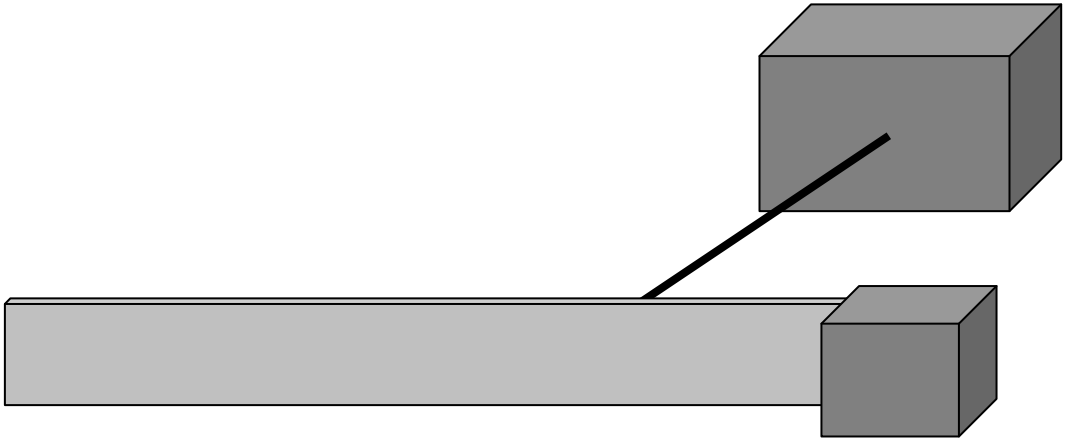
ASSESSMENT OF CONTROL FEEDBACK MODAL SPACE EXPANSION FOR DAMAGE DETECTION



Adam Cardi – Purdue University
Ben Kosbab – Rice University
Timmy Overly – University of Cincinnati
Dr. John Schultze

Natural frequencies have not been effectively utilized for damage detection

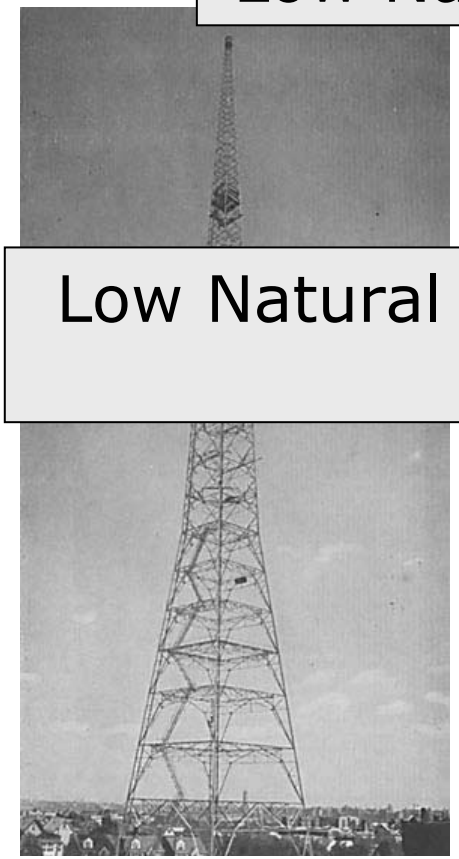
Low Natural Frequencies are Global

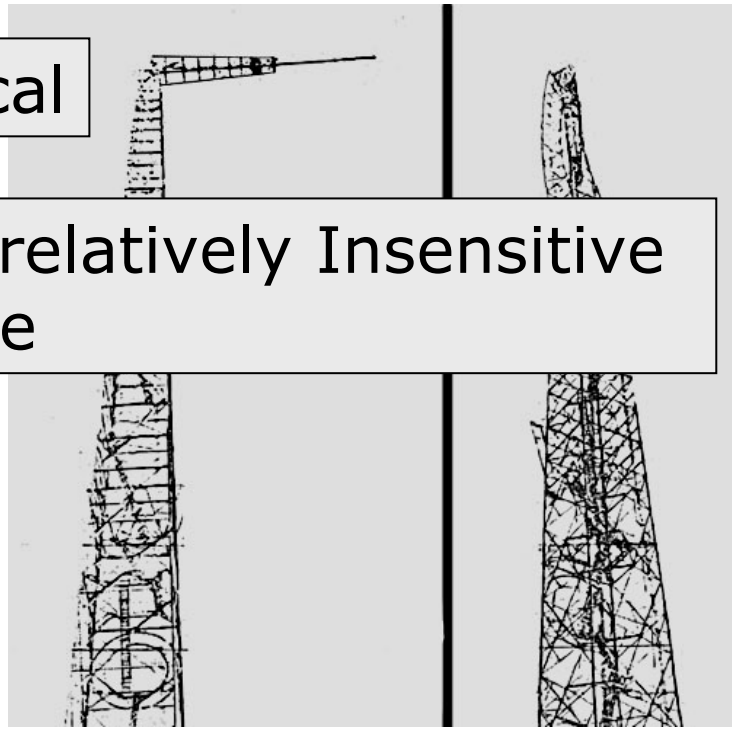
+

Damage is Local

=

Low Natural Frequencies are relatively Insensitive to Damage





hawkins.pair.com/ wor-tv-NBergenNJ.html

More natural frequencies within a given frequency band increase damage detection ability

Simply put:

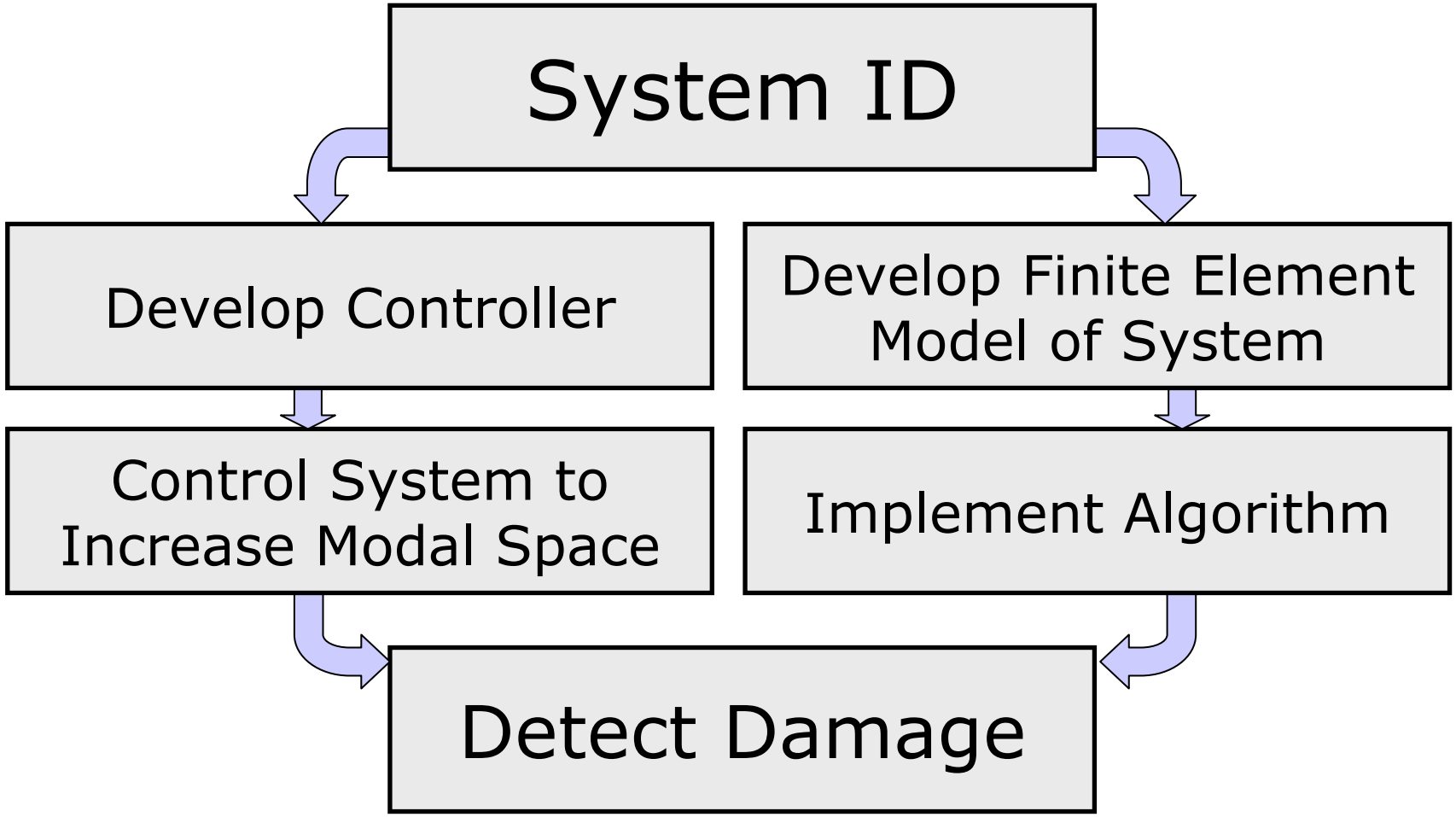
If you have a set of natural frequencies, with X amount of modal information, but you need: 10X amount of information

Lew and Juang propose a technique to do this using multiple controllers

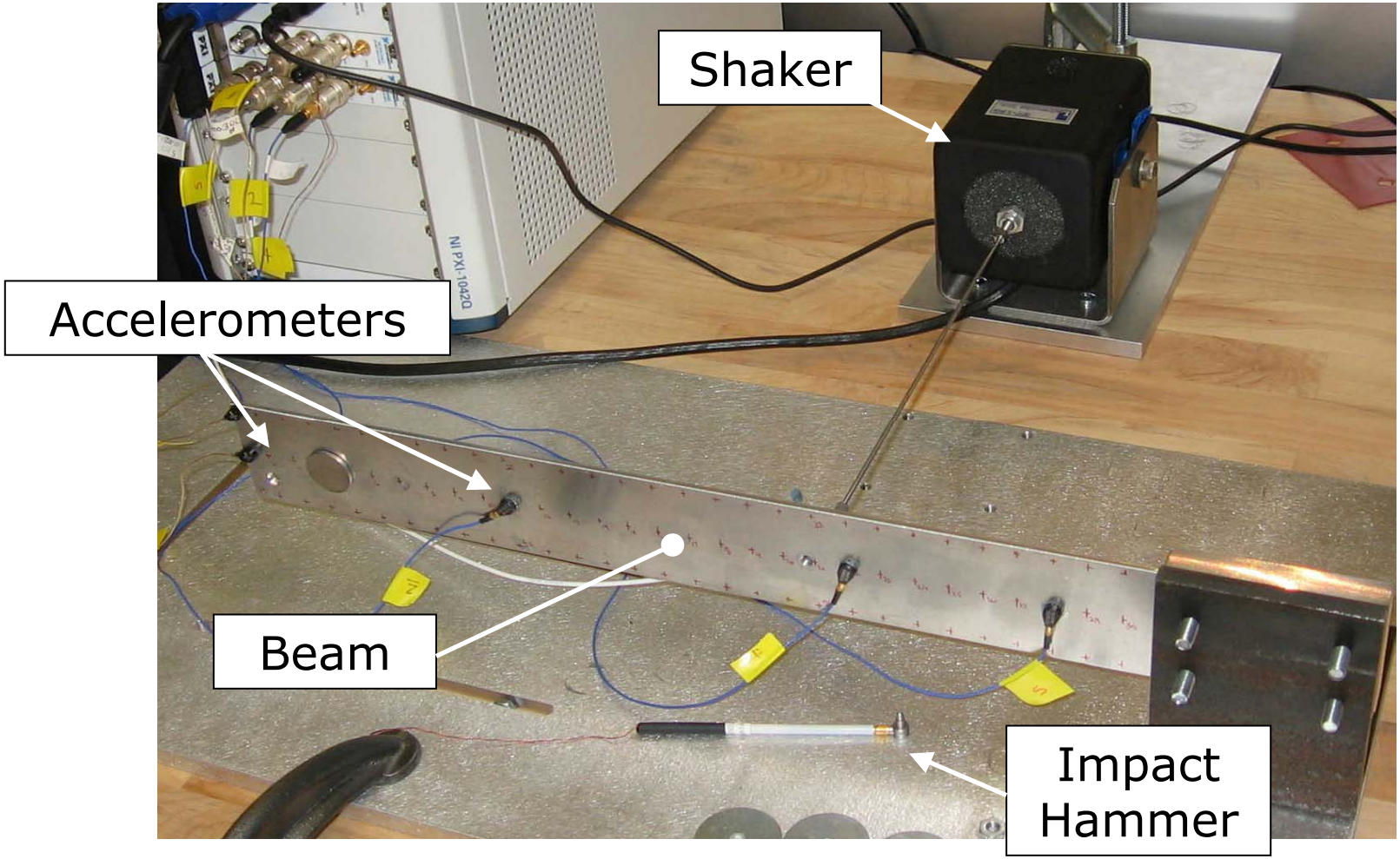
The controllers perturb system boundaries to give the required number of frequency sets

* Lew, J.-S., Juang, J.-N., "Structural Damage Detection Using Virtual Passive Controllers," *Journal of Guidance, Control, and Dynamics*, Vol. 25, No. 3, 2002, pp. 419-424.

Overview of Project Process

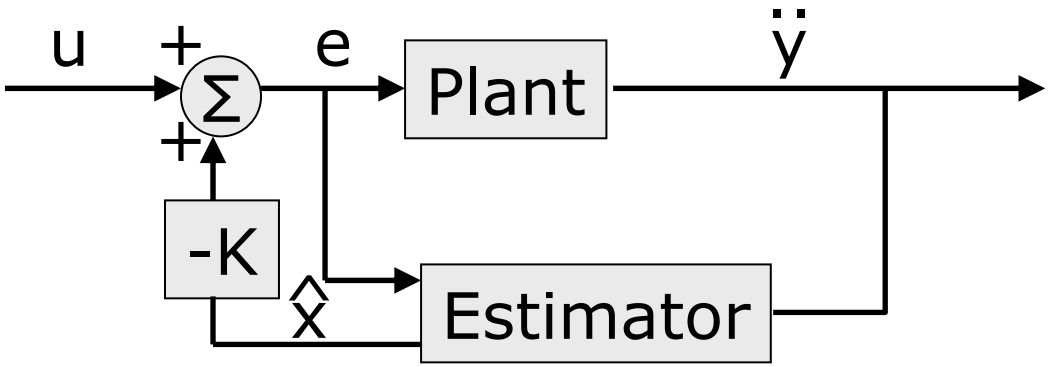


System to be Analyzed

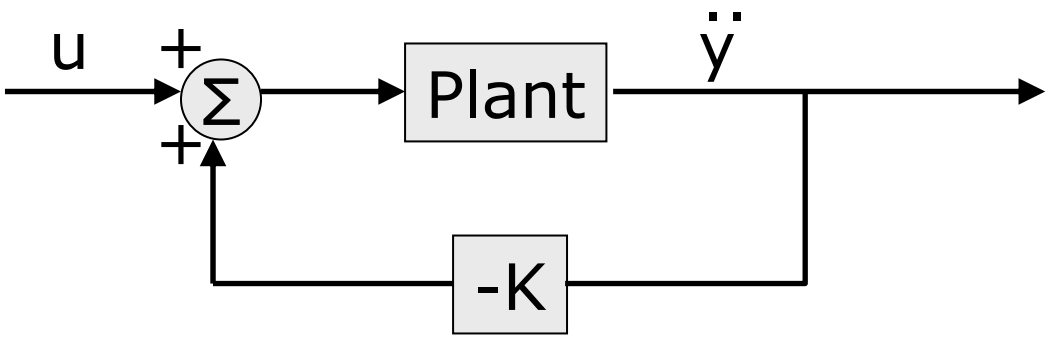


Controller was developed to increase modal space

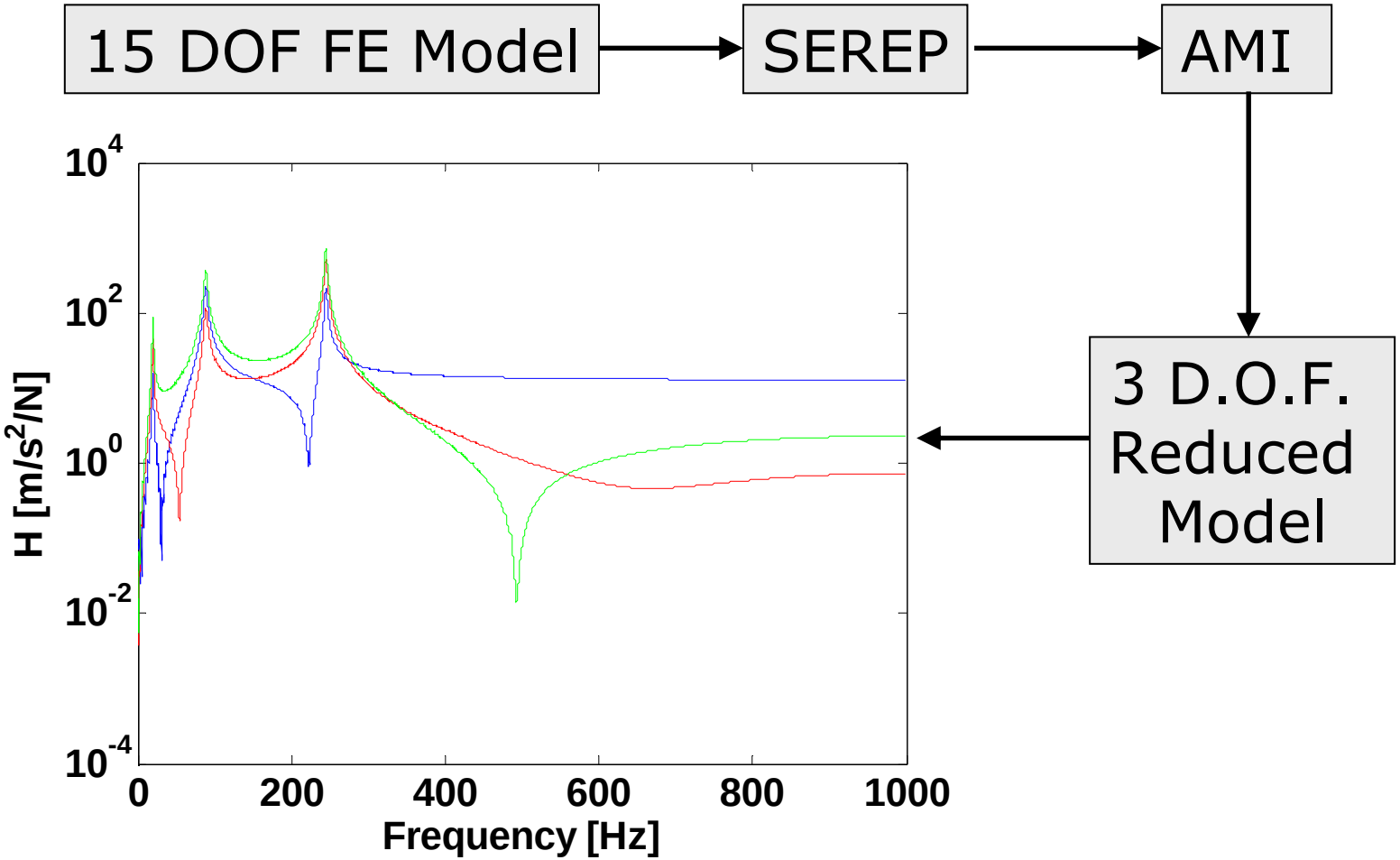
Controller with Second Order Dynamics



Direct Acceleration Feedback Controller

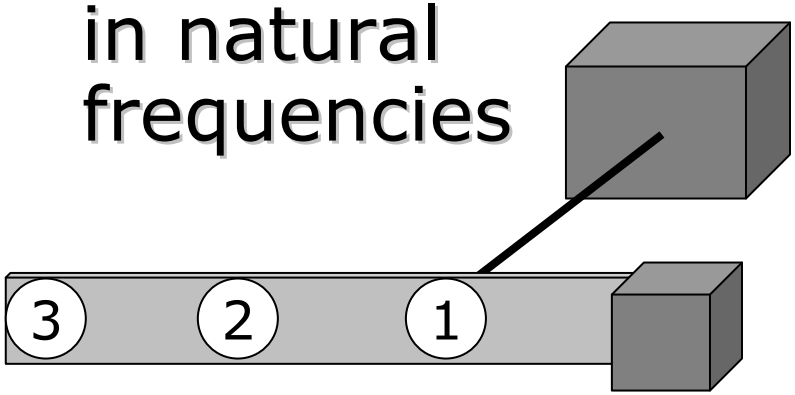


Model reduction was needed for controller simulation and estimator

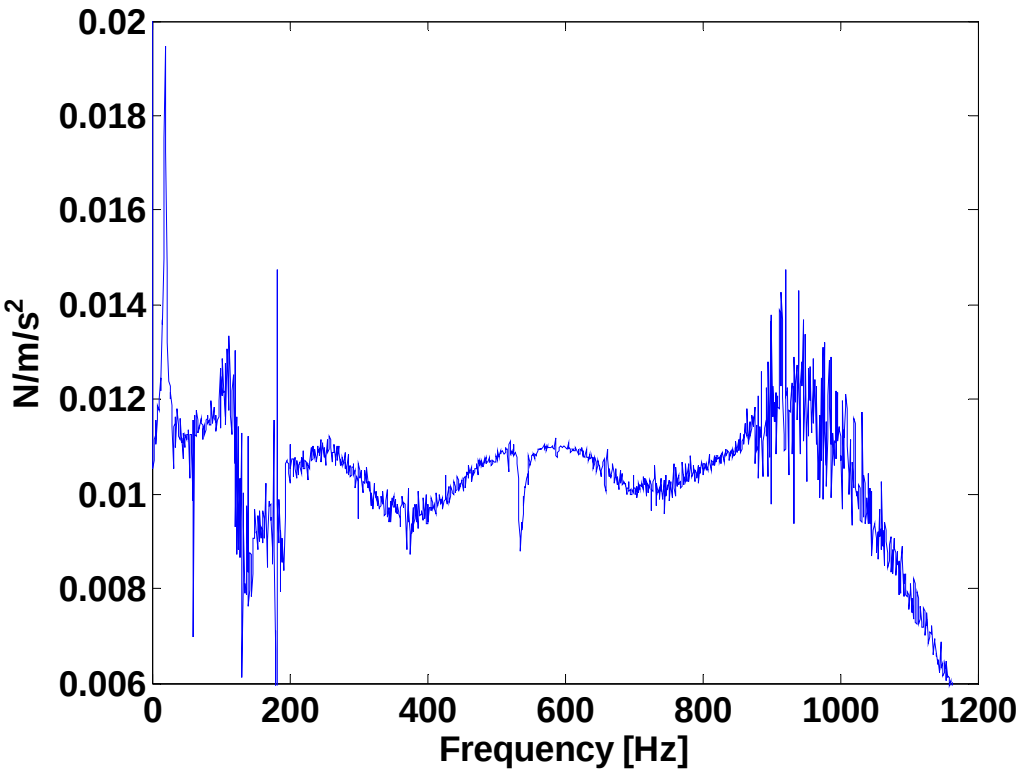


Controller adds error

- Gain of 0.010 on acceleration at DOF #1
- System was marginally unstable at a gain of 0.012
- No detectable shift in natural frequencies



FRF of Shaker Force to Acceleration at DOF 1

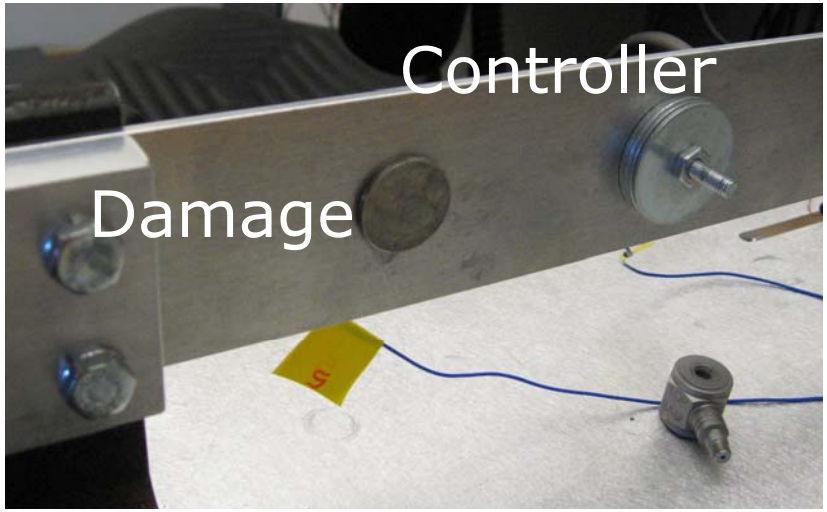


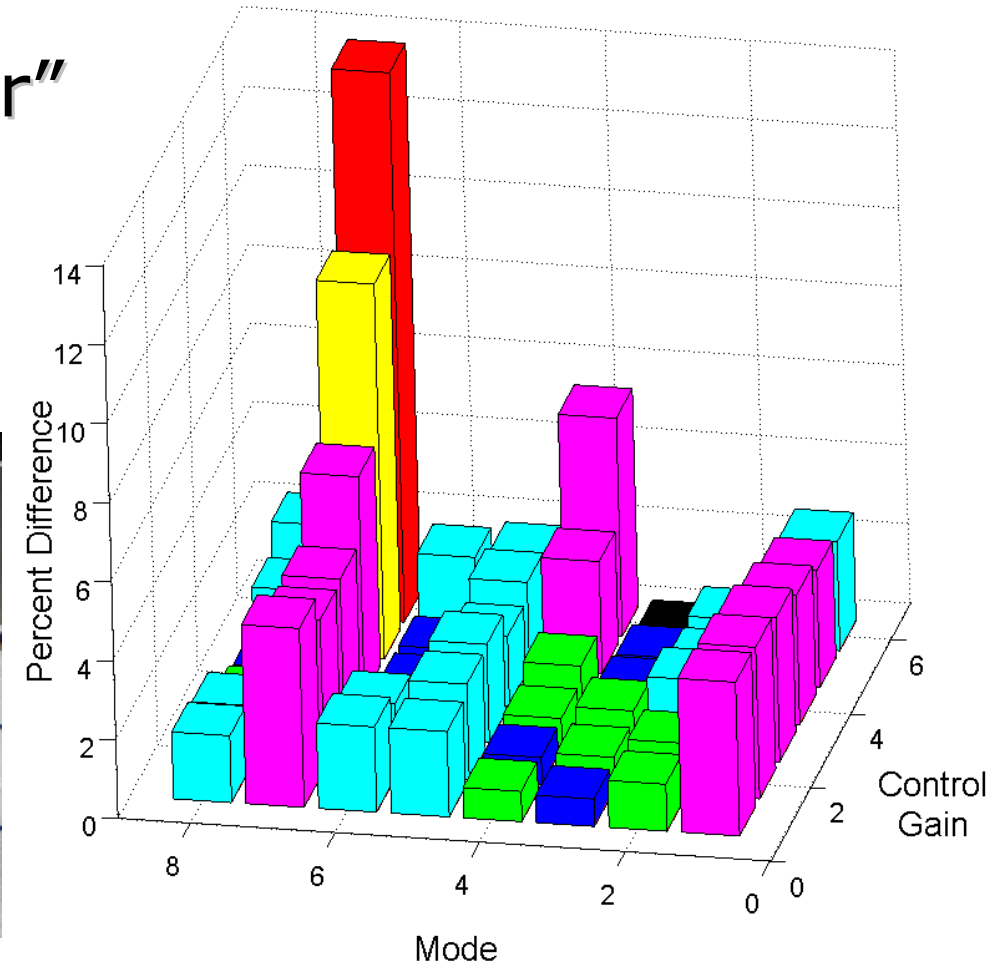
Hardware limitations

- No sample and hold on data acquisition box
- Amplifier and shaker dynamics not part of FE model
- Successful controller implementation contingent upon modeling the **FULL** system
- Forgo shaker control

Mass perturbations used as more reliable way to increase modal space

Point mass "controller"
= ideal perturbation





Basic Finite Element Model

Euler-Bernoulli 2-D Beam Elements

$$[m] = \frac{\rho AL}{420}\begin{bmatrix} 156 & 22L & 54 & -13L \\ 22L & 4L^2 & 13L & -3L^2 \\ 54 & 13L & 156 & -22L \\ -13L & -3L^2 & -22L & 4L^2 \end{bmatrix}$$

$$[k] = \frac{EI}{L^3 + 12Lg}\begin{bmatrix} 12 & 6L & -12 & 6L \\ 6L & 4L^2 + 12g & -6L & 2L^2 - 12g \\ -12 & -6L & 12 & -6L \\ 6L & 2L^2 - 12g & -6L & 4L^2 + 12g \end{bmatrix}$$

15 elements (enough for convergence of natural frequencies)

Constant cross-section

Aluminum properties

Mass of accelerometers added at nodes

Implemented in MATLAB

Natural frequency difference is evidence of damage

$$\Delta\omega = \omega_t - \omega(z)$$

$\Delta\omega$	Detect damage by minimizing difference in natural frequencies
ω_t	Experimental natural frequencies of damaged structure
$\omega(z)$	Frequencies computed with damage vector z

Algorithm utilizes FEM M, K

Damage Variables

$$z = \begin{bmatrix} z_1 & z_2 & \dots & z_r \end{bmatrix}^T$$

Open-Loop System

$$\left[\omega_{0i}^2 M(z) + K(z)\right]\phi_i = 0$$

Closed-Loop Systems

$$\left[\left(\omega_{ci}^j\right)^2 M_c^j(z) + K_c^j(z)\right]\phi_i = 0$$

Sensitivity Matrix

$$A = \begin{bmatrix} \frac{\partial \omega_o}{\partial z_1} & \frac{\partial \omega_o}{\partial z_2} & \dots & \frac{\partial \omega_o}{\partial z_r} \\ \frac{\partial \omega_c^1}{\partial z_1} & \frac{\partial \omega_c^1}{\partial z_2} & \dots & \frac{\partial \omega_c^1}{\partial z_r} \\ & \vdots & \ddots & \\ \frac{\partial \omega_c^m}{\partial z_1} & \frac{\partial \omega_c^m}{\partial z_2} & & \frac{\partial \omega_c^m}{\partial z_r} \end{bmatrix}$$

Each iteration updates damage vector

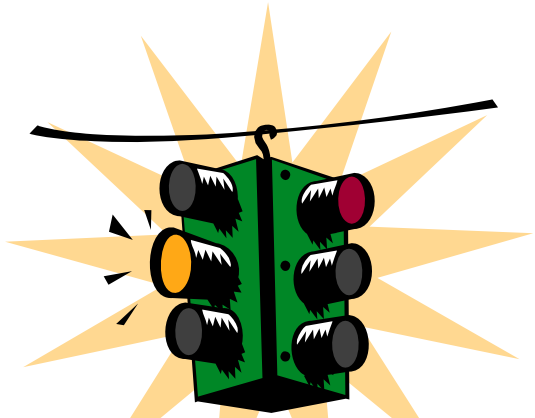
$$\omega(z+\Delta z) = \omega(z) + A(z)\Delta z + \cdots$$

Δz = damage variable step

$$\omega(z+\Delta z) \approx \omega(z) + A(z)\Delta z$$

$$A(z)\Delta z \approx \Delta\omega$$

$$\Delta z \approx (A^T A)^{-1} A^T \Delta\omega$$



PSEUDOINVERSE

Choosing iteration parameters

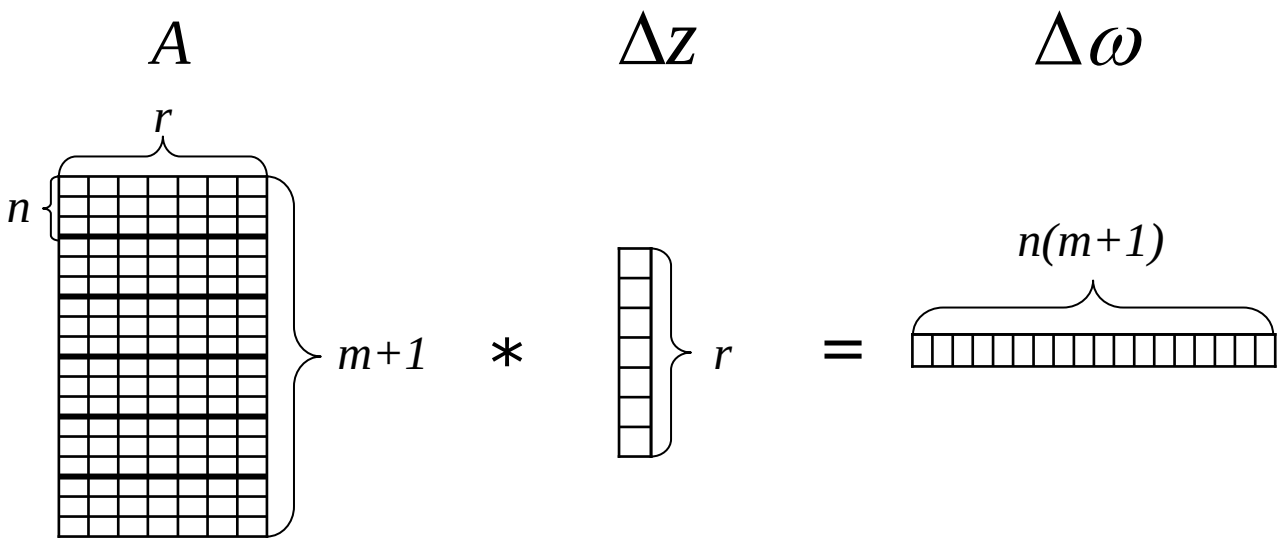
$$n(m+1) \geq r$$

$$n \geq \frac{r}{2}$$

n # observed natural frequencies

m # control gains

r # damage variables



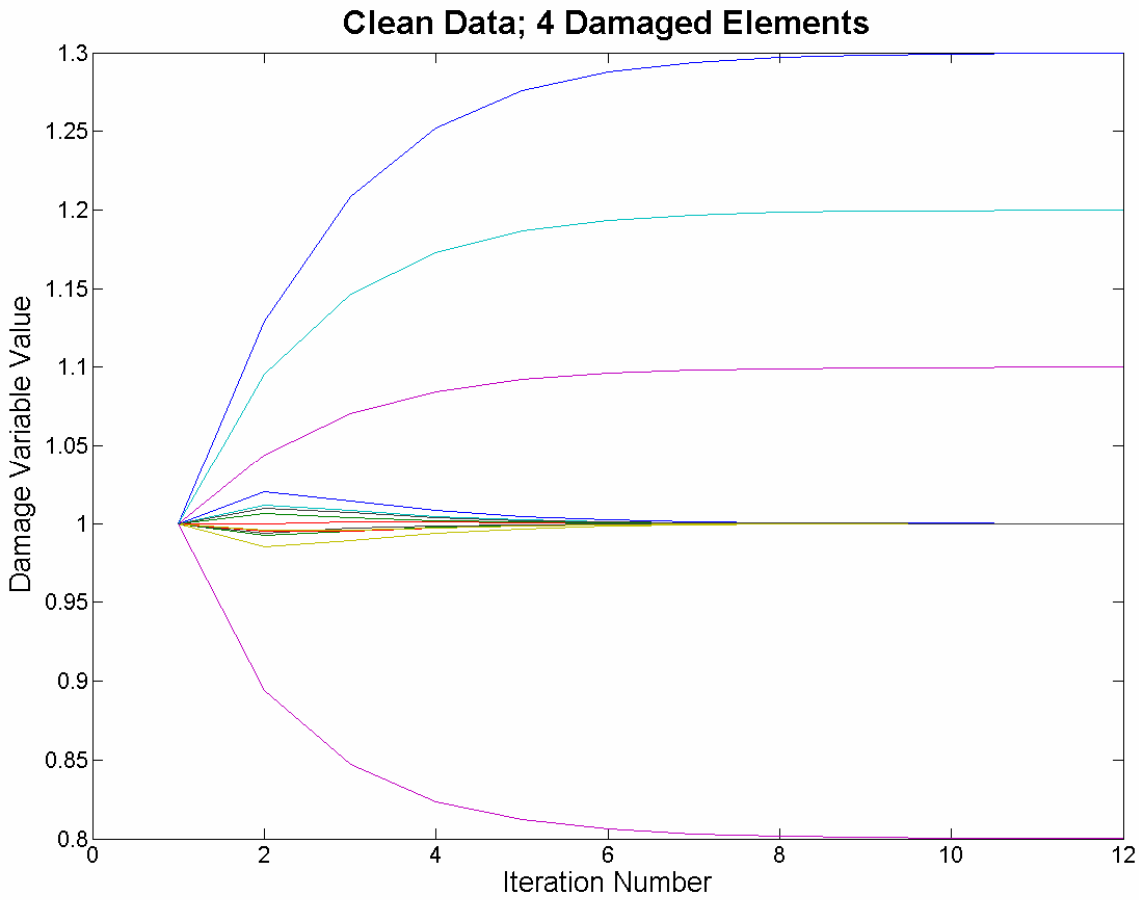
Algorithm Summary

1. Compute $\omega(z_{new})$ from

$$\left[\omega_{0i}^2 M(z) + K(z)\right]\phi_i = 0 \qquad \left[\left(\omega_{ci}^j\right)^2 M_c^j(z) + K_c^j(z)\right]\phi_i = 0$$

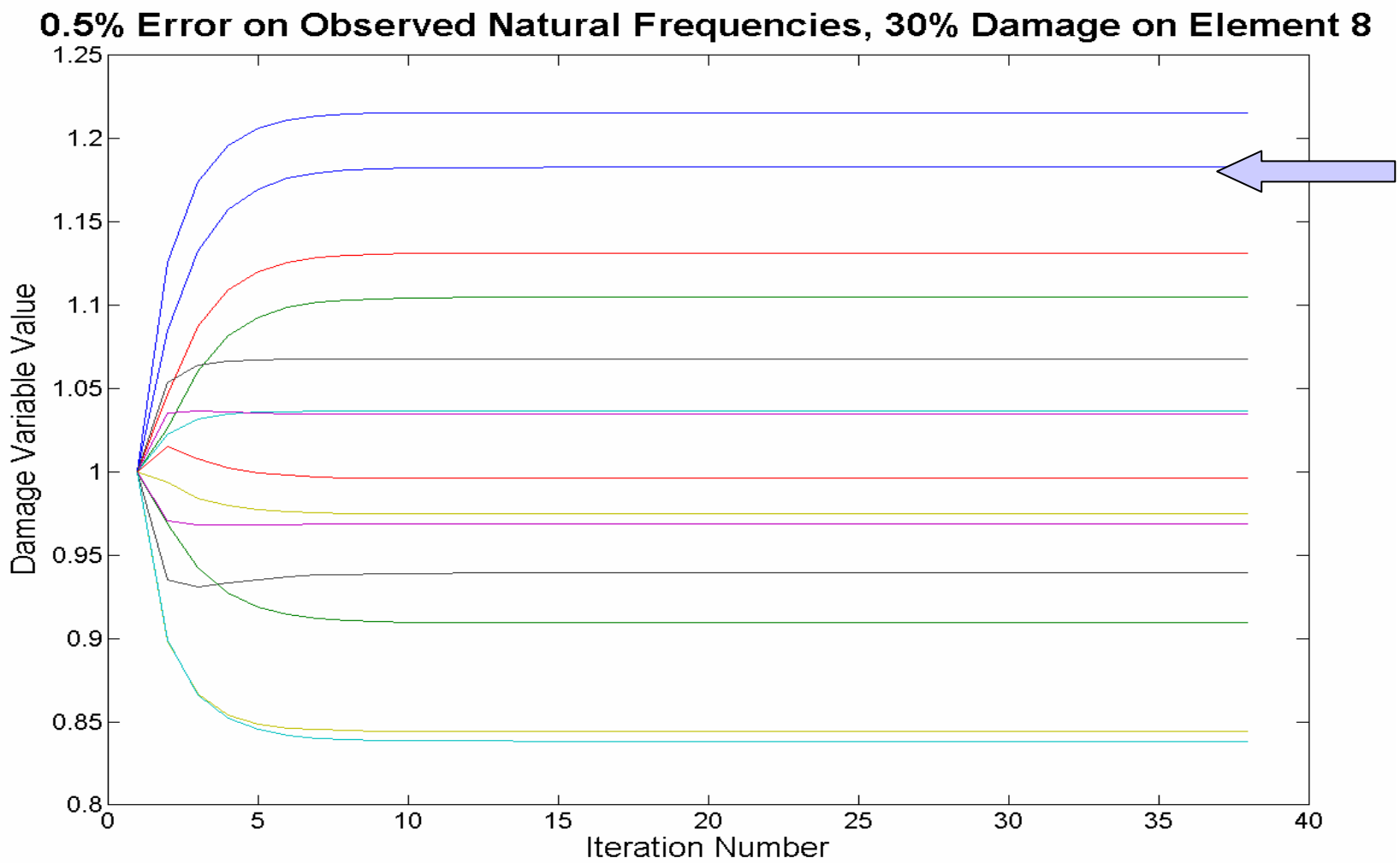
2. Compute $\Delta\omega = \omega_t - \omega(z)$
3. Compute A
4. Find $\Delta z \approx (A^T A)^{-1} A^T \Delta\omega$
5. Check convergence and repeat if necessary

Theoretical Algorithm Implementation

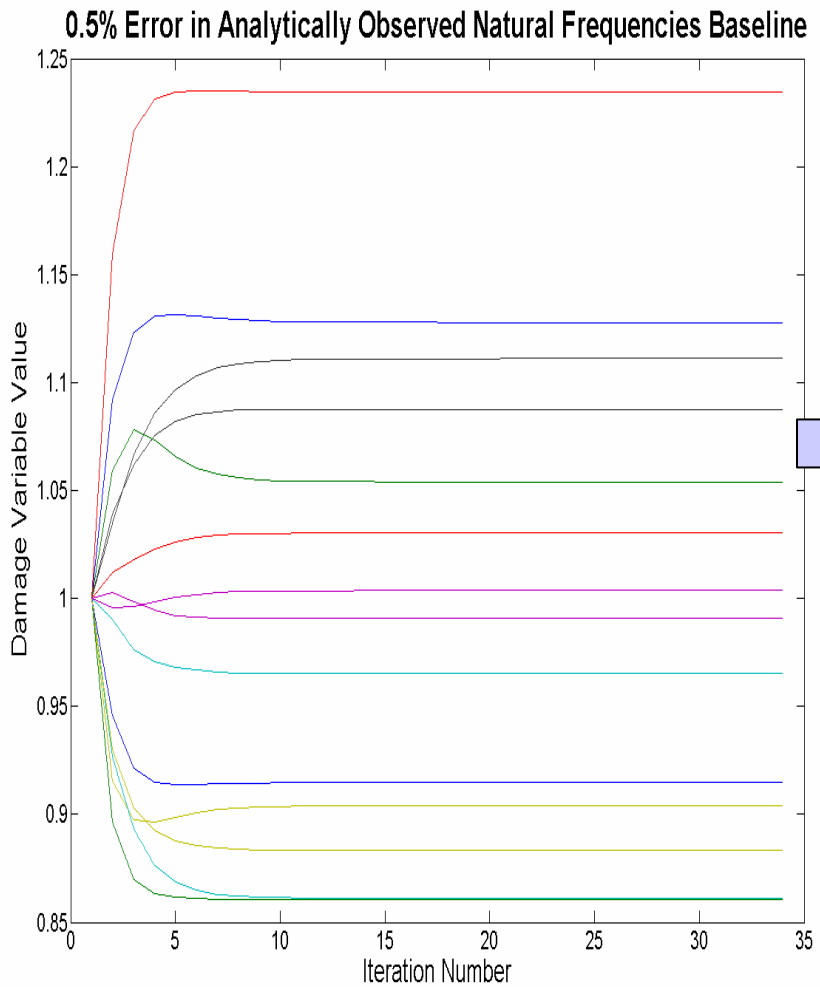


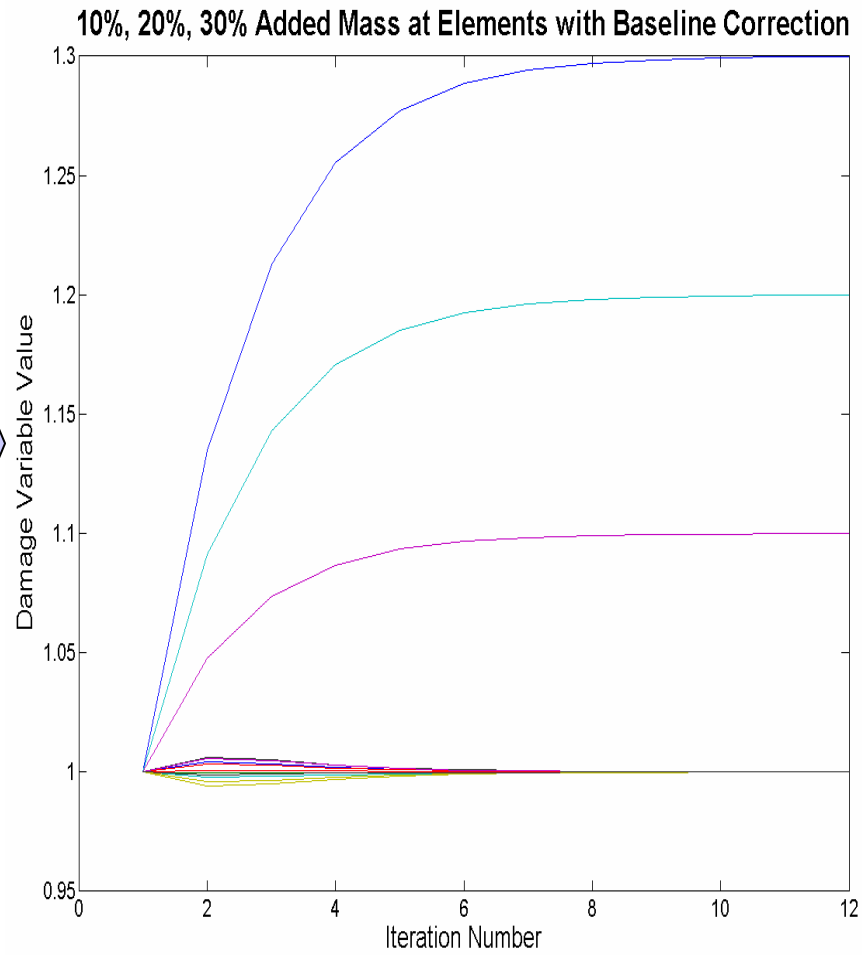
Element	Z
1	1
2	1
3	1
4	1
5	1.1
6	1
7	1
8	1.3
9	1
10	1
11	1.2
12	0.8
13	1
14	1
15	1

Algorithm is very sensitive to variance

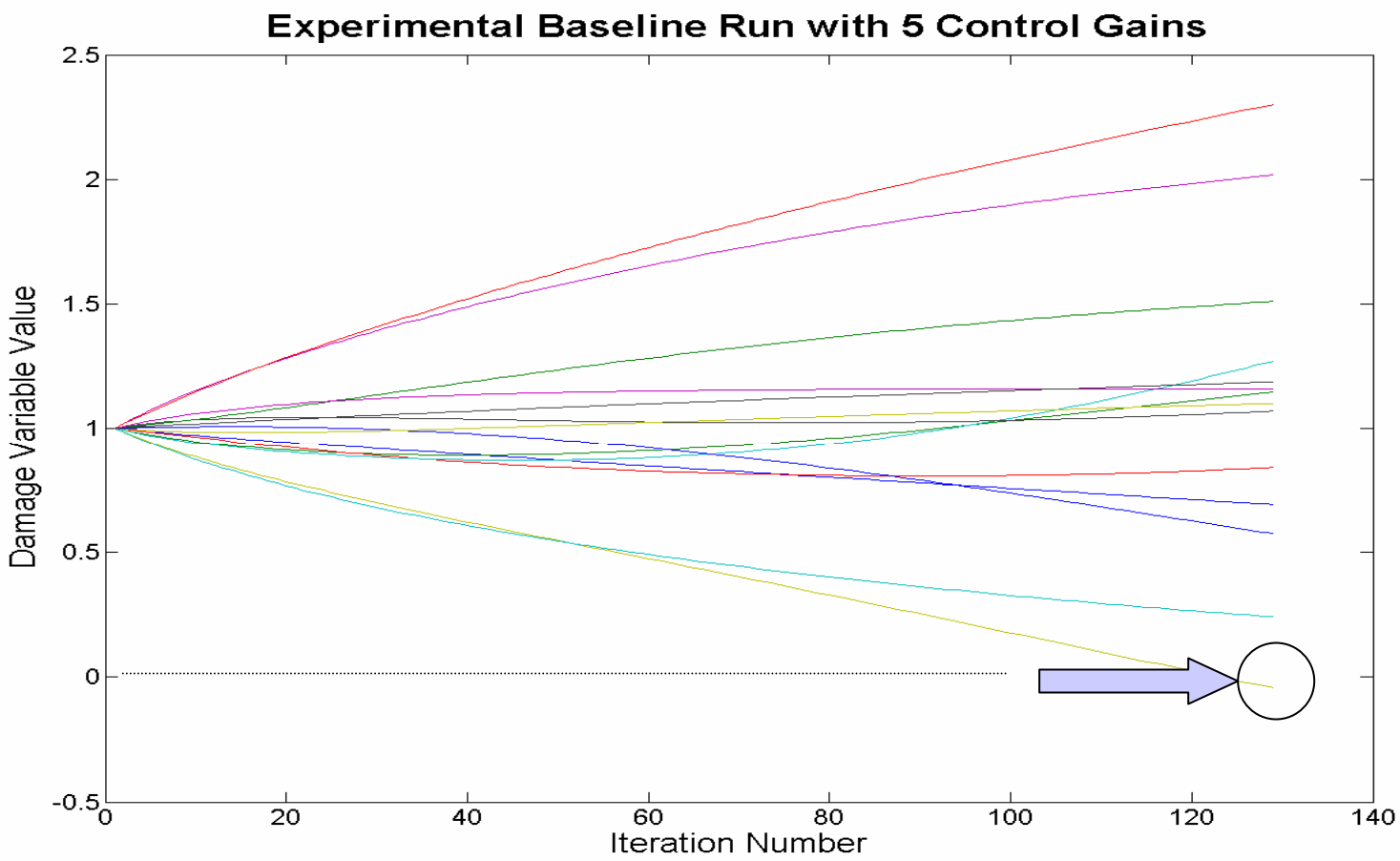


Damage can be Detected if Algorithm Converges

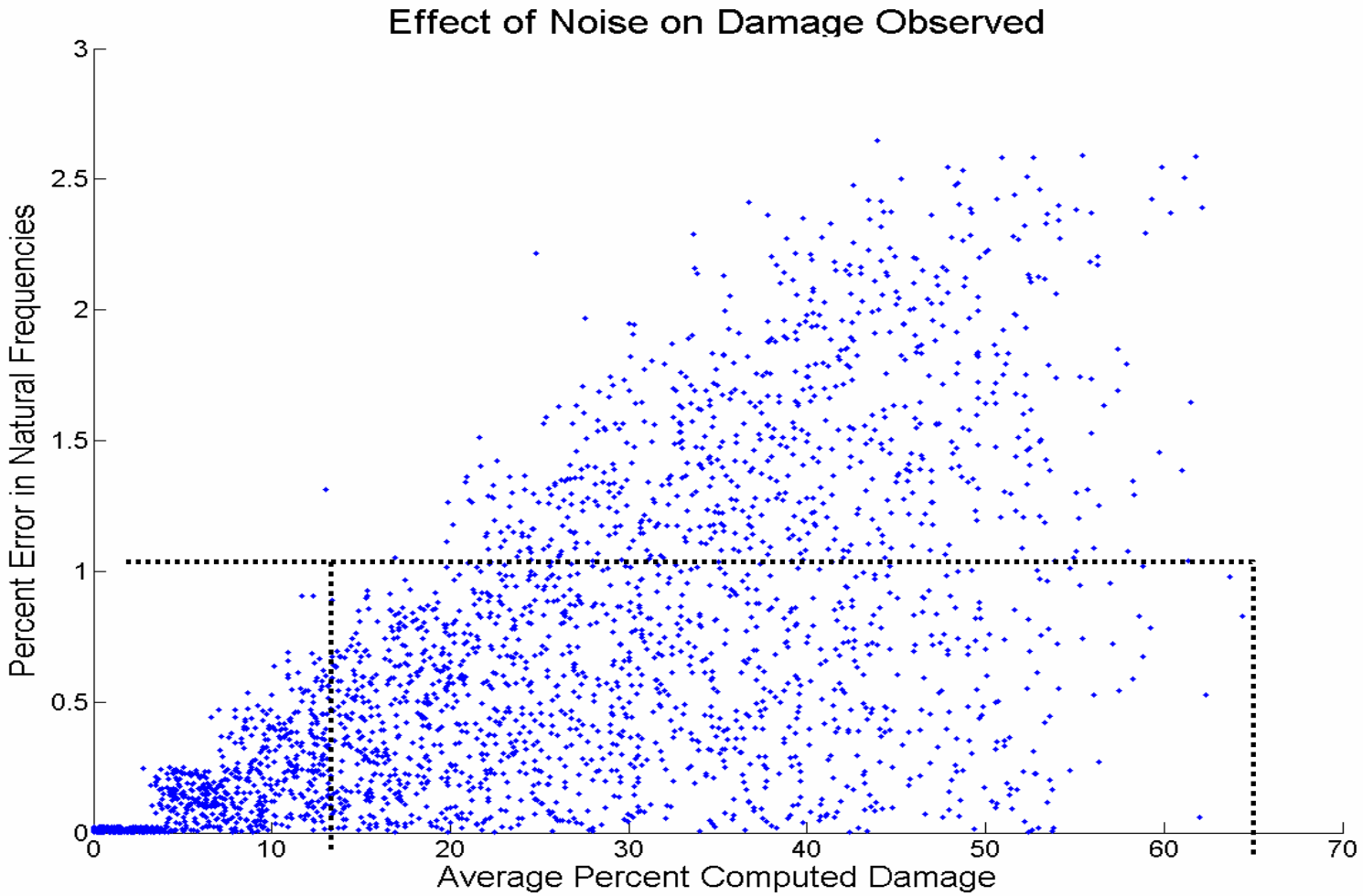




No convergence with mass pertubation model



Algorithm and system are sensitive to the point of impracticality



Conclusions/Summary

Algorithm is not currently practical

Error in model +

Error in controller +

Error in frequencies

If $\Delta\omega_n > 1\%$

Exceeds limit of algorithm

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Three evident areas limiting experimental implementation

Algorithm

- Simplex Method
- Genetic Algorithm
- Seeded Gradient

Controller

- Phase delay
- Frequency dependent gain
- 2nd order dynamic controller

Model

- More complex FE model
- Complete system model

We would like to acknowledge….

- Engineering Sciences and Applications Division at Los Alamos National Laboratory
- The Mathworks, Inc. (MATLAB Software)
- ABAQUS, Inc. (ABAQUS Finite Element Software)
- Vibrant Technologies (ME'scope Software)