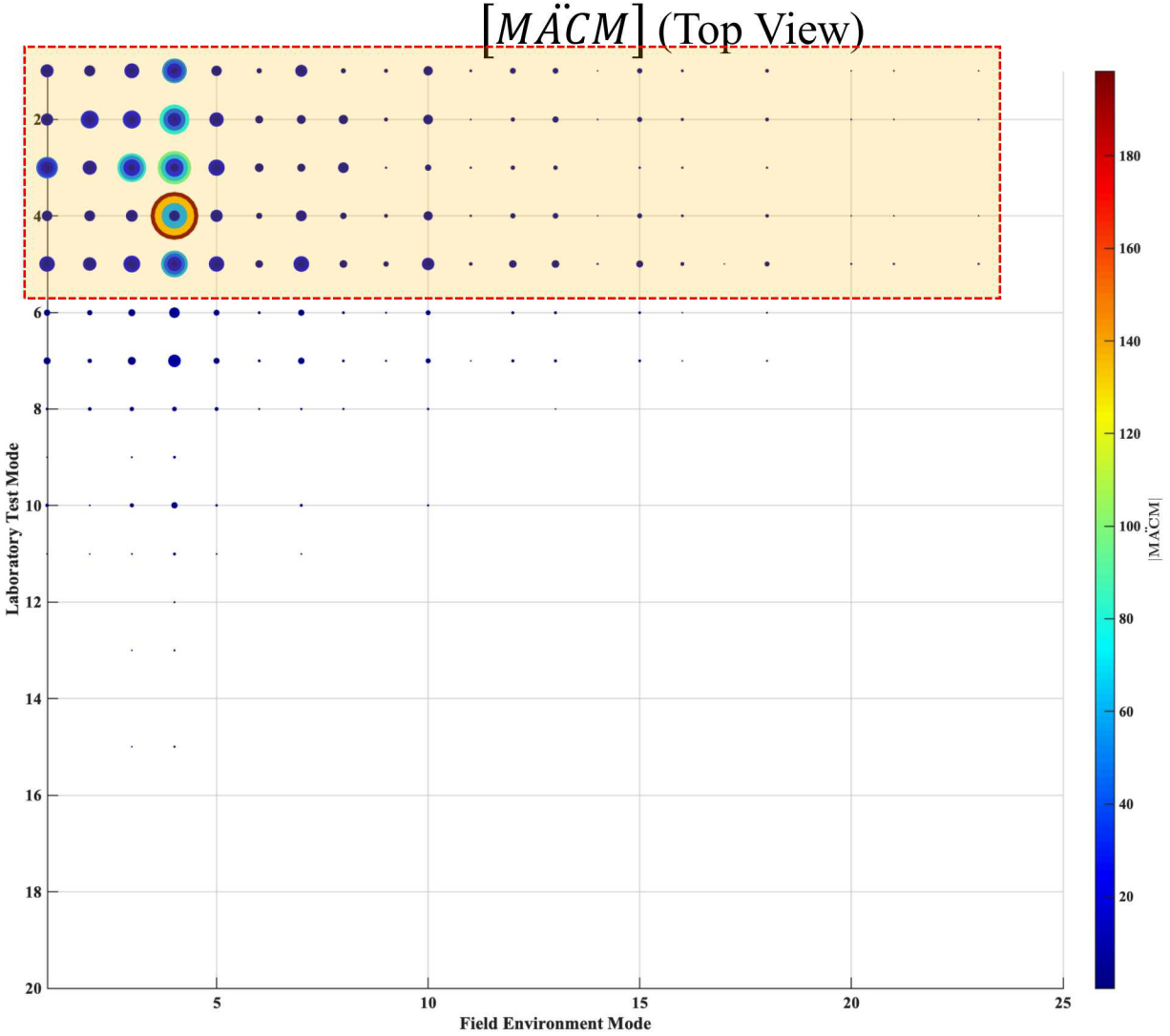


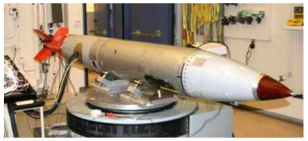

The first 15 modes of the laboratory test model should be included to avoid truncation errors

# Sine Excitation



The majority of the response is created using the first 5 laboratory test modes

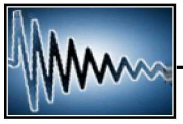




# Sine Excitation

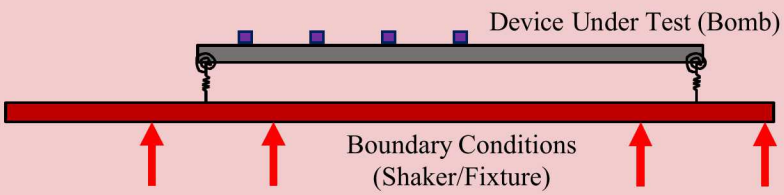
The majority of the response is created using the first 5 laboratory test modes

→ We can use this information to go back and design a better test by optimizing the shaker locations to excite the first five laboratory test modes.

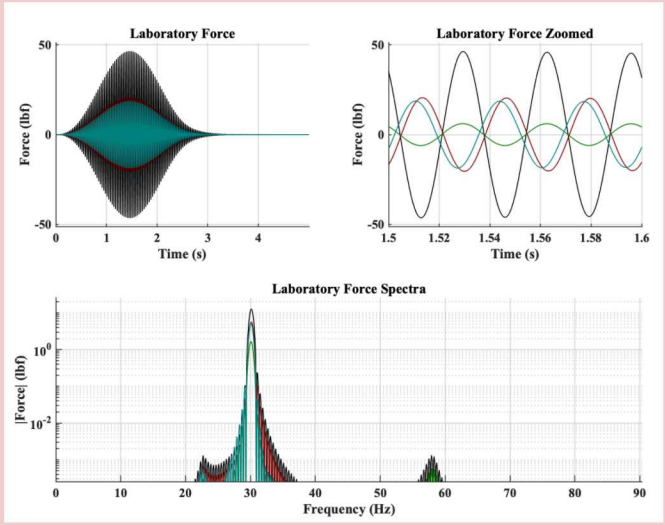


# Sine Excitation

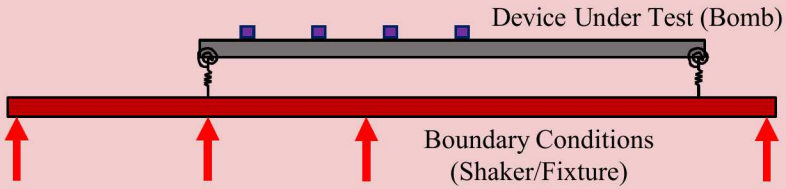
## Original Excitation Locations

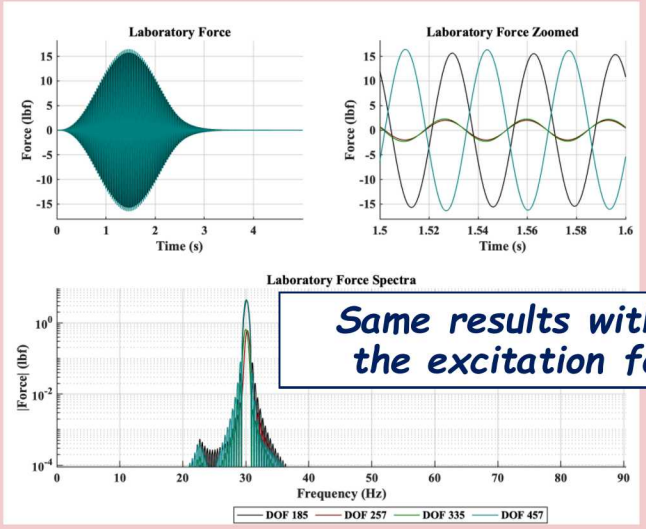



## Excitation Force



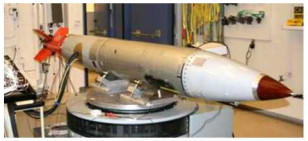

## Optimized Excitation Locations



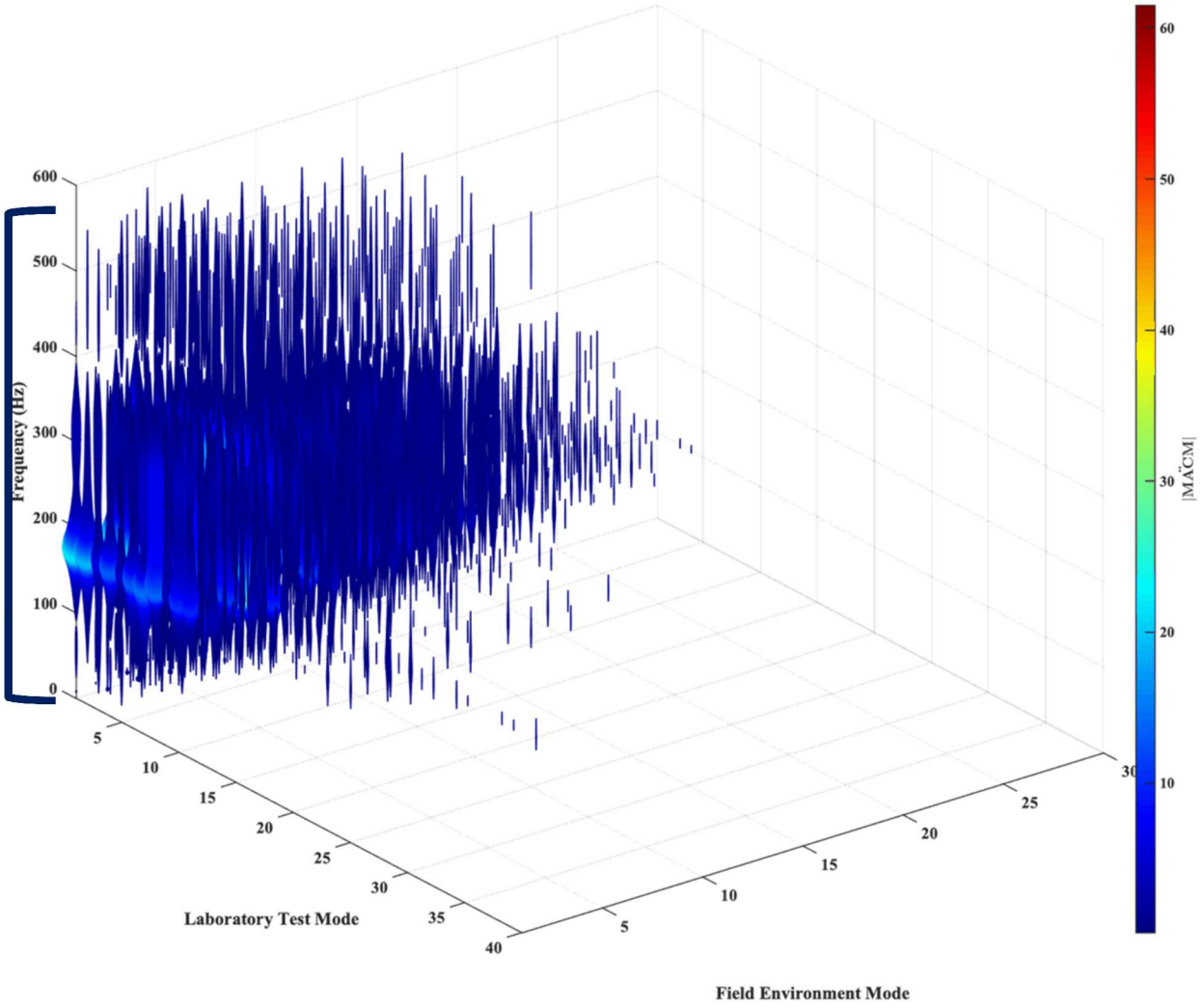




**Same results with 1/3 the excitation force!**

# Impulse Excitation



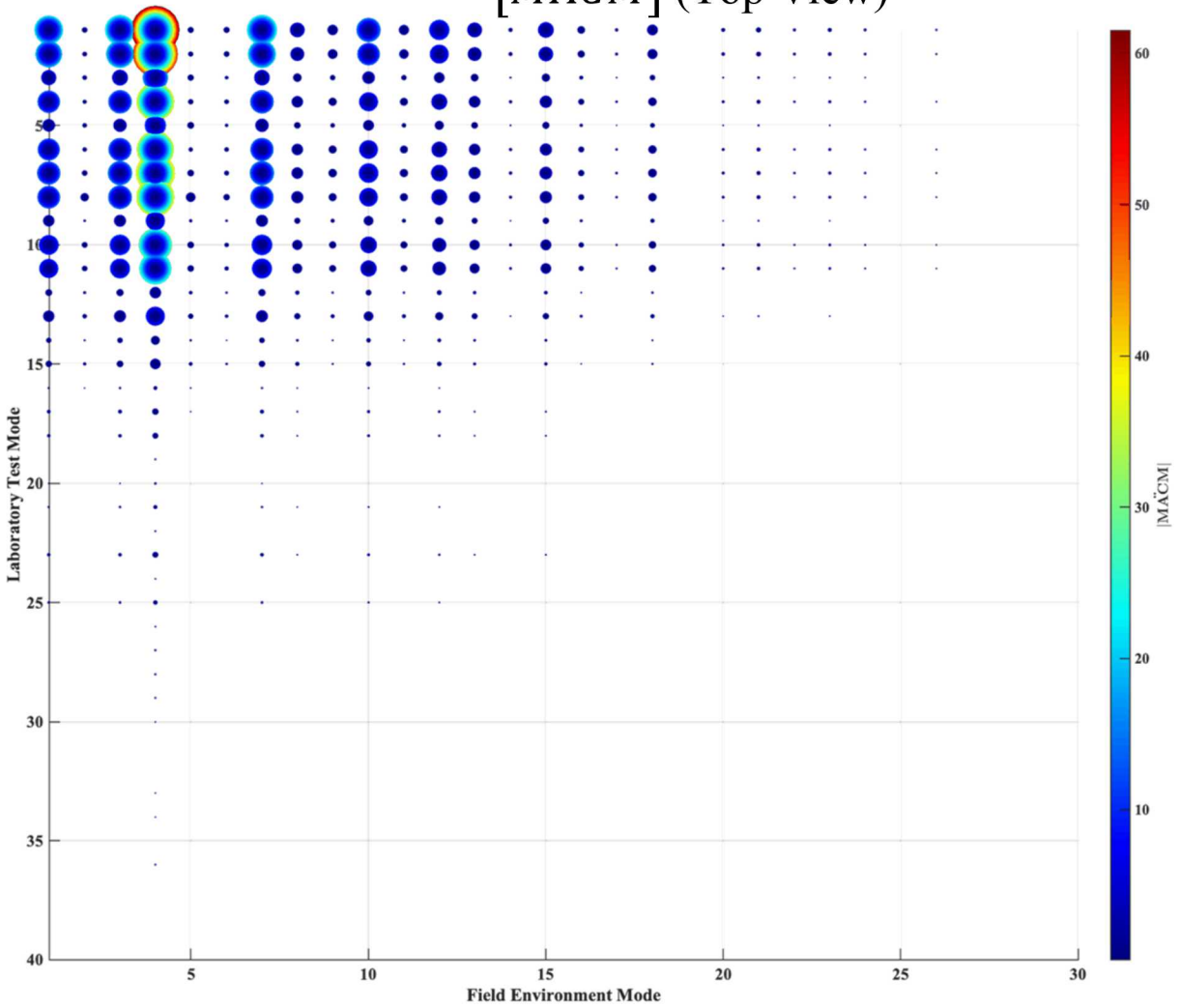
$[M\ddot{A}CM]$



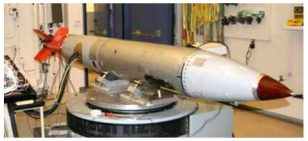

*Impulse has excited a broad frequency band*

# Impulse Excitation

$[M\ddot{A}CM]$ (Top View)

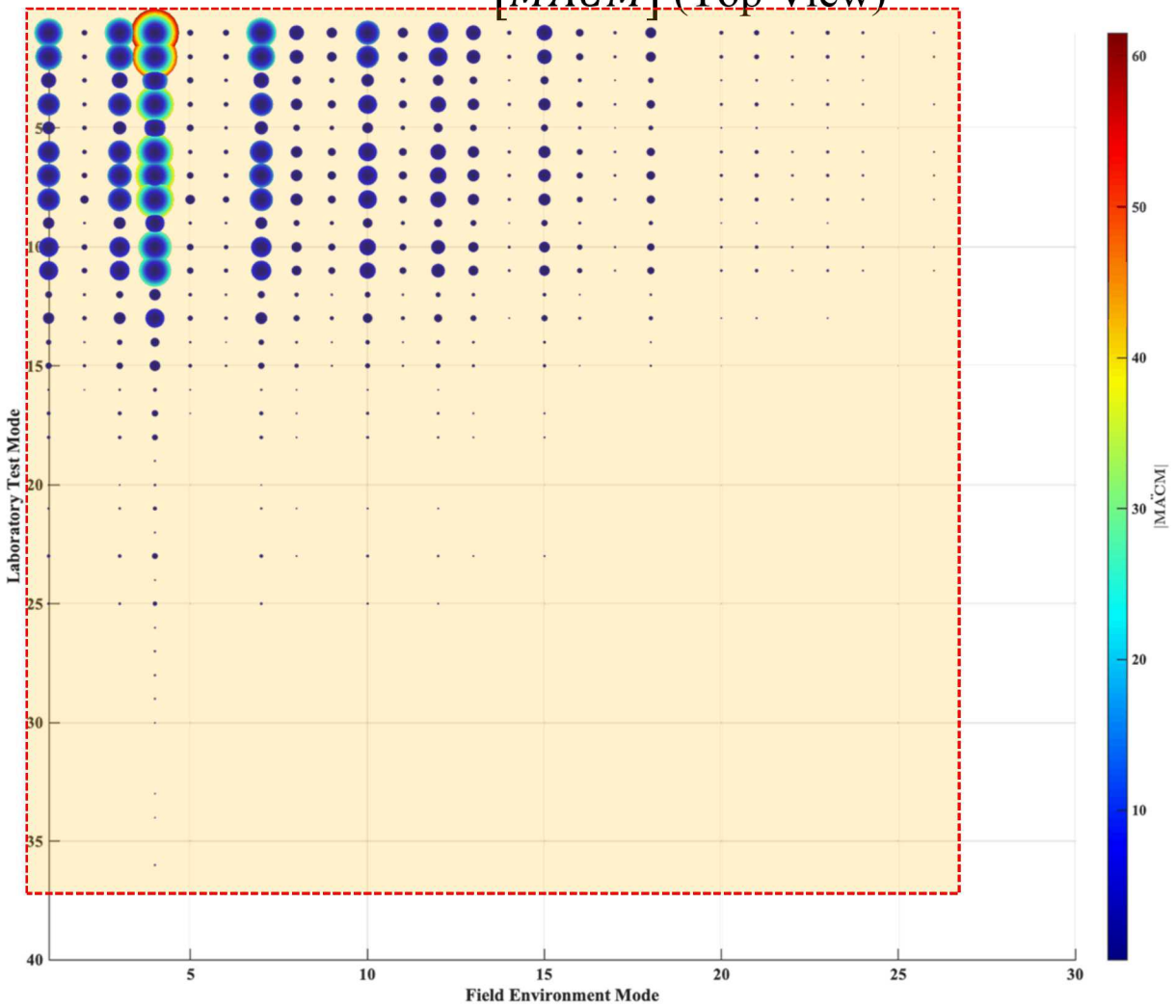


# Impulse Excitation



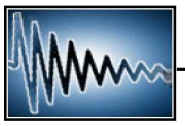
Many more Laboratory test modes are required to replicate the field environment response

$[M\ddot{A}CM]$ (Top View)



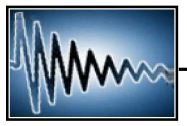
# Conclusions

- The Modal Amplitude Contribution Matrix (MACM) matrix between field and laboratory modal response was derived.



# Conclusions

- The Modal Amplitude Contribution Matrix (MACM) matrix between field and laboratory modal response was derived.
- The MACM matrix gives physical insight into how laboratory test modes are used to create a field environment response.
  - Which laboratory modes are important
  - Which field modes are important



# Conclusions

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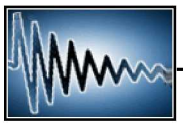
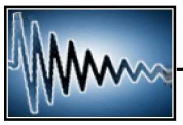
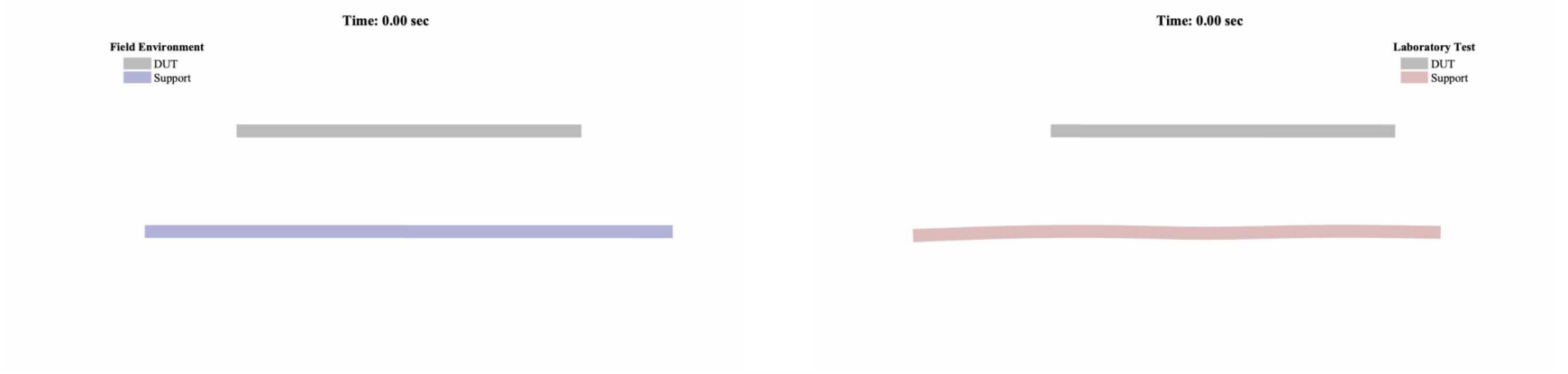
- The MACM matrix gives physical insight into how laboratory test modes are used to create a field environment response.
  - Which laboratory modes are important
  - Which field modes are important
- Physical insight into the transformation process can help us design better tests.



# Acknowledgements

Sandia National Laboratories provided funding for this research. I am extremely grateful for their support.






# Boundary Condition Compensation Map (From Field to Laboratory Response)

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Structural Dynamics and Acoustic Systems Laboratory
University of Massachusetts Lowell

D. Gregory Tipton
Structural Dynamics Group
Sandia National Laboratories