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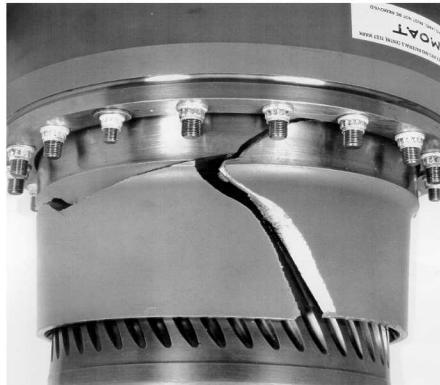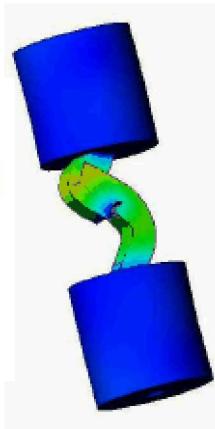
Force Reconstruction at Mechanical Interfaces

Deborah Fowler (UMass Lowell), Samuel Parker(UT Austin), Matthew Cleal (University of New Mexico)

Peter Avitabile , Patrick Logan (UMass Lowell)

Dan Roettgen, Ben Pacini , Rob Kuether (Sandia)

Motivation

- Joints are a source of nonlinearities in many common structures

- The dynamic force due to a joint's bolted area is challenging to predict and confirm experimentally

- Better techniques are needed to analyze the effects of a bolted joint on a structure
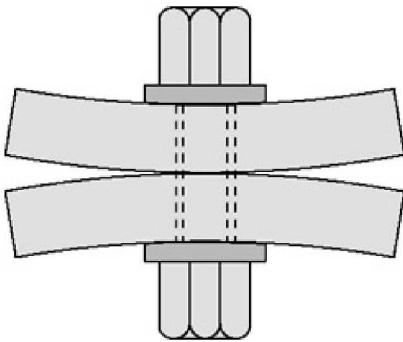

Image from Spacecraft Thermal Control Handbook, Vol. 1

Image from smartbolts.com
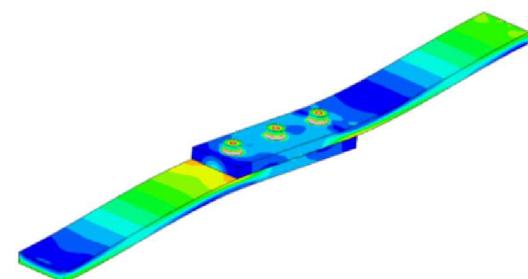
Image from simuleon.com

To explore these applications, a force reconstruction technique will be used to reconstruct the nonlinear contact forces from a mechanical interface

Presentation Outline

- Theory
- Analytical Case Studies
- Experimental Case Studies
- Summary and Conclusions
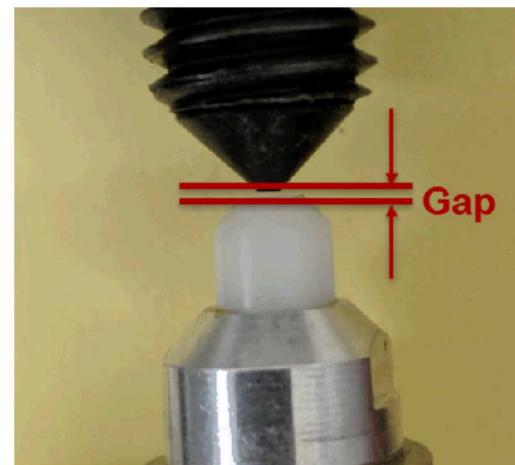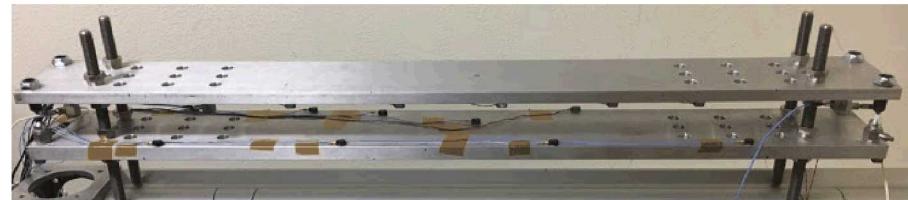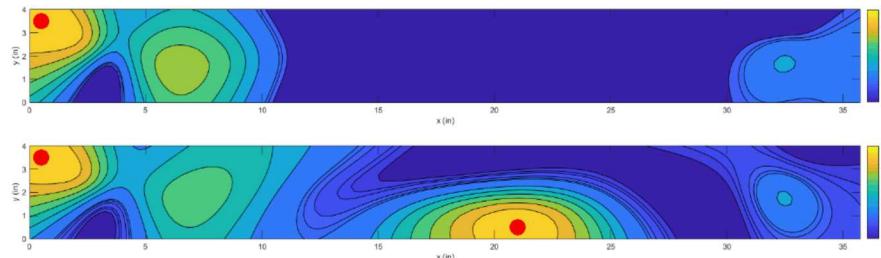
Force Reconstruction Theory

- Modal coordinates can be estimated from responses using

$$\{p(j\omega)\} = \left[U_{o,m}\right]^{\dagger}\{X(j\omega)\}$$

- Modal forces can be estimated from modal coordinates as

$$\{\overline{F}_m(j\omega)\} = \left[\overline{H}_m(j\omega)\right]^{-1}\{p(j\omega)\}$$

- A singular value decomposition of the modal forces is then conducted

$$[U_\Sigma][\Sigma][V]^T = \left[\{\overline{F}_m(j\omega_1)\} \quad \cdots \quad \{\overline{F}_m(j\omega_k)\}\right]$$

- From which the primary locator can be calculated

$$PL_j = \frac{\left|\left(\left[U_\Sigma^*\right]\left[U_\Sigma^*\right]^{\dagger}\left[U_{j,m}\right]^T\right)^h\left[U_{j,m}\right]^T\right|^2}{\left(\left(\left[U_\Sigma^*\right]\left[U_\Sigma^*\right]^{\dagger}\left[U_{j,m}\right]^T\right)^h\left[U_\Sigma^*\right]\left[U_\Sigma^*\right]^{\dagger}\left[U_{j,m}\right]^T\right)\left(\left[U_{j,m}\right]\left[U_{j,m}\right]^T\right)}$$

4

Source Identification

$$[\overline{F}(j\omega)] \in C^{m \times k}$$
$$[U]^T \in R^{m \times N}$$
$$F(j\omega) \in C^{N \times k}$$

MODAL FORCES = MODE SHAPES PHYSICAL FORCES

PHYSICAL DOFS

MODAL COEFFICIENTS

SVD

$$\left[\Upsilon^a\right] \in C^{m \times a}$$
$$\left[\Sigma^a\right] \in R^{a \times a}$$
$$\left[V^a\right]^h \in C^{a \times k}$$

Negligible S.V.s

DOF modal coefficients exist outside truncated basis

DOF modal coefficients exist within truncated basis

$$\left[\Upsilon^a\right]$$

PRIMARY LOCATOR
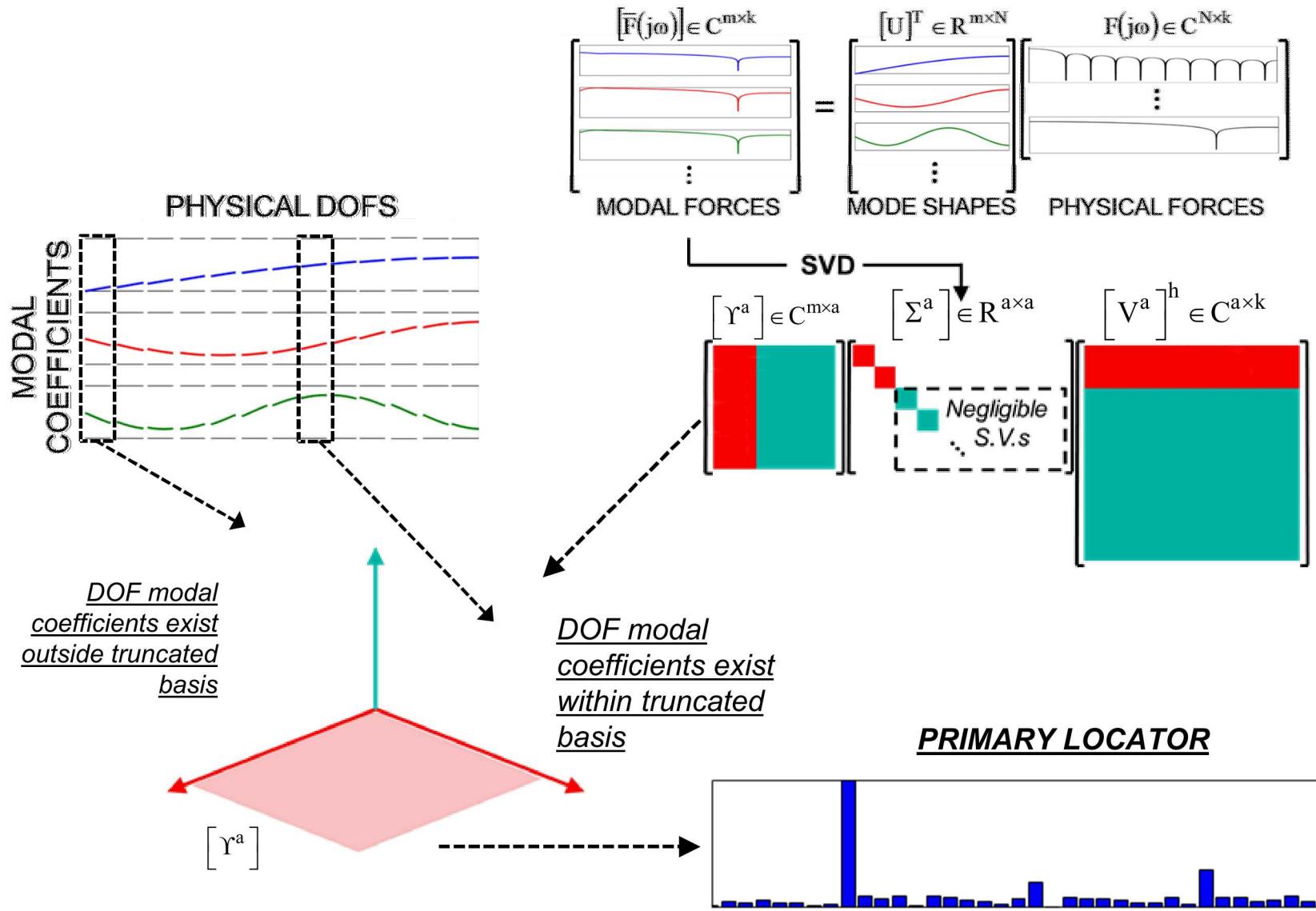
Reconstruction Process
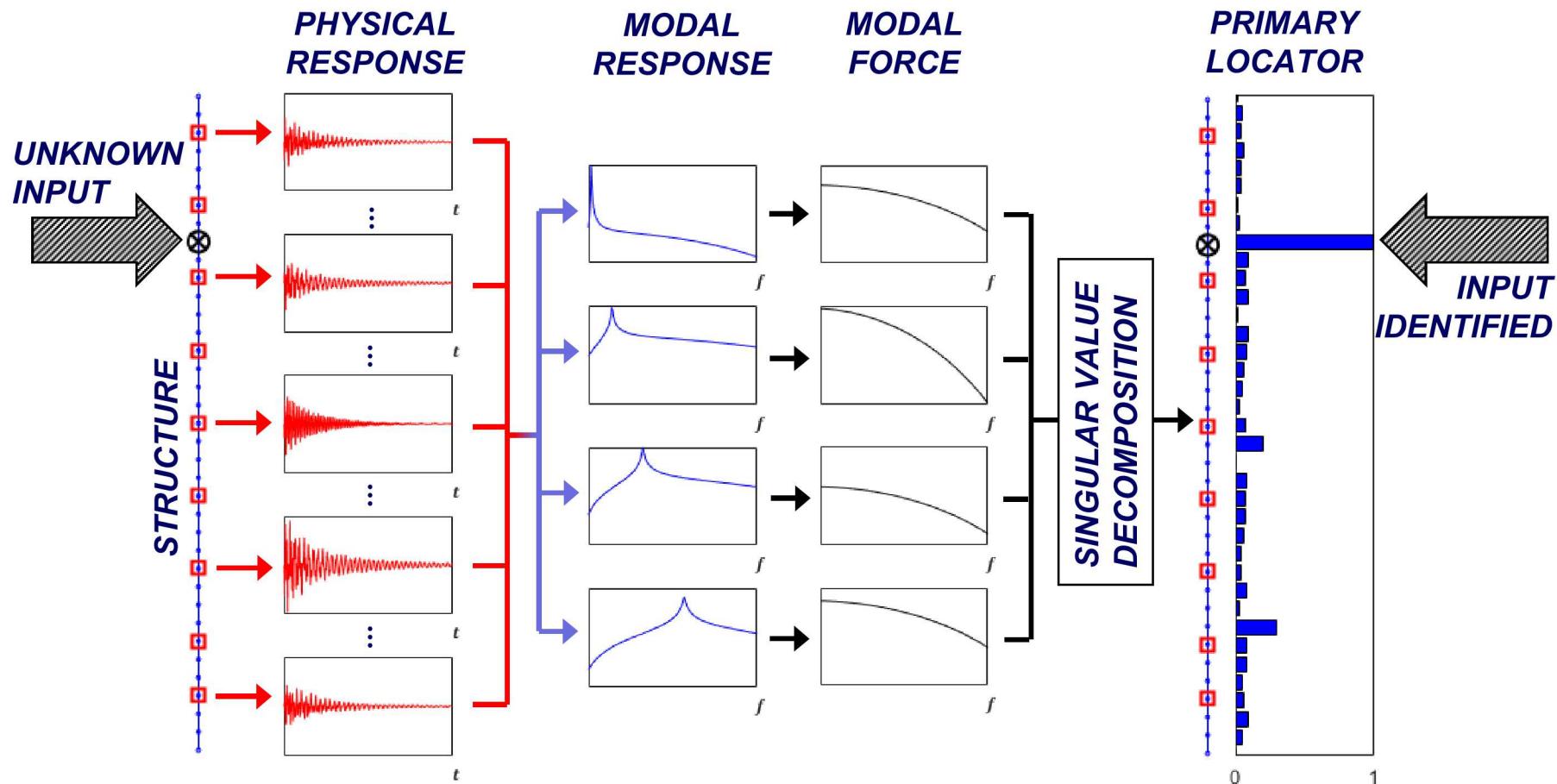
Forces can be identified beyond measured points

Analytical Case Studies

Guiding Questions

▪ Can internal forces due to nonlinear gap contacts be identified?

▪ What should be the focus of experimental cases?

Selected Case Studies

▪ **Case 1:** Reconstruction of single input

▪ **Case 2:** Reconstruction of multiple uncorrelated inputs

▪ **Case 3:** Reconstruction of multiple correlated inputs

Model Description

To study the reconstruction of internal, nonlinear forces, a structure was designed with a mechanical interface that exhibits nonlinear gap contact behavior

Equal and Opposite Nonlinear Forces

A simplified FEA model was developed to represent the physical structure, which is used for the following analytical cases

Case 1: Single input
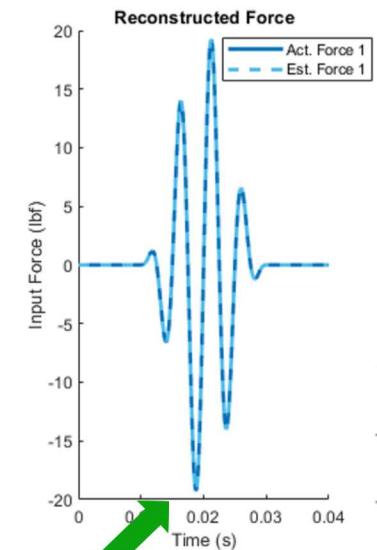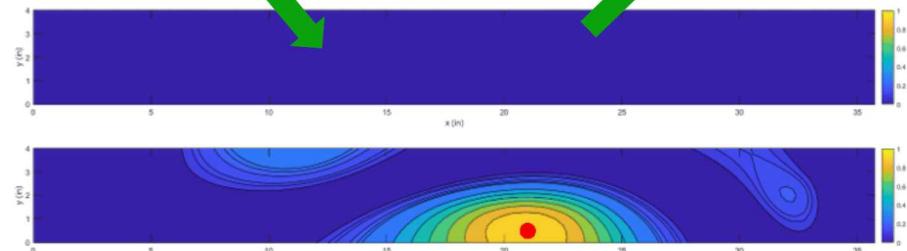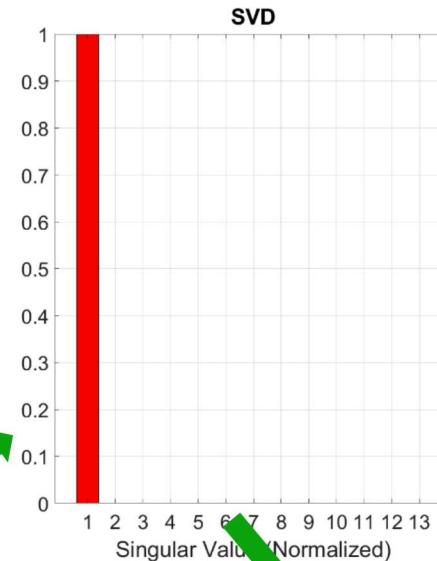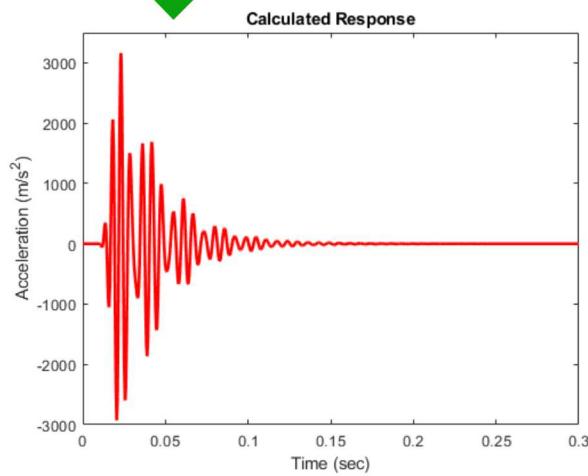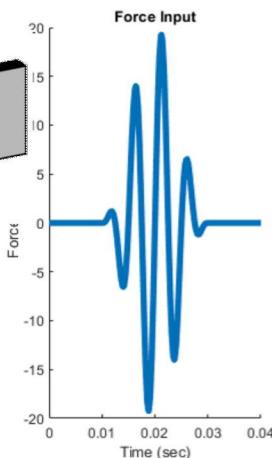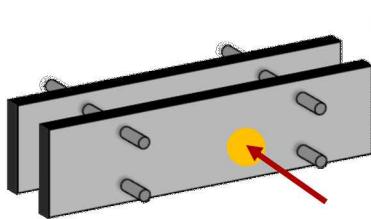
Correct location and reconstruction

Case 2: Multiple input, uncorrelated

Asynchronous pulse

Force Input

Calculated Response

SVD

Reconstructed Force
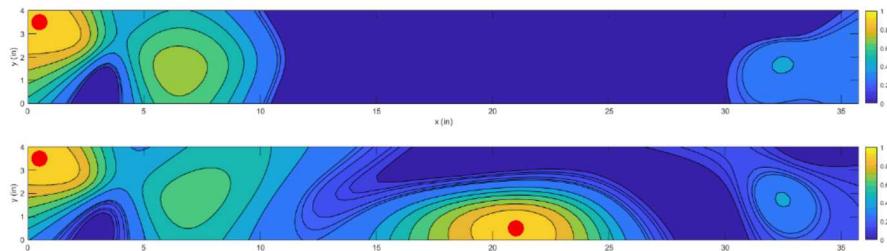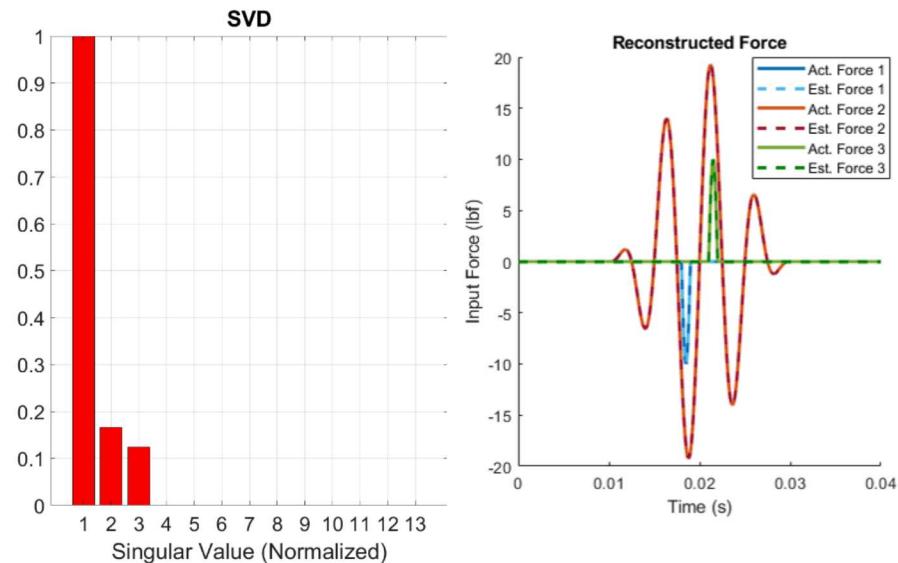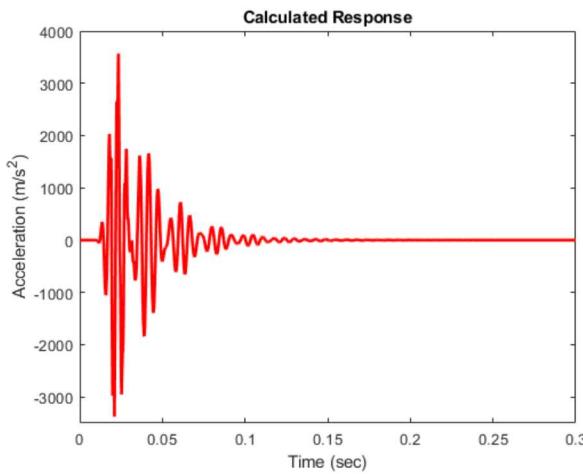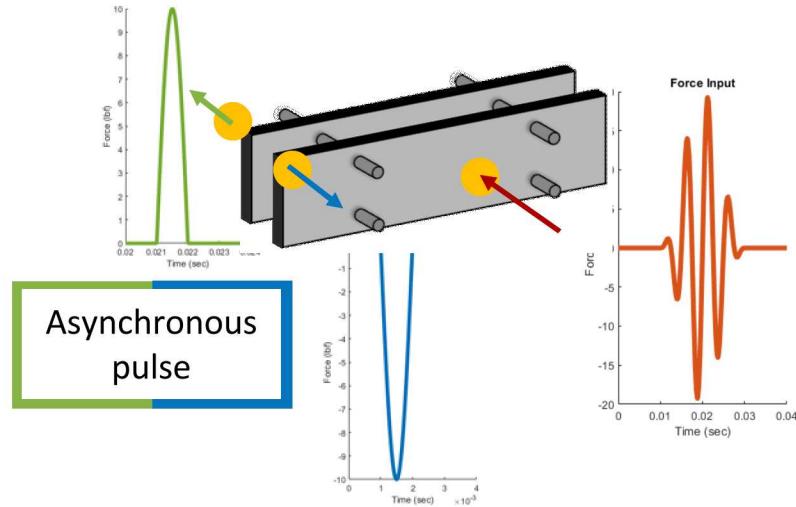
Correct location and reconstruction

Case 3: Multiple input, correlated

Synchronous pulse

Force Input

SVD

Reconstructed Force
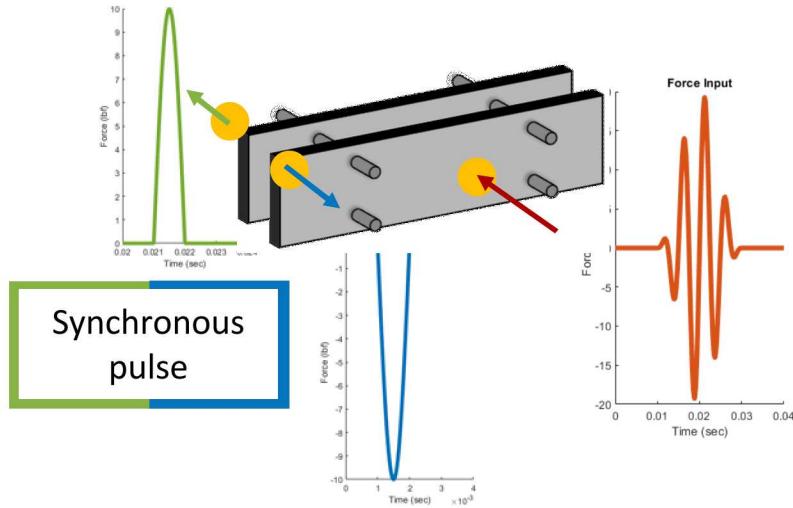
Calculated Response
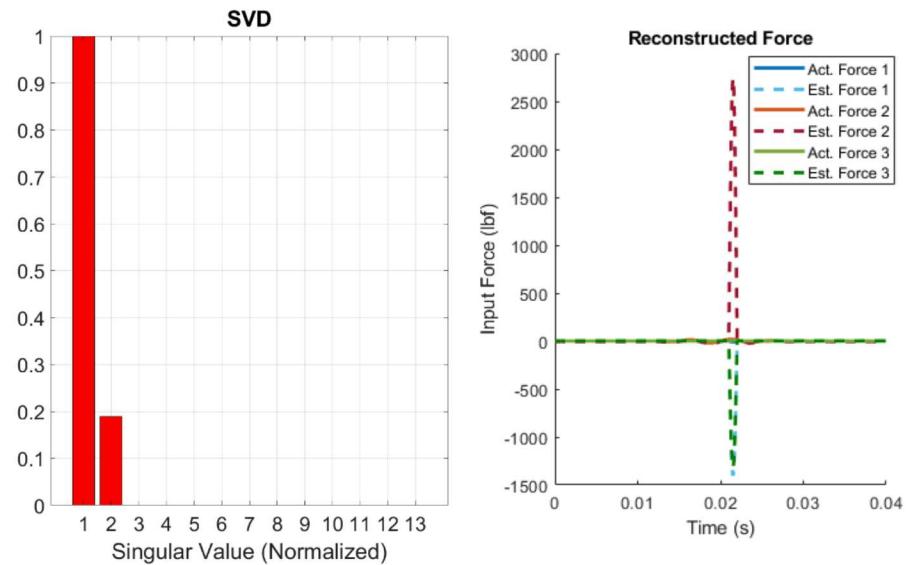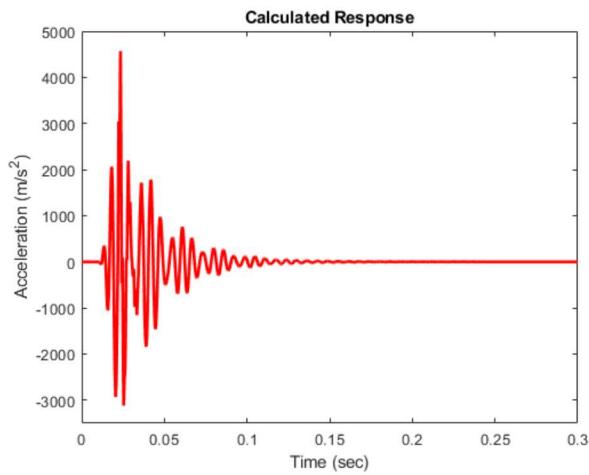
Incorrect location and reconstruction
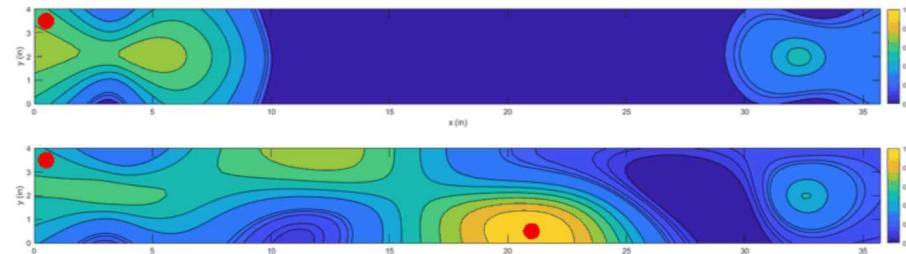
Analytical Results
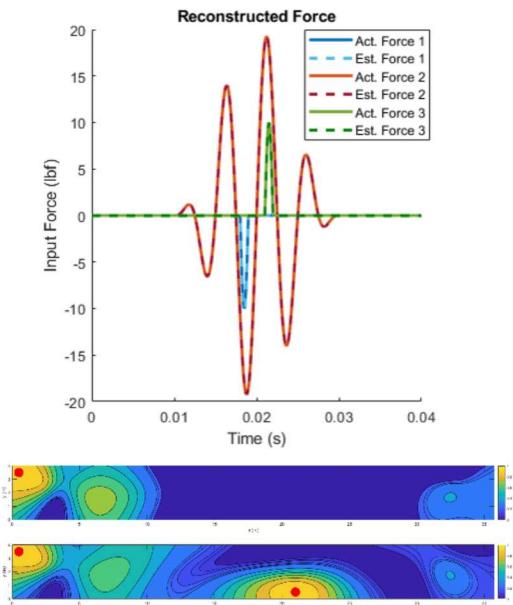
Uncorrelated forces can be correctly located and reconstructed...
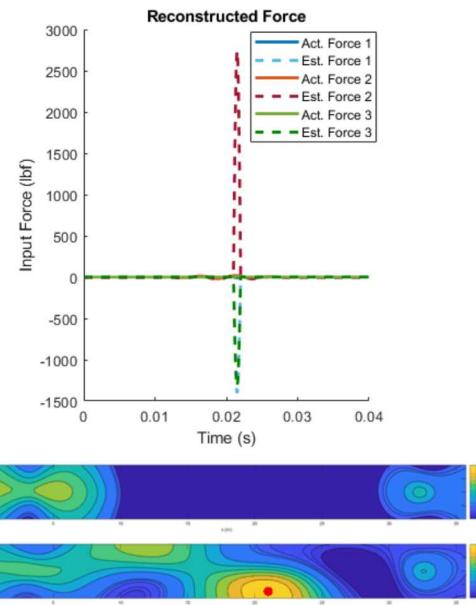

...but difficulty arises when forces are correlated

Modifications to the existing locator function are needed to correctly locate correlated forces

Composite Locator Function

Case 3: Multiple input, correlated

Has difficulty locating correlated forces
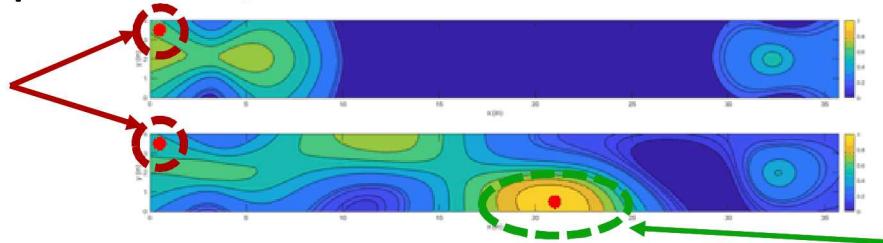
Correctly locates uncorrelated forces

Composite Locator Function

U_{top} = Mode Shapes of the Top Beam

U_{bot} = Mode Shapes of the Bottom Beam
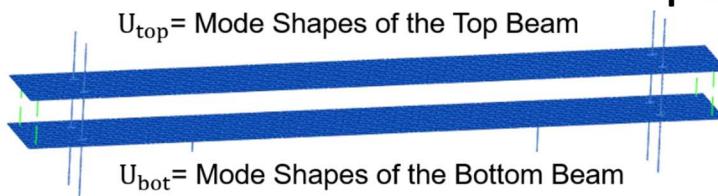
$$U_{diff} = U_{bot} - U_{top} \qquad PLF(U_{diff})$$

Correctly locates correlated forces!

13
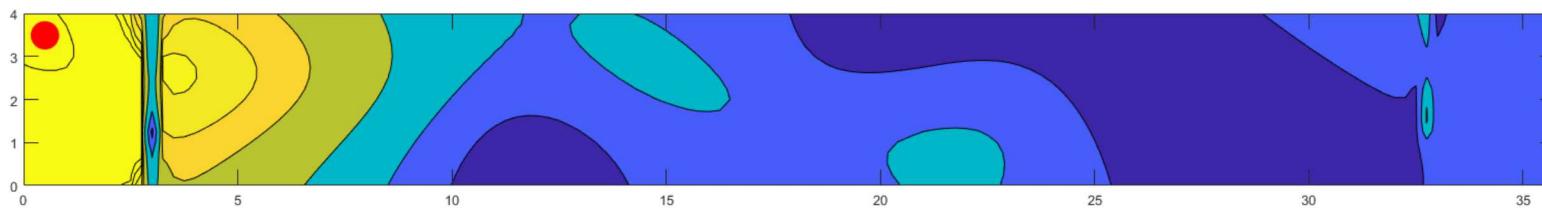
Composite Locator Function

Case 3: Multiple input, correlated

For this structure's dynamics in the frequency range studied, the estimation is accurate but less precise

X **0.5**
Y **3.5**
Level **1**

X **1.75**
Y **3.75**
Level **0.999**

X **3.75**
Y **2.5**
Level **0.9834**

X **1.25**
Y **1.5**
Level **0.9991**

X **0.25**
Y **0.25**
Level **0.9984**

Y

X
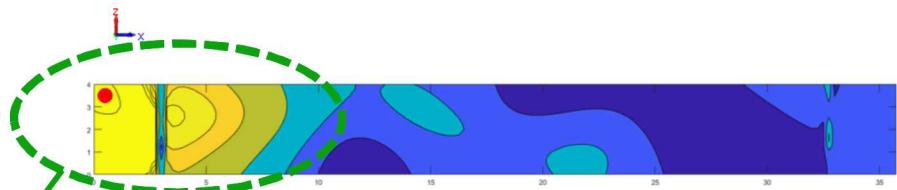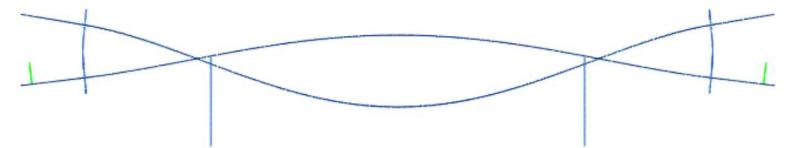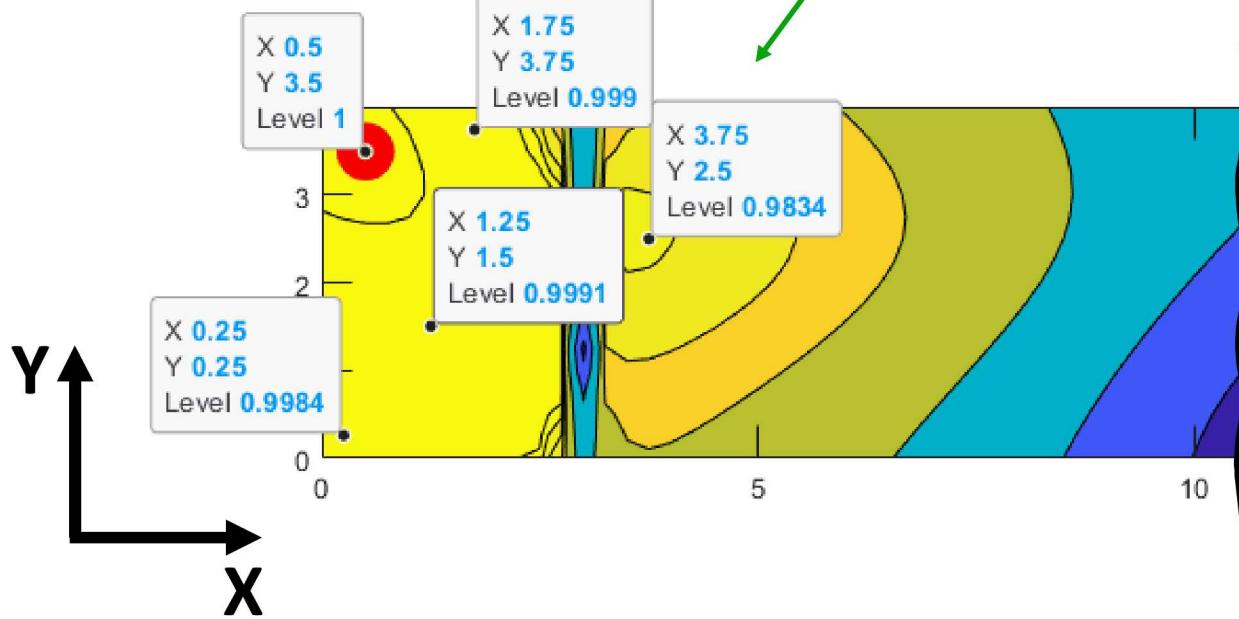
Experimental Case Studies

- Case 1: Linear Hammer Impact

- Case 2: Nonlinear Single Gap Impact

- Case 3: One Preloaded Point (similar to a loosening bolt)

- Case 4: Two Preloaded Points

0.07mm Nonlinear Gap Connection

Gap

Preloaded Connection

No Gap
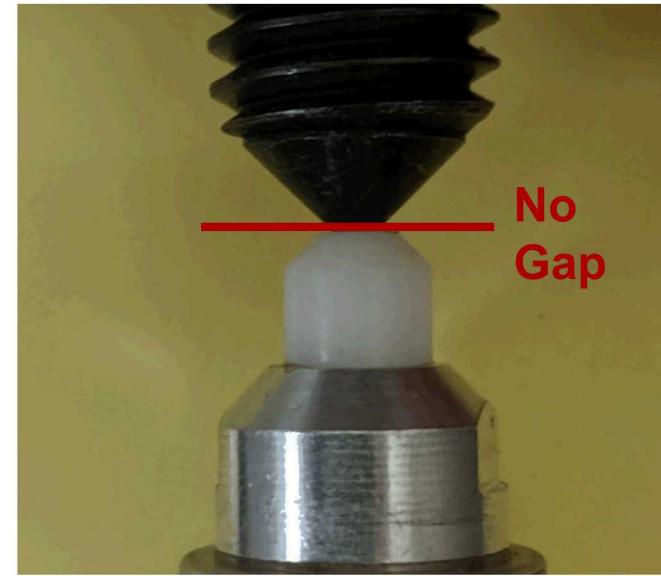
Test Setup

- The structure was instrumented with 23 uniaxial accelerometers, 4 triaxial accelerometers, and 4 force gages integrated in the nonlinear mechanical interface


Test Geometry

≈ 3 ft

4"

2.5"
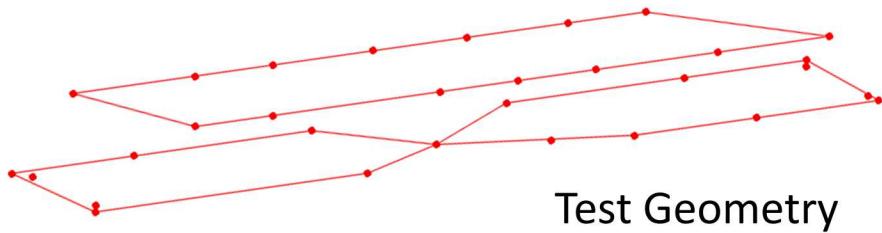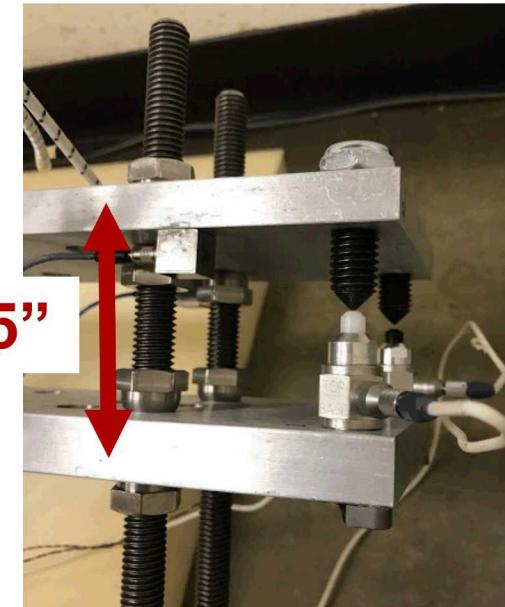
FE Model and Correlation

FEA	Hz	EMA	Hz	Diff. (%)	MAC (%)	POC (%)
1	96.933	1	85.197	13.77	98.9	99.7
2	155.52	2	151.07	2.94	99.4	99.8
3	199.16	3	189.1	5.32	98.3	99.3
4	262.88	4	257.07	2.26	99.1	99.8
5	282.69	5	261.22	8.22	96.8	99.2
6	422.62	6	413.76	2.14	98.8	99.5
9	555.55	7	487.55	13.95	96.9	98.5
7	518.25	8	509.08	1.8	76.1	96.4
9	538.84	9	513.77	4.88	97.4	91.3
8	549.84	10	540.05	1.81	13.6	83.6
11	678.5	11	608.52	11.5	98.4	99.8
12	743.8	12	690.98	7.64	98.3	98.9
13	877.86	13	744.65	17.89	94.5	94.8

MAC

Introduction → Theory → Analytical Results → Experimental Results → Conclusions
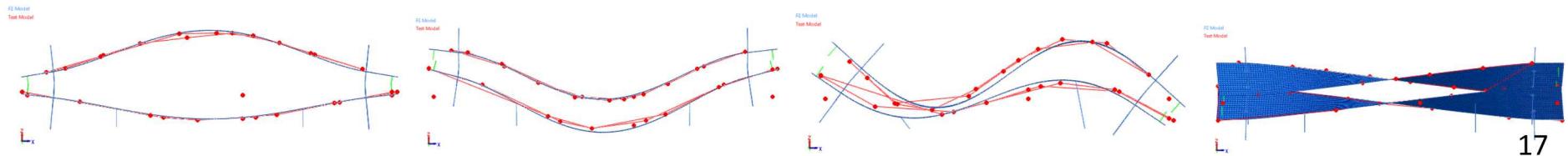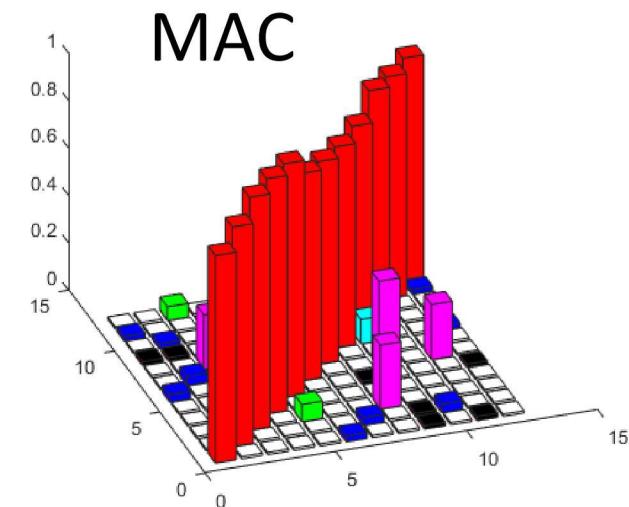
Case 1: Linear Hammer Impact


0.7% Error

18
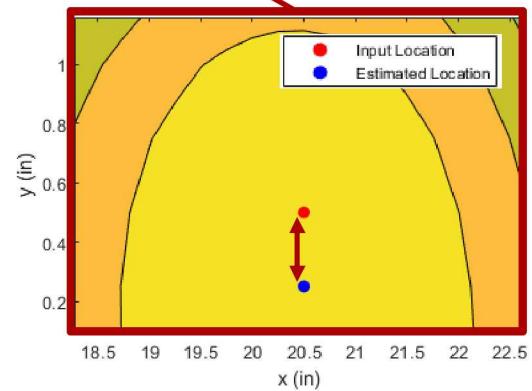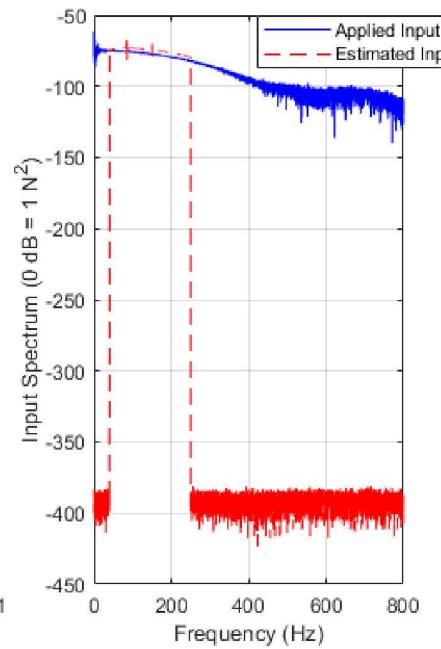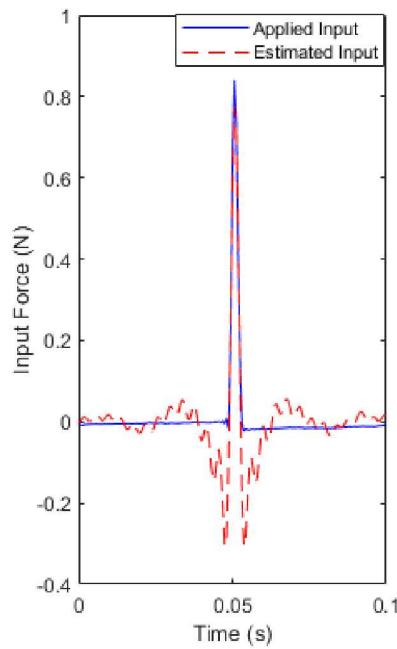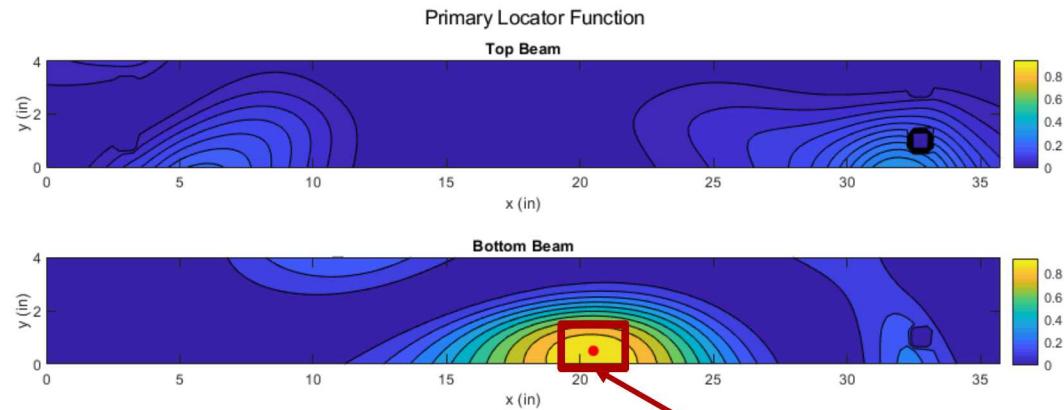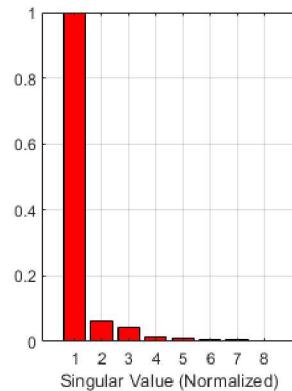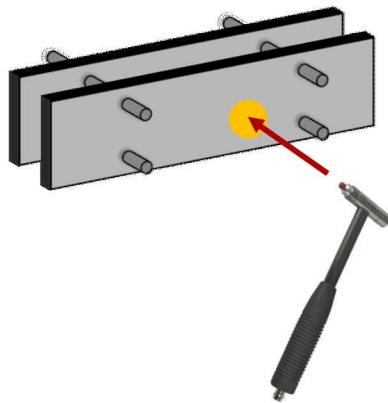
Case 2: Nonlinear Single Gap Impact

**Reconstructing Shaker Input Force**

Reconstructing Nonlinear Contact Force

Gap

1.4% Error

Input Location
Estimated Location

Singular Value (Normalized)

Primary Locator Function

Top Beam

Bottom Beam

1.4% Error

Input Location
Estimated Location

Singular Value (Normalized)

Composite Locator Function

Case 2: Nonlinear Single Gap Impact

Reconstructing Shaker Input Force

99% TRAC

99.8% FRAC

Reconstructing Nonlinear Contact Force

53% TRAC   95% FRAC

57% TRAC   99% FRAC
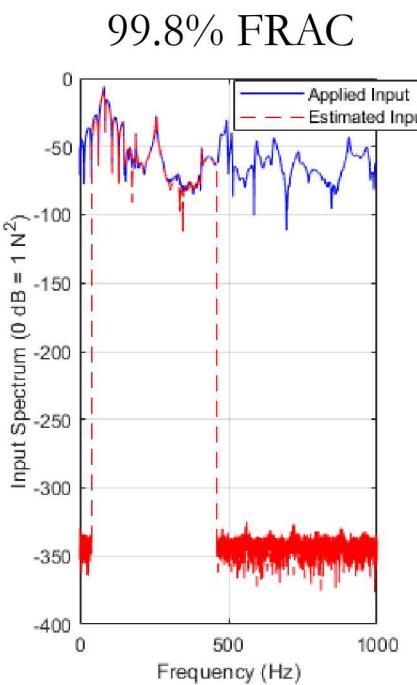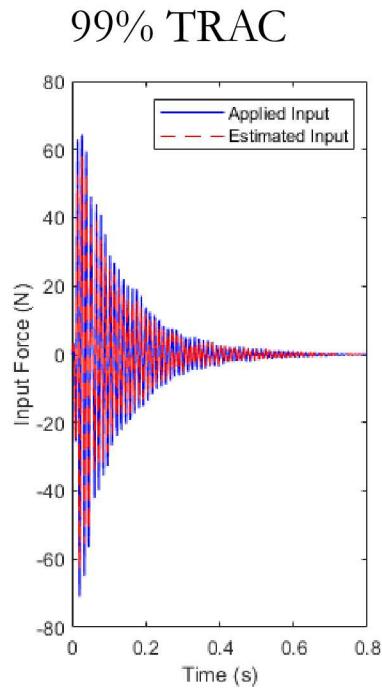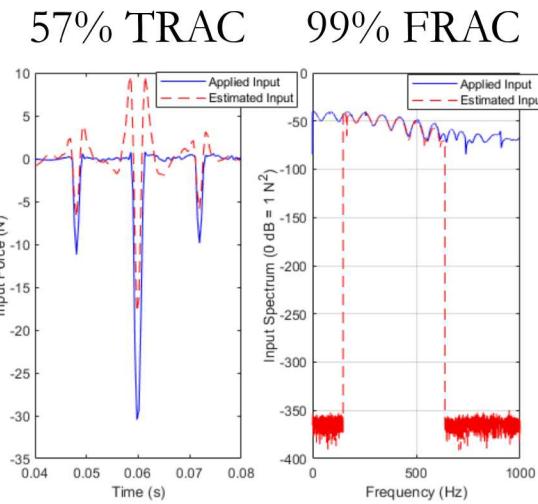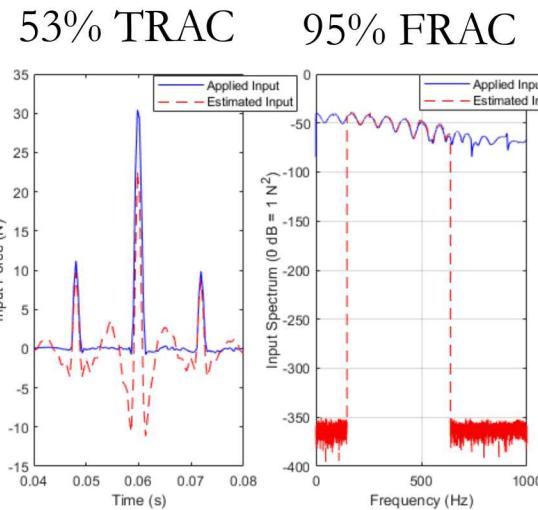
The frequency domain reconstruction is highly accurate, indicating time domain error is due to frequency truncation.

Introduction → Theory → Analytical Results → Experimental Results → Conclusions

Case 3: One Preloaded Point

Locating Shaker Input Force

Locating Contact Force

No Gap

1.6% Error

4.2% Error
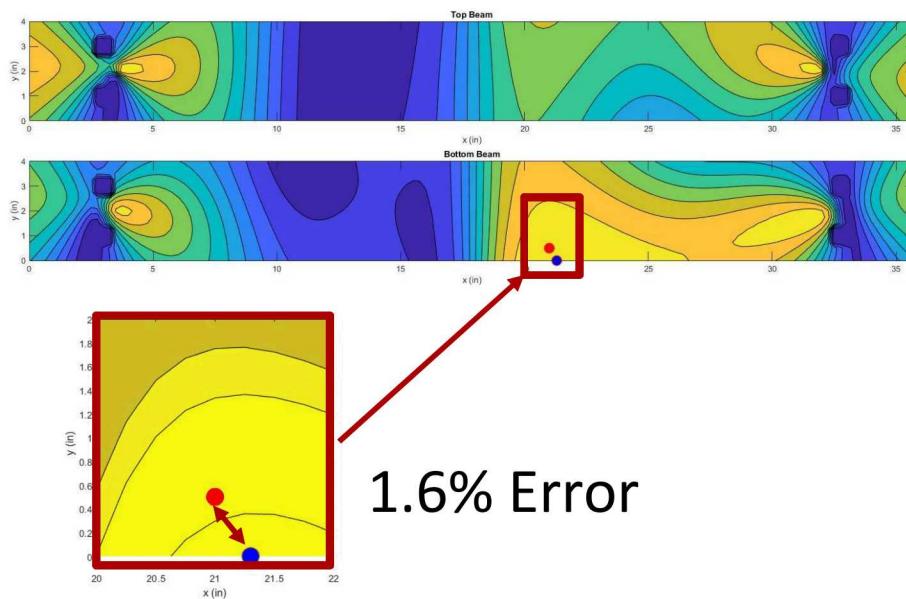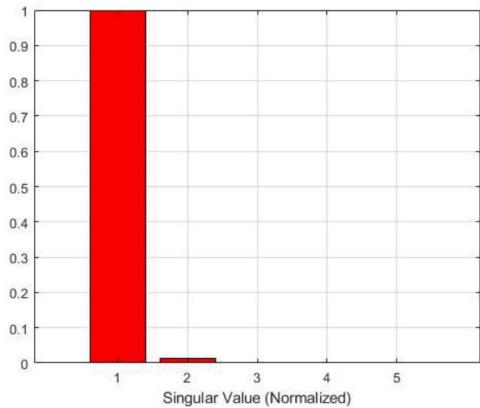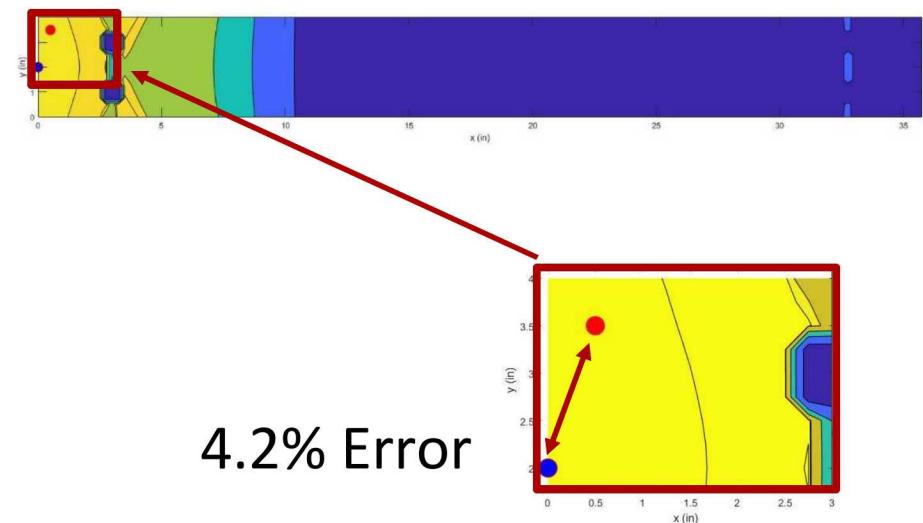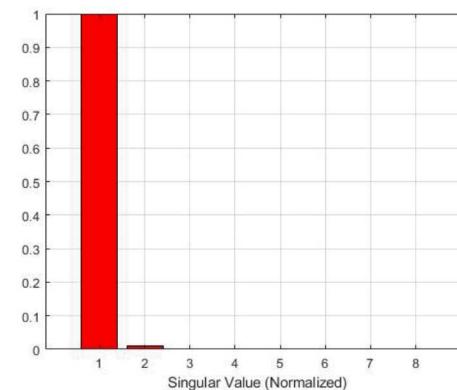
Case 3: One Preloaded Point

Reconstructing Shaker Input Force
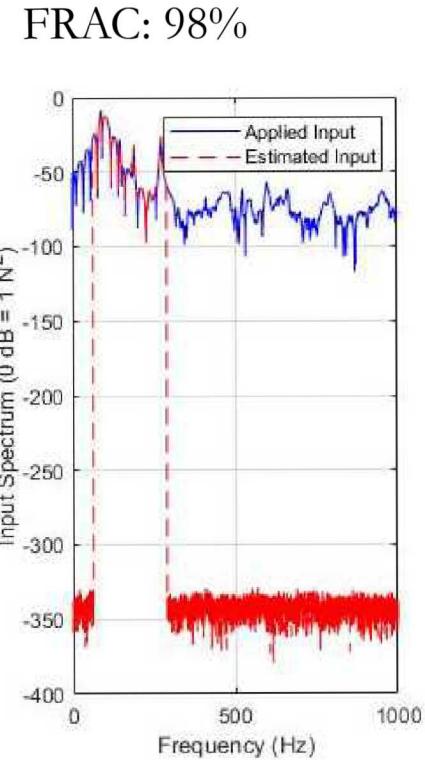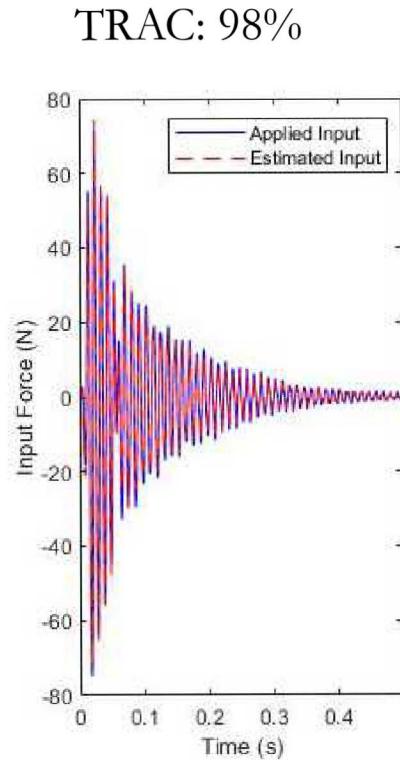
TRAC: 98%   FRAC: 98%

Reconstructing Contact Force

Top Beam
TRAC: 97%
FRAC: 99%
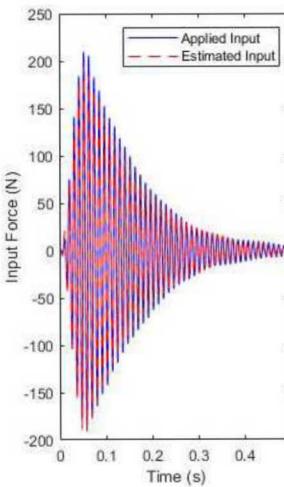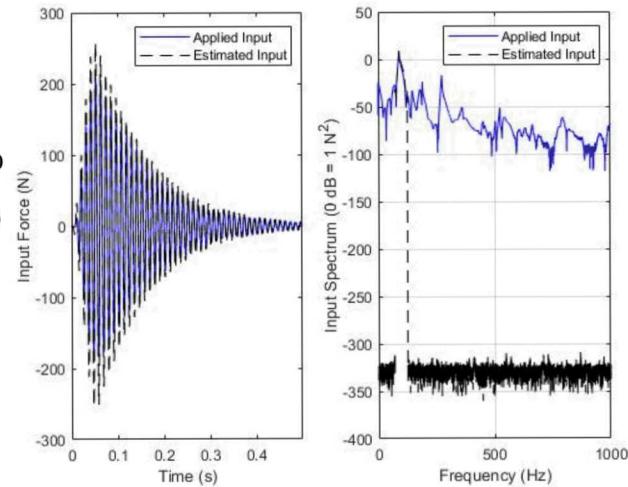
Bot Beam
TRAC: 98%
FRAC: 99%

The reconstruction was highly accurate for the preloaded contact forces

Case 4: Two Preloaded Points

Locating Shaker Input Force

Locating Contact Force

No Gap

1.1% Error
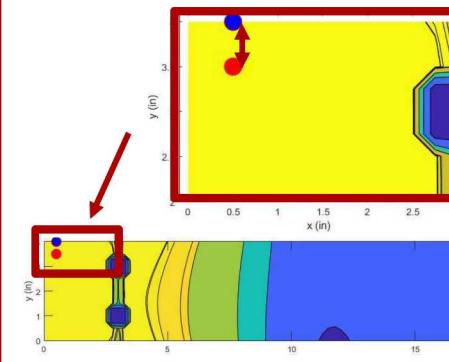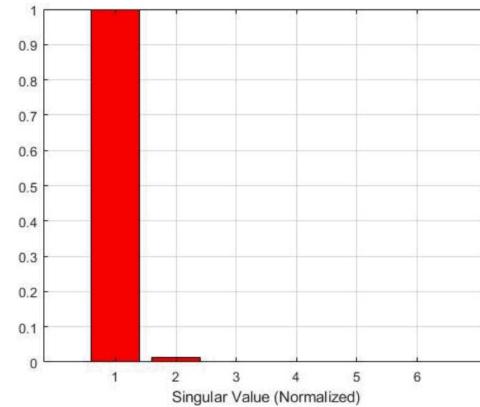
Force: 2
1.4% Error

Force: 3
4.2% Error
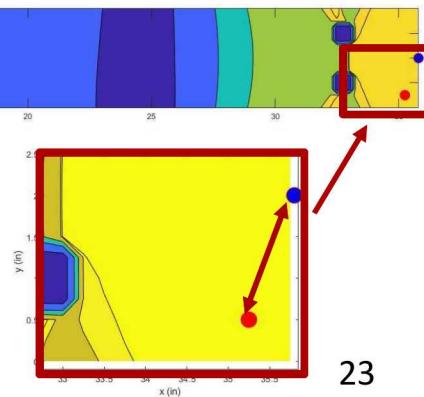
Case 4: Two Preloaded Points

**Reconstructing Shaker Input Force**
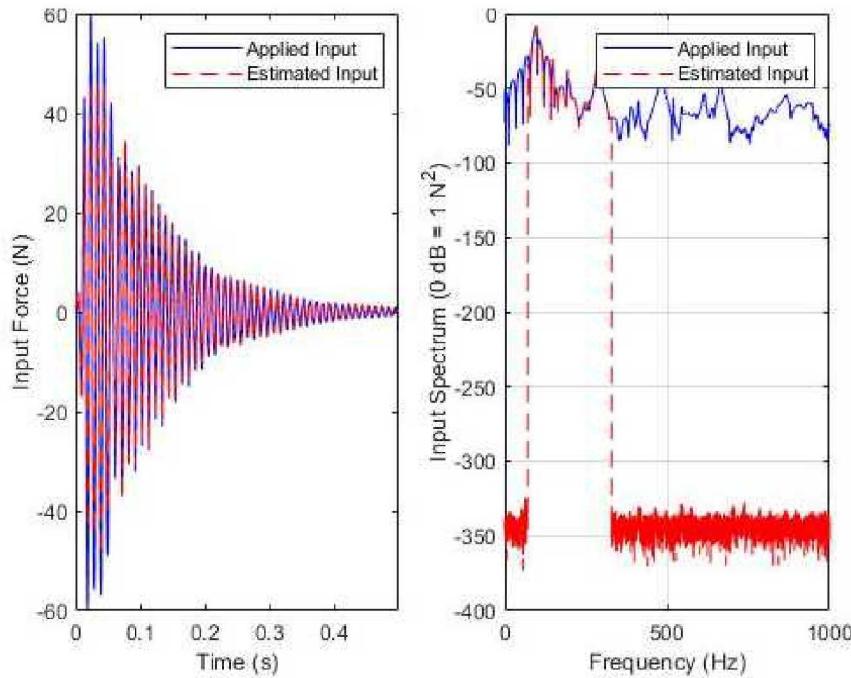
TRAC: 95%

FRAC: 97%

# Case 4: Two Preloaded Points

Reconstructing Contact Force

Force 2
Top Beam
TRAC: 98%
FRAC: 98%

Force 3
Top Beam
TRAC: 99%
FRAC: 99%

Force 2
Bot Beam
TRAC: 98%
FRAC: 98%
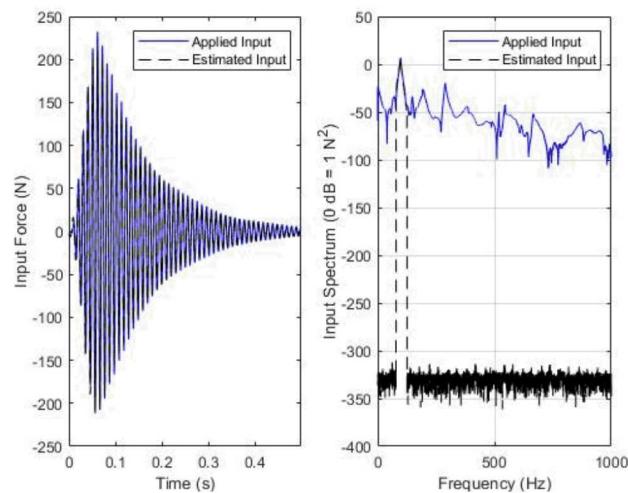
Force 3
Bot Beam
TRAC: 99%
FRAC: 99%
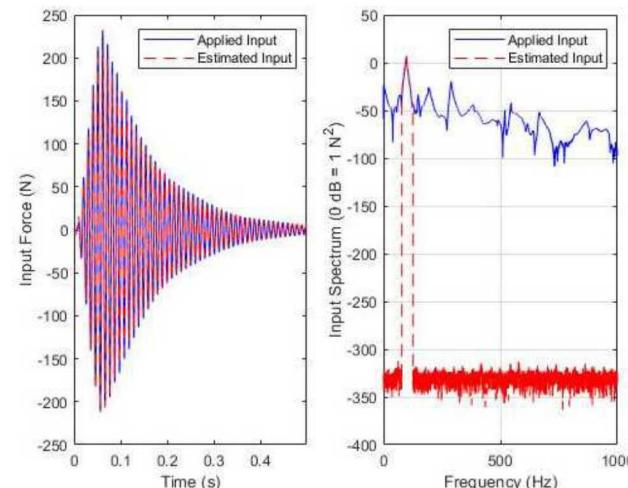
Summary and Conclusions

- The Primary Locator Function is an effective tool for locating forces applied to a system

- The Composite Locator Function allows for the localization of internal, correlated forces

- Nonlinear gap impacts from the mechanical interface were successfully located and reconstructed

- Force resulting from an uncharacterized, preloaded contact was reconstructed with a high degree of accuracy

- Future work will focus on extending this technique to identify loosened bolts.

Acknowledgements

Related Presentation

- #8064, 12:00 – 12:20pm on Wednesday in the Dogwood Room: "Reconstruction of Nonlinear Contact Forces Beyond Limited Measurement Locations Using an SVD Modal Filtering Approach". Patrick Logan, Deborah Fowler, Peter Avitabile, Jacob Dodson.
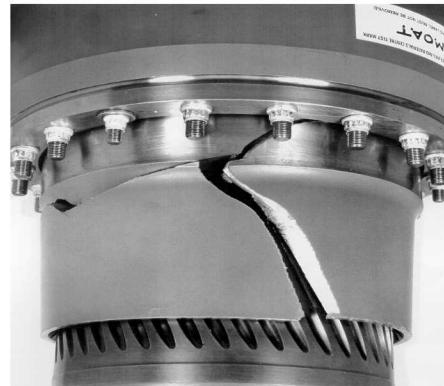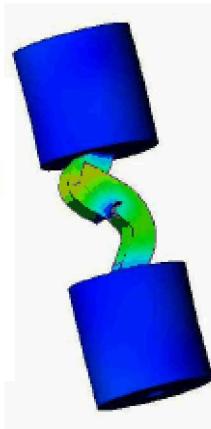
Introduction ⟹ Theory ⟹ Analytical Results ⟹ Experimental Results ⟹ Conclusions

Force Reconstruction at Mechanical Interfaces

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Experimental Force Reconstruction

Effect of inadequately characterizing modal information on reconstruction

Modal Response: 20
Reconstruction: 20
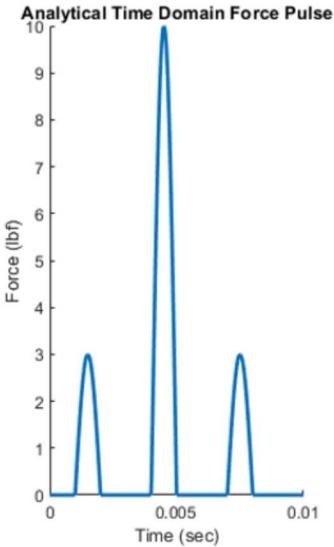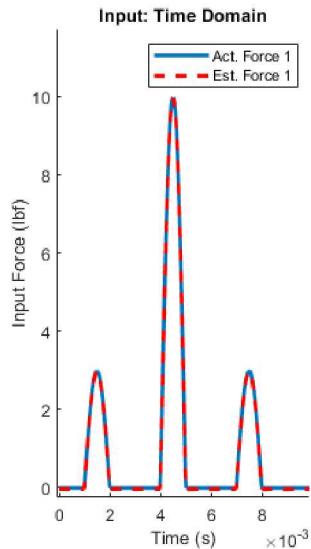
Modal Response: 20
Reconstruction: 13
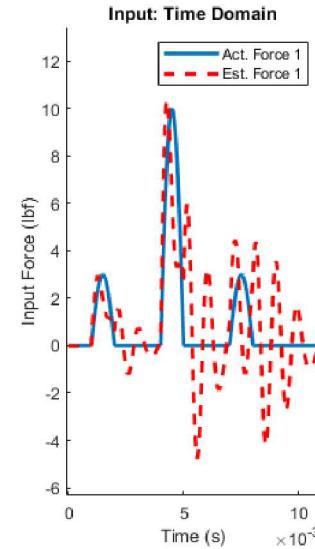
Improper characterization leads to errors in reconstruction