Model Validation of Loose Bolted Joints in Damaged Structural Systems

Los Alamos Dynamic Summer School Program - 2006

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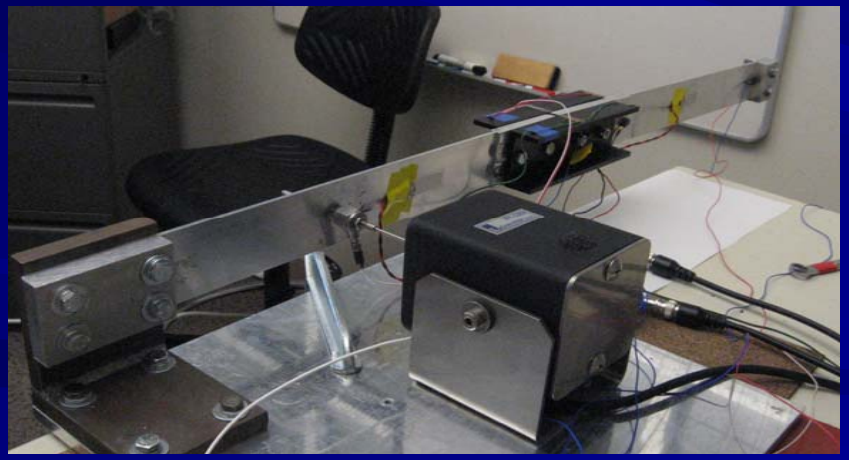
Mentor: Alan Barhorst

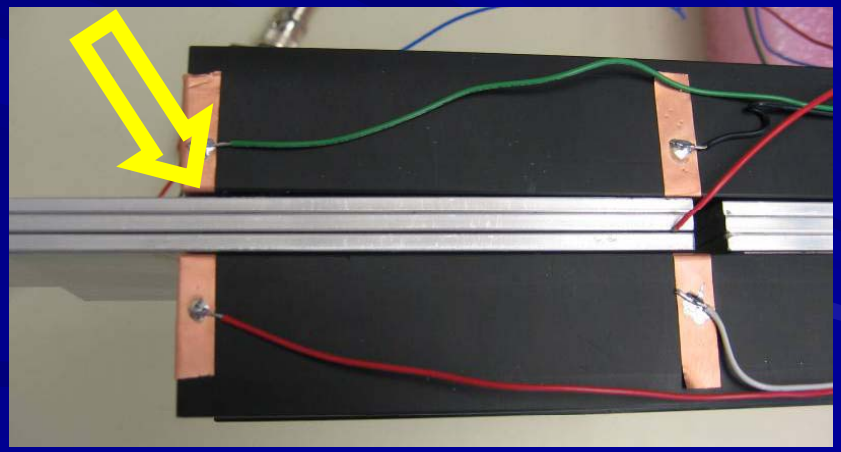
Roadmap

- Introduction, motivation and background research – Joel
- Experimental setup – Brandon
- Results and conclusion - Tyler

Introduction

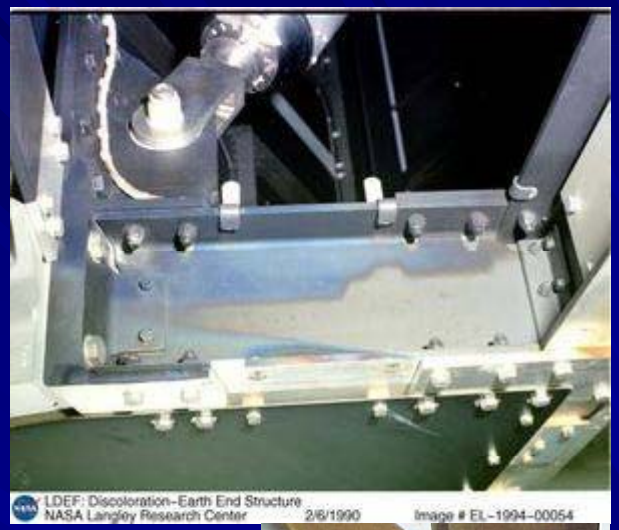
- Bolted lap joints are very common
- Damaged joints exhibit complex nonlinear behavior
- Useful to be able to model the dynamics
- Validate a low order model of the joint and beams
- Modeled joint has gap that simulates damage





Motivation

- Buildings, aircraft, robots, bridges, etc… use bolted joints
- Damaged joint model could be useful in extending service life
  - Could mitigate effects of damage ↔ control
- Low order model = low cost



Background Research

- Microslip and macroslip research
  - Microslip – parts of the joint interface slip
  - Macroslip – entire joint slips
  - Contributes significantly to the damping of the system
- Sandia - Lower order Iwan models to study microslip and macroslip
- Others - Larger (7000) DOF finite element models

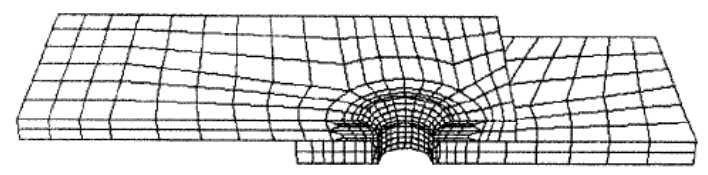


Fig. 7. Panel discretization—2.0 mm

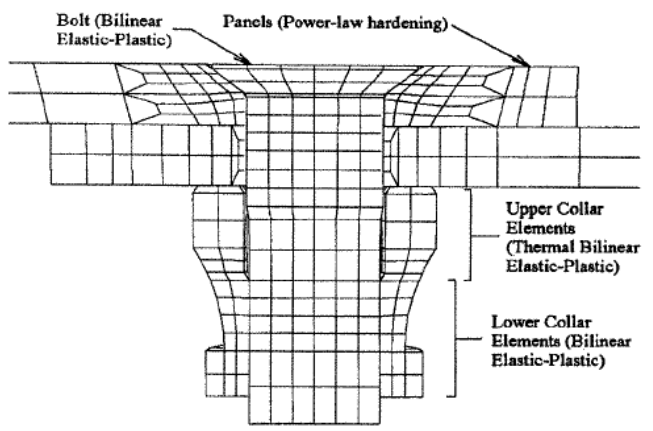
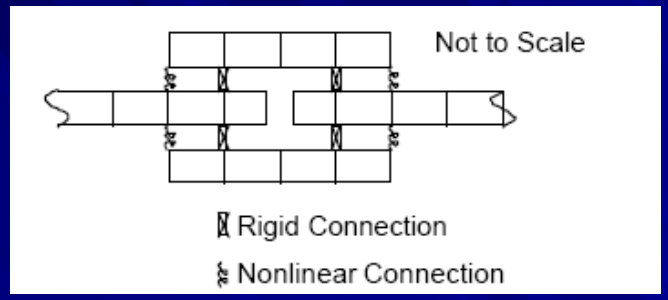


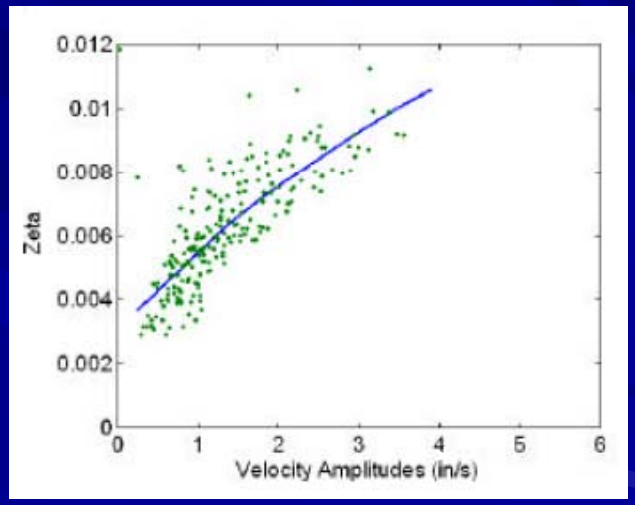
Fig. 8. Threaded pin-and-collar discretization

* Figures from Pratt and Pardoen

Background Research

- Moloney, Peairs and Roldan
  - Lower order finite element model with bristle friction
  - Damping is a function of input amplitude
- Others - found power law between excitation and energy loss, exponent between 2 and 3
- None of the research covered the extreme wear/damage that Barhorst includes in the model
- Collins, Nothnagel, and Pretko started to look at the problem

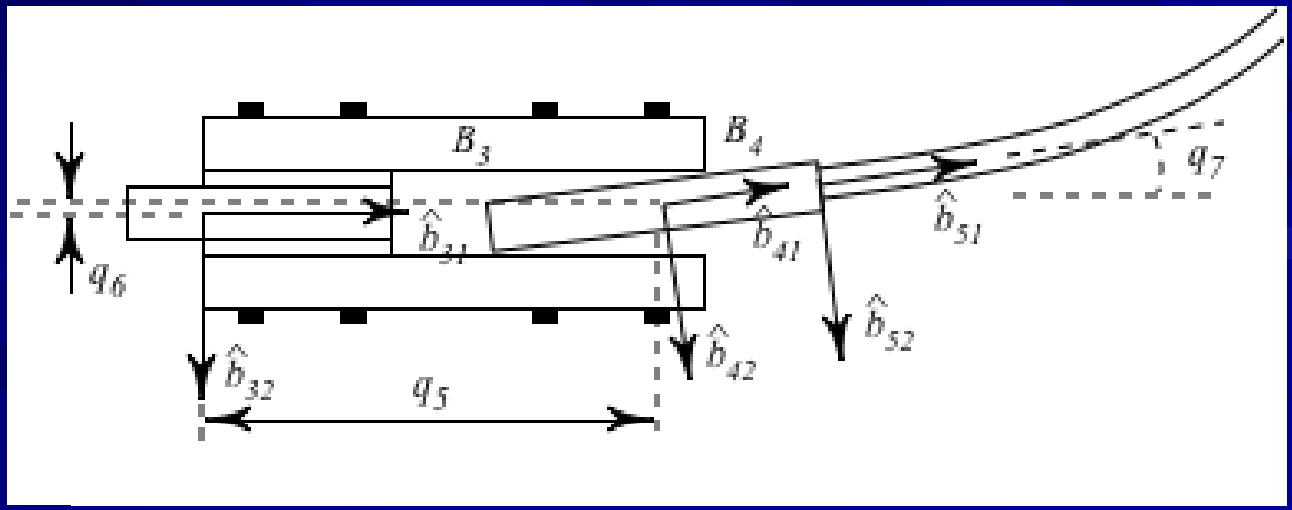




* Figures from Moloney, Peairs and Roldan

Analytical Model

- Developed using variational approach of Gibbs-Appell
- Low order model (9 DOF)
  - 3 DOF per flexible body = 6 DOF
  - 3 DOF for rigid body motion of outer beam
- No penalty methods or coefficients of restitution for constraints

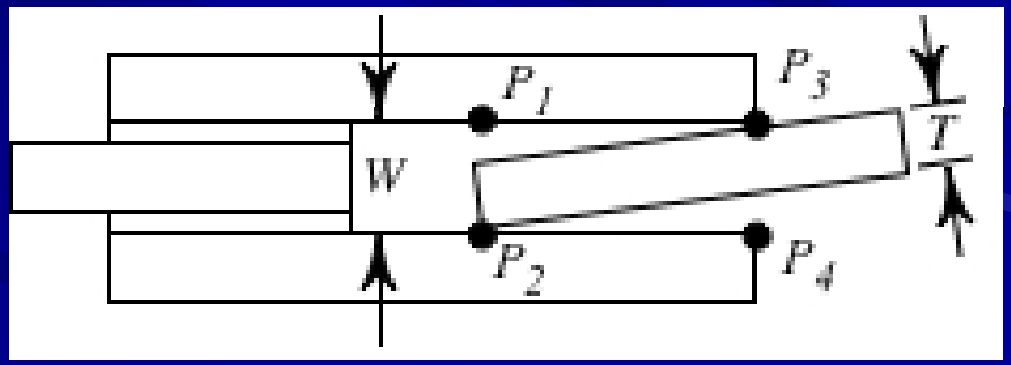


Analytical Model

- 17 motion regimes
  - Sticking/slipping with 1 contact point (1, 2, 3, 4)
  - Sticking/slipping with 2 contact points (1-3, 1-4, 2-3, 2-4)
  - Free flight
- Different regimes have different number of DOF
- Transfer momentum when contact regime changes (54 equations!)

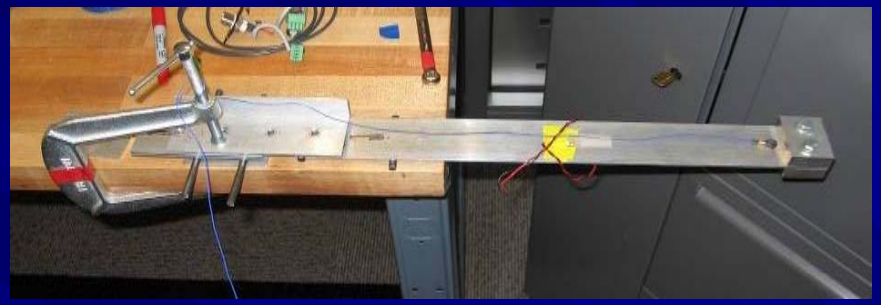
$$[I(q)]\{\dot{s}\} = \{f(q,s,t)\}$$
$$\{\dot{q}\} = \{s\}$$

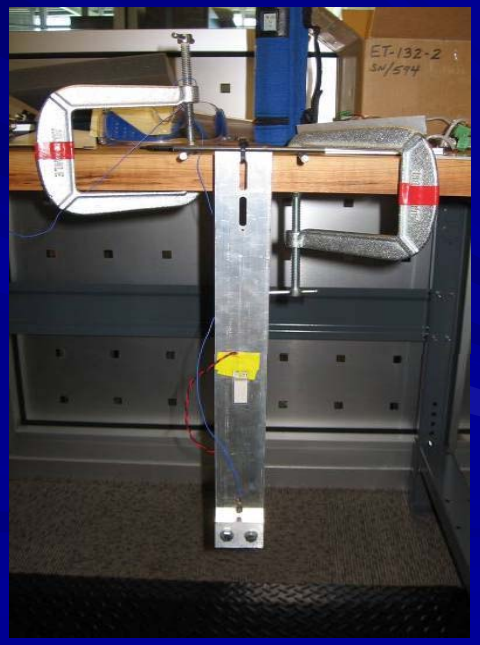
$$\left[I(q|_{t_o^-})\right]\left\{s|_{t_o^+}\right\} = \left\{Mom|_{t_o^-}\right\}$$



Parameter Identification

- Parameters to identify:
  - Damping
  - Stiffness
  - Inertia
  - Mass
  - Length
- Modal tests for damping identification
- Transform to model space
- Inertia was found using ABAQUS
- Values used as a starting point





$$W_n = \sqrt{U^{-1}\left(M^{-1}K\right)U}$$

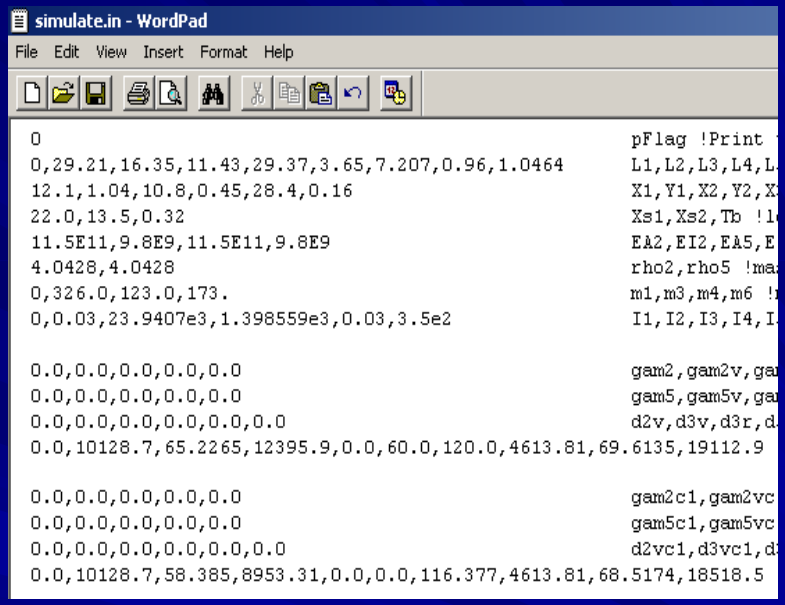
$$C_{model} = M\,U\left(2\zeta_{modal}W_n\right)U^{-1}$$

Simulation

- FORTRAN program running under Cygwin
- Varied parameters:
  - Damping
  - Energy loss due to impact
  - Forcing frequency and amplitude
  - Gap width
- Discrete sine and sine chirp input force
- Outputs:

$$q,\ \dot{q},\ \ddot{q},\ \varepsilon, \alpha, \text{contact}\ ,\ F$$

- Analyzed resulting data with Matlab

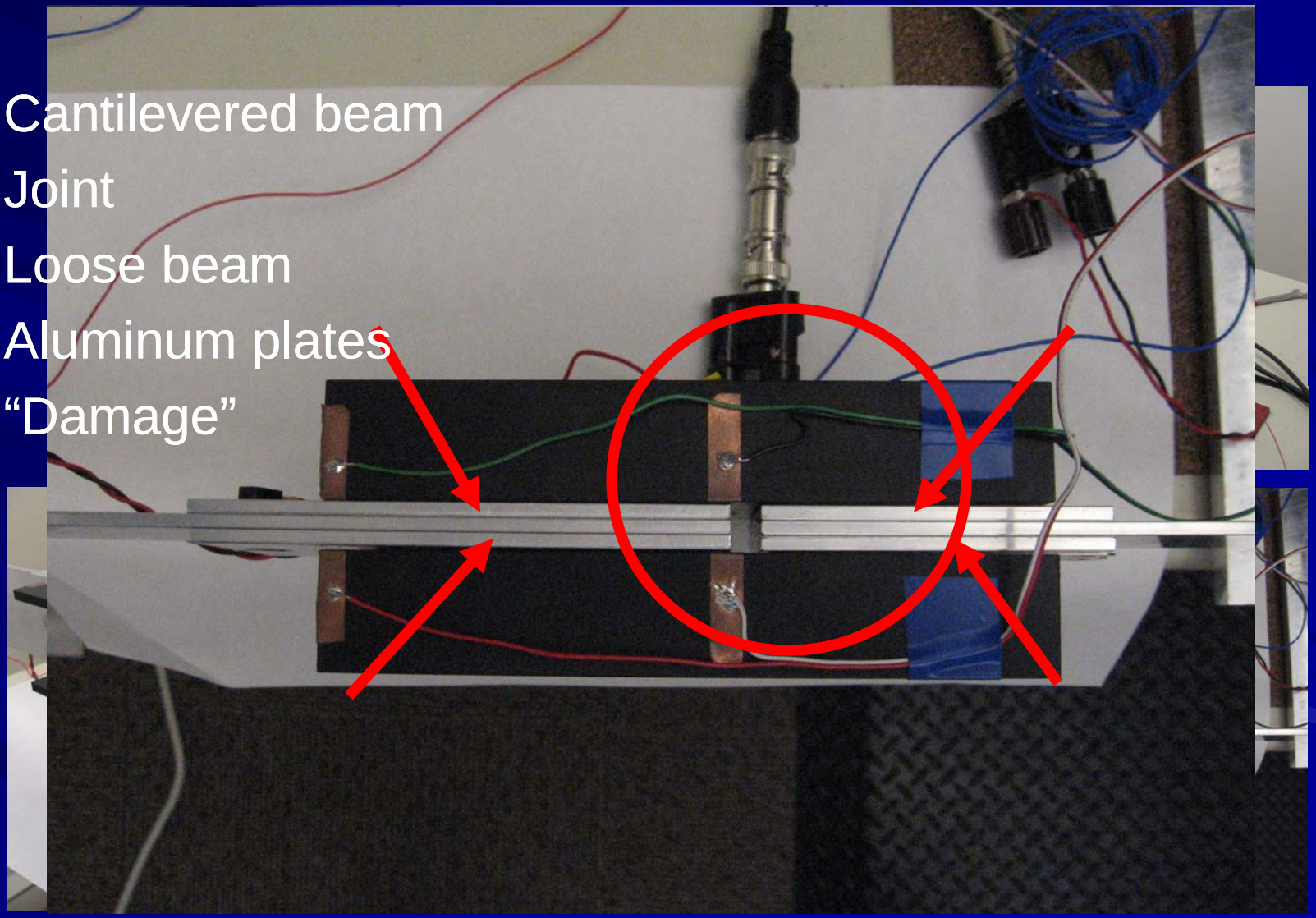


Experiment

- Test apparatus
- Sensors
- Contact detection
- Excitation
- Data acquisition
- Observations

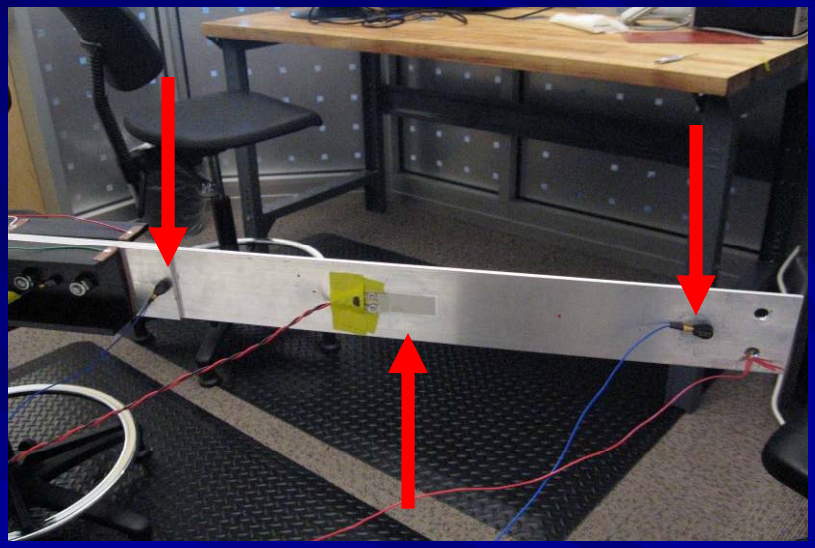
Test Apparatus

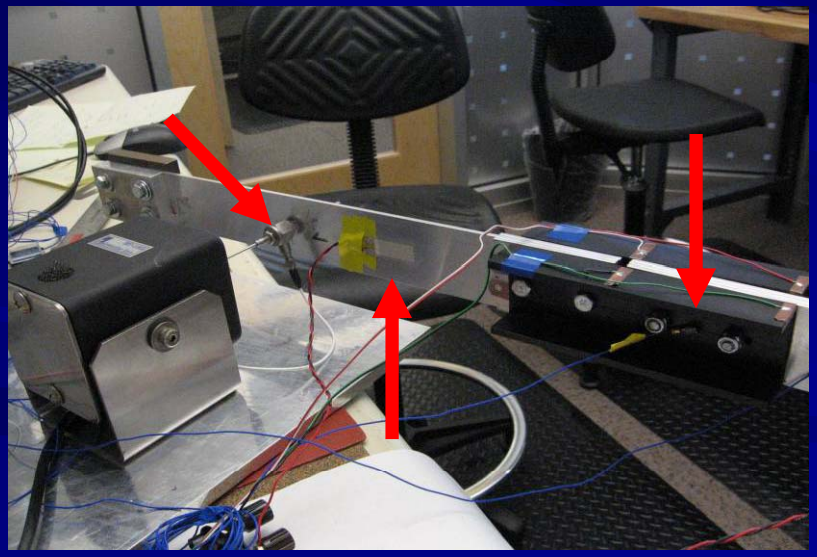
- Cantilevered beam
- Joint
- Loose beam
- Aluminum plates
- “Damage”



Sensors

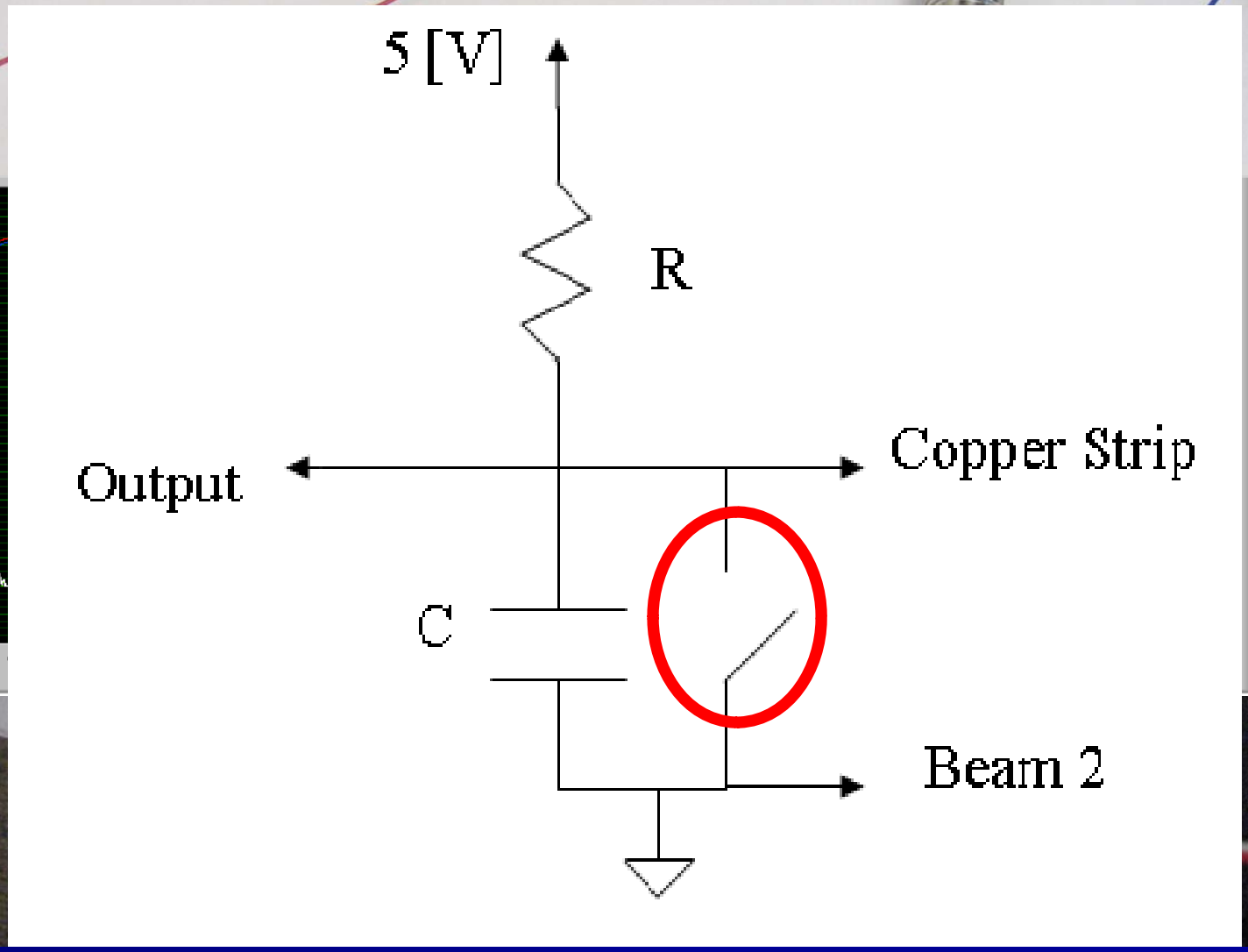
- 3 Accelerometers
- 2 Strain gauges
- 1 Force transducer





Contact Detection

- Cop



Excitation

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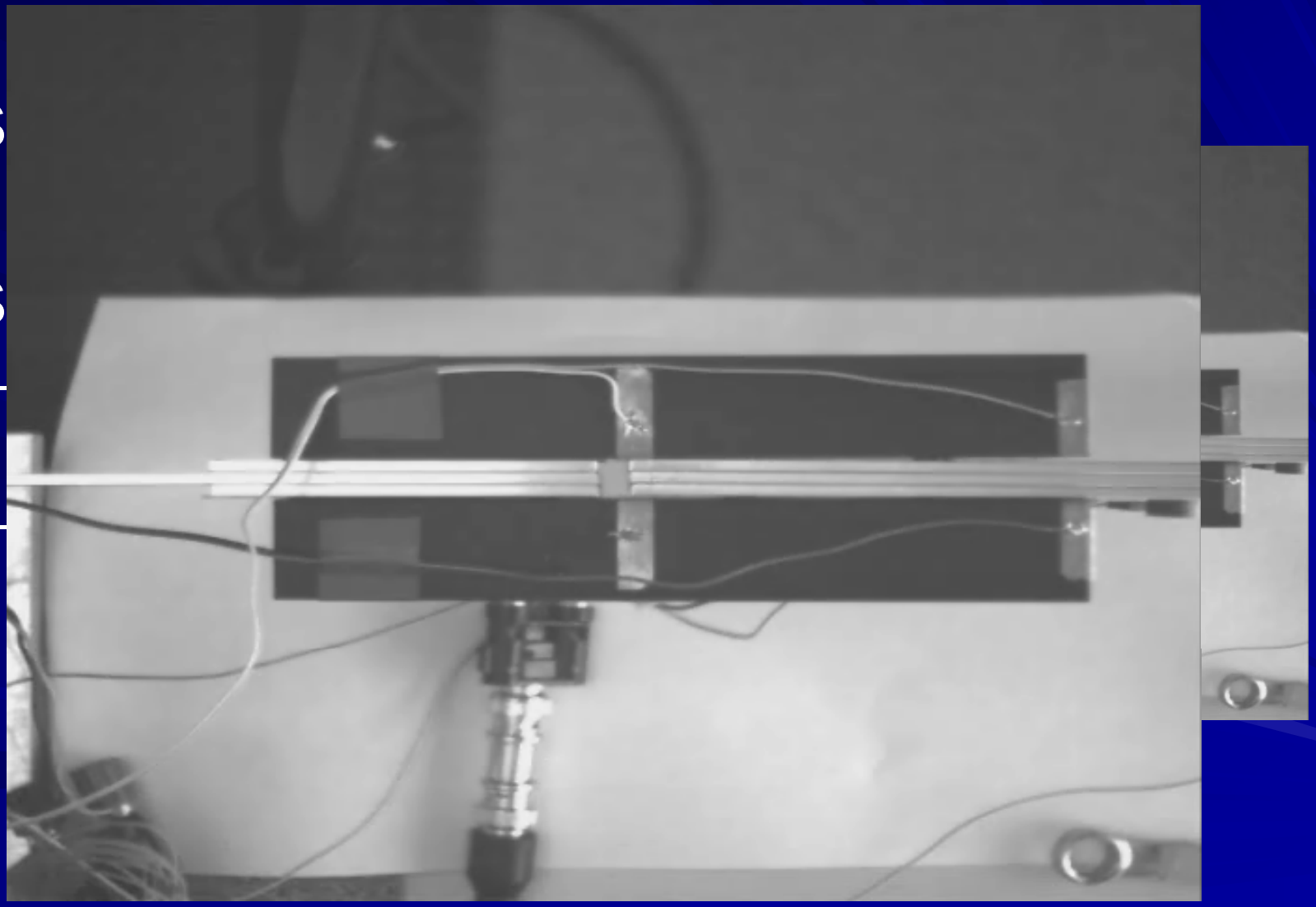
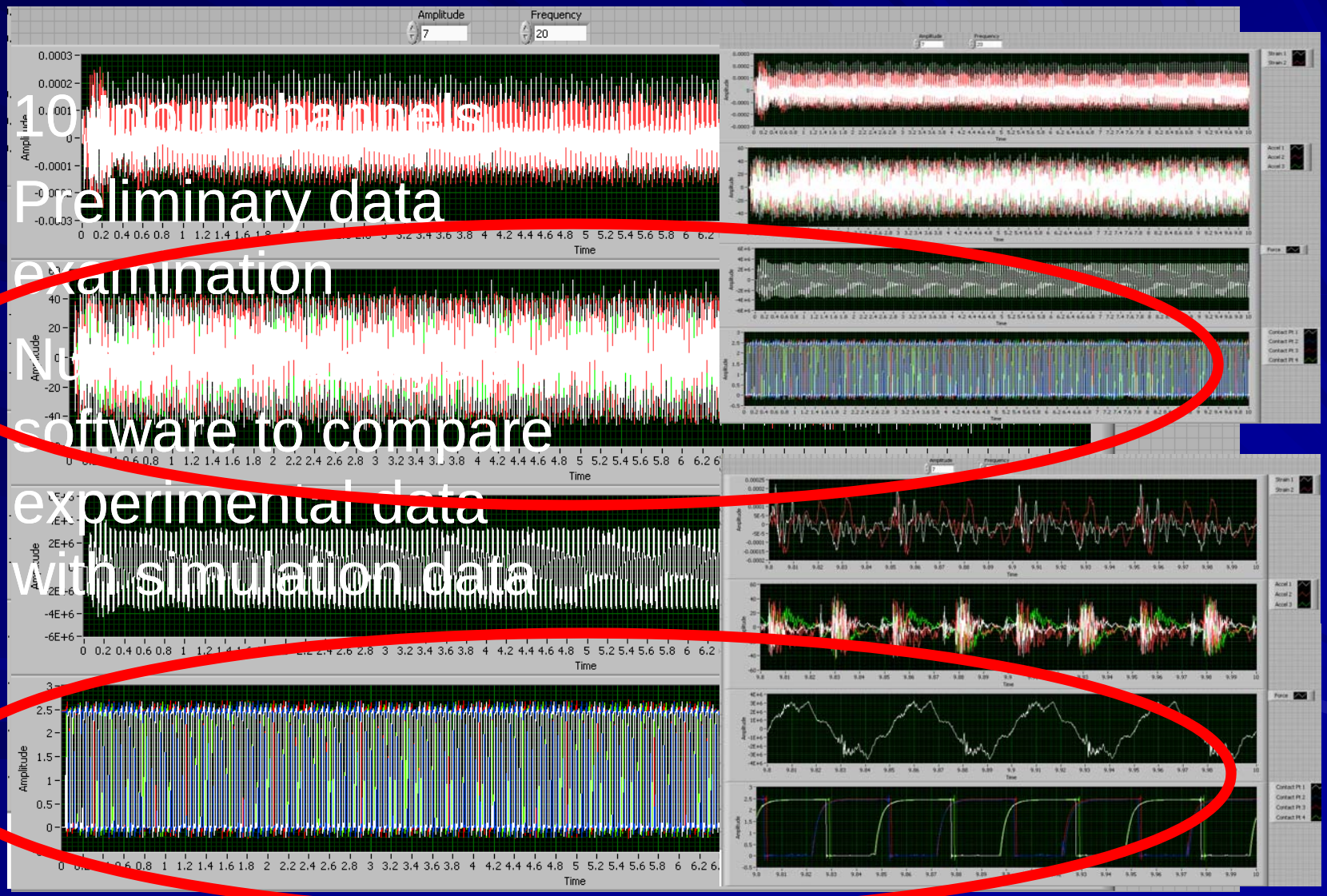


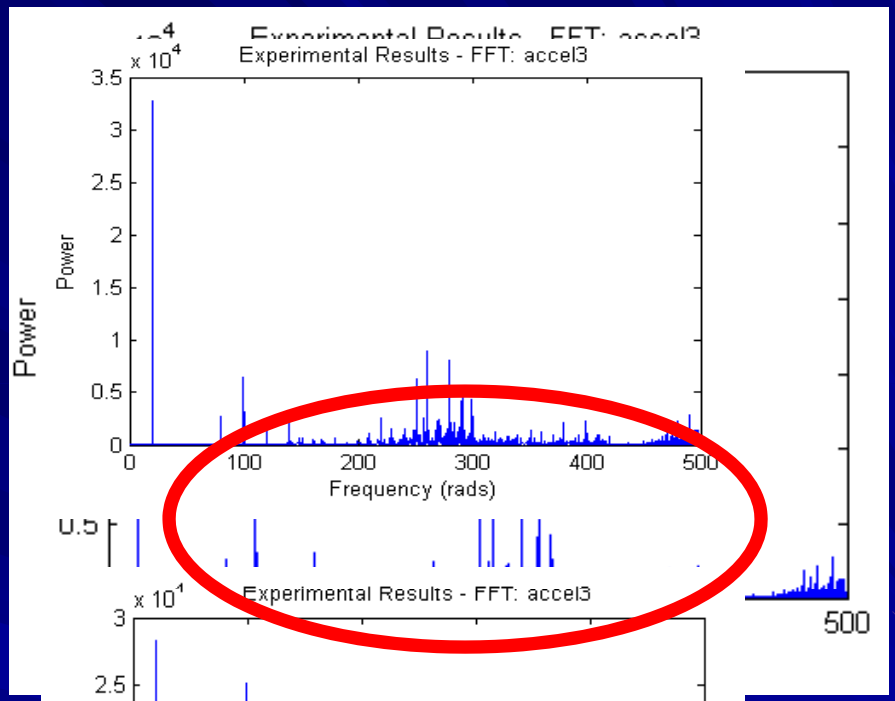
Data Acquisition

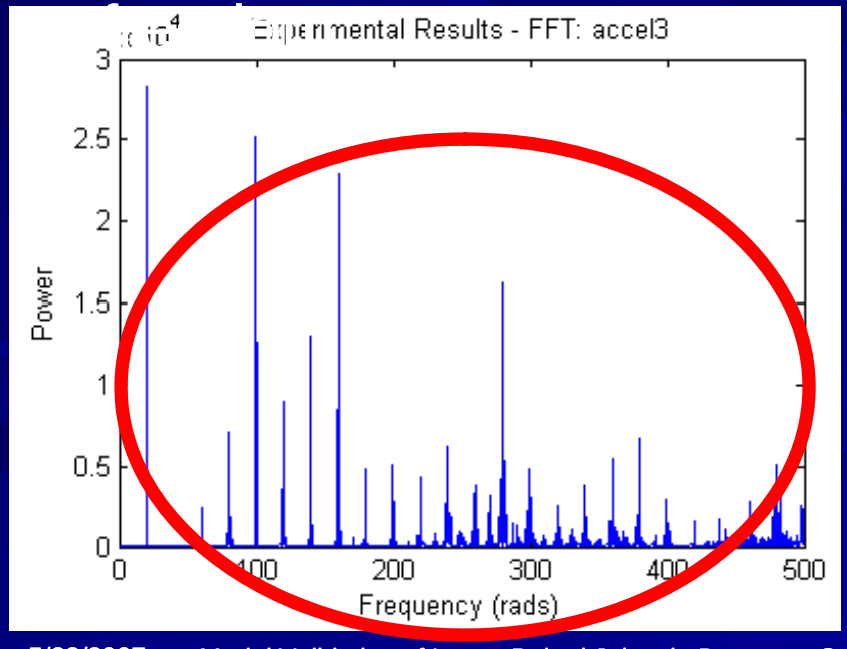
- 10 [illegible] channels
- Preliminary data examination
- Nu[illegible] software to compare experimental data with simulation data

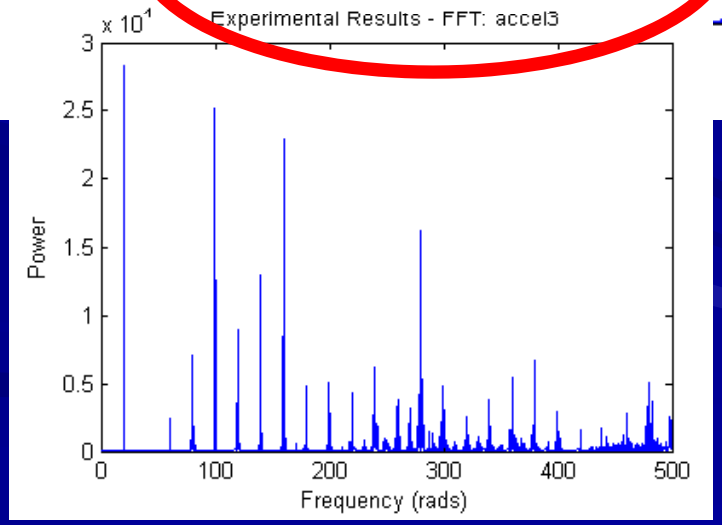


Observation 1

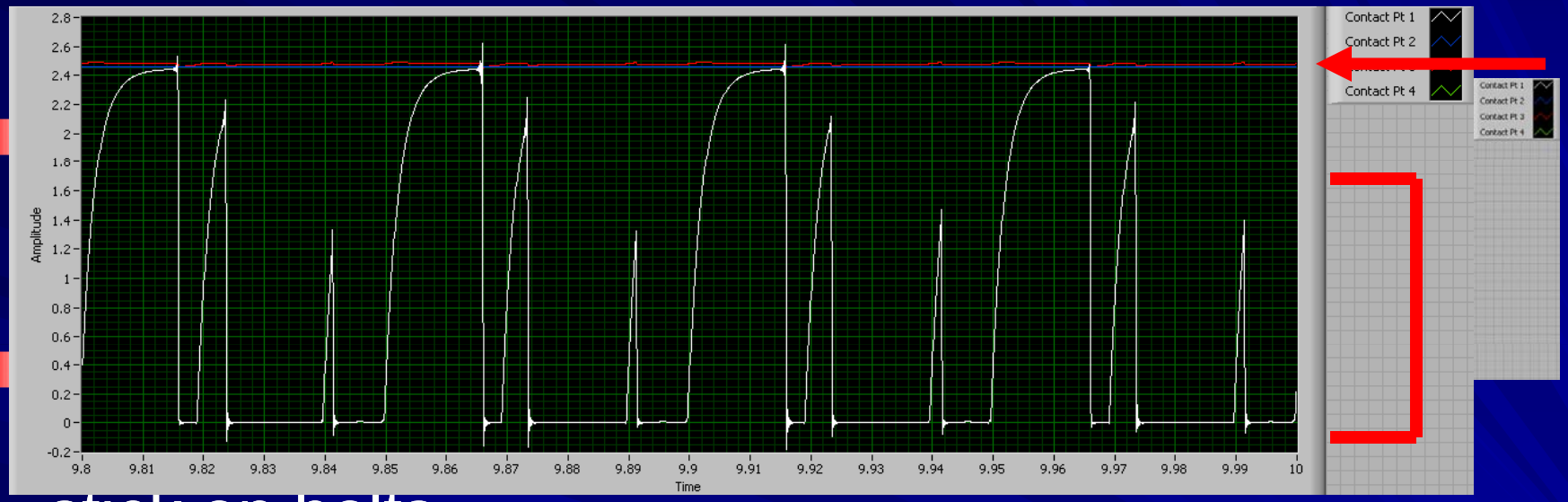
- Gap width affects nonlinearities
- Smaller gap causes more linear response
- Larger gap allows for more

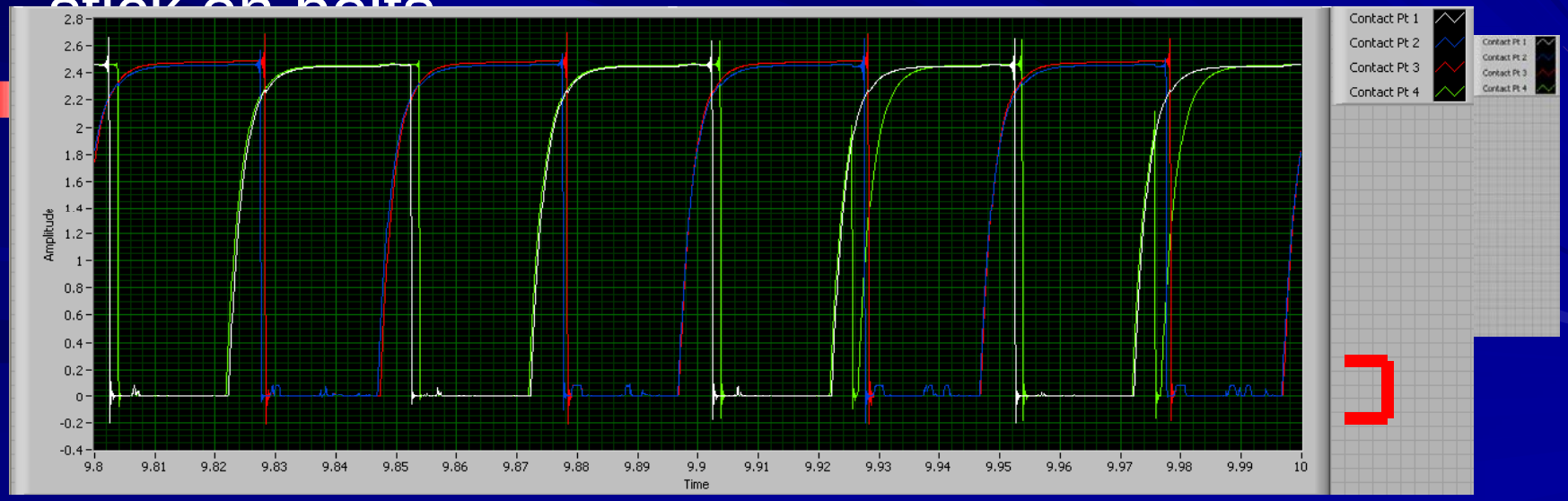






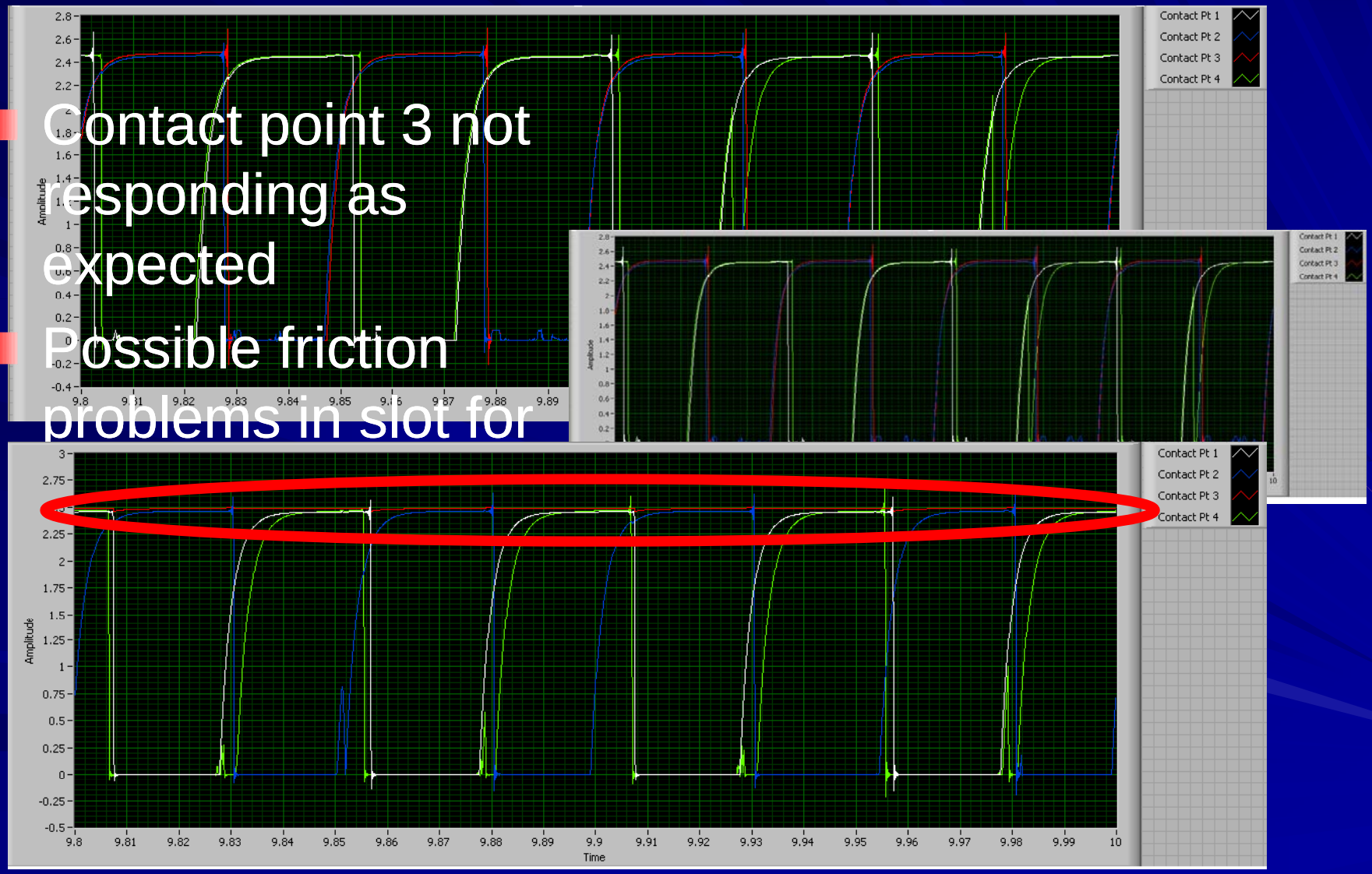
Observation 2





Observation 3

- Contact point 3 not responding as expected
- Possible friction problems in slot for



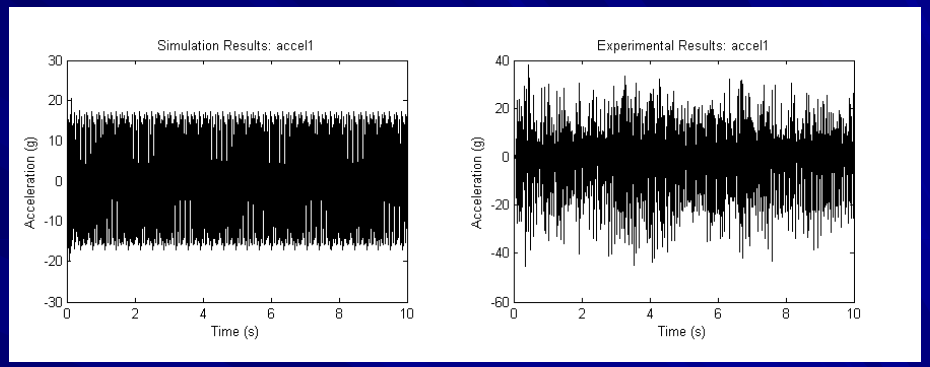
Results

- Nonlinear system = qualitative match only
- Time domain visual analysis (amplitudes)
- Frequency domain analysis
- Contact point history and histogram
- Sine chirp
- Wavelet analysis

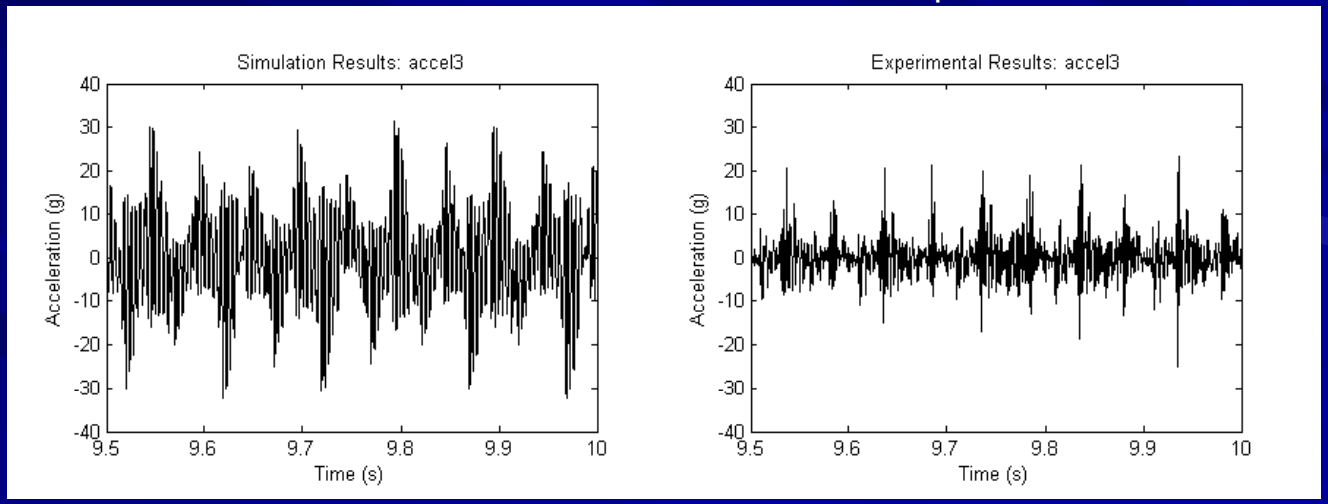
Time Domain Analysis - Acceleration

- Not best for nonlinear analysis
- Capture peaks
- More energy in simulation

Simulation Experiment

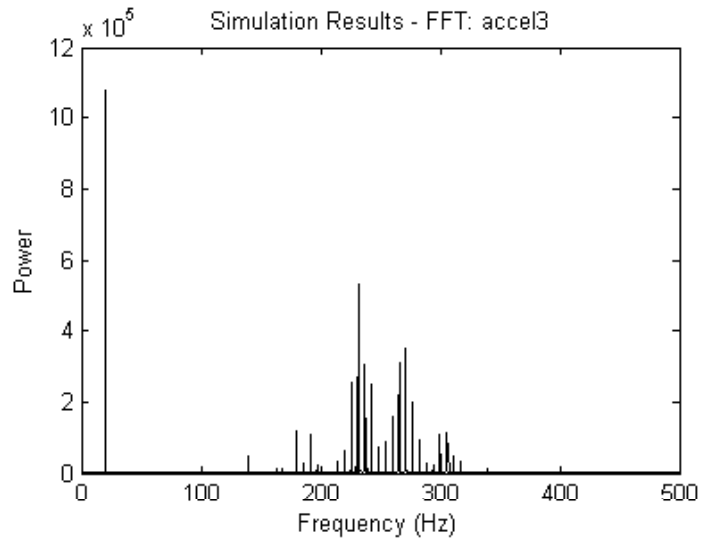


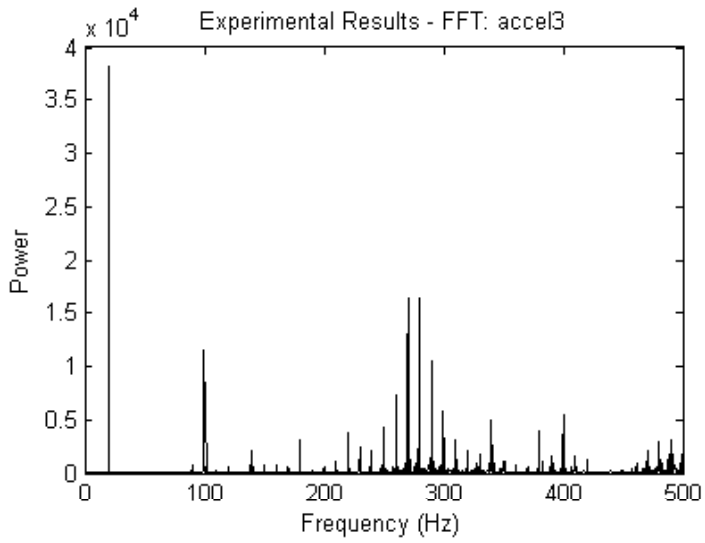
Simulation Experiment



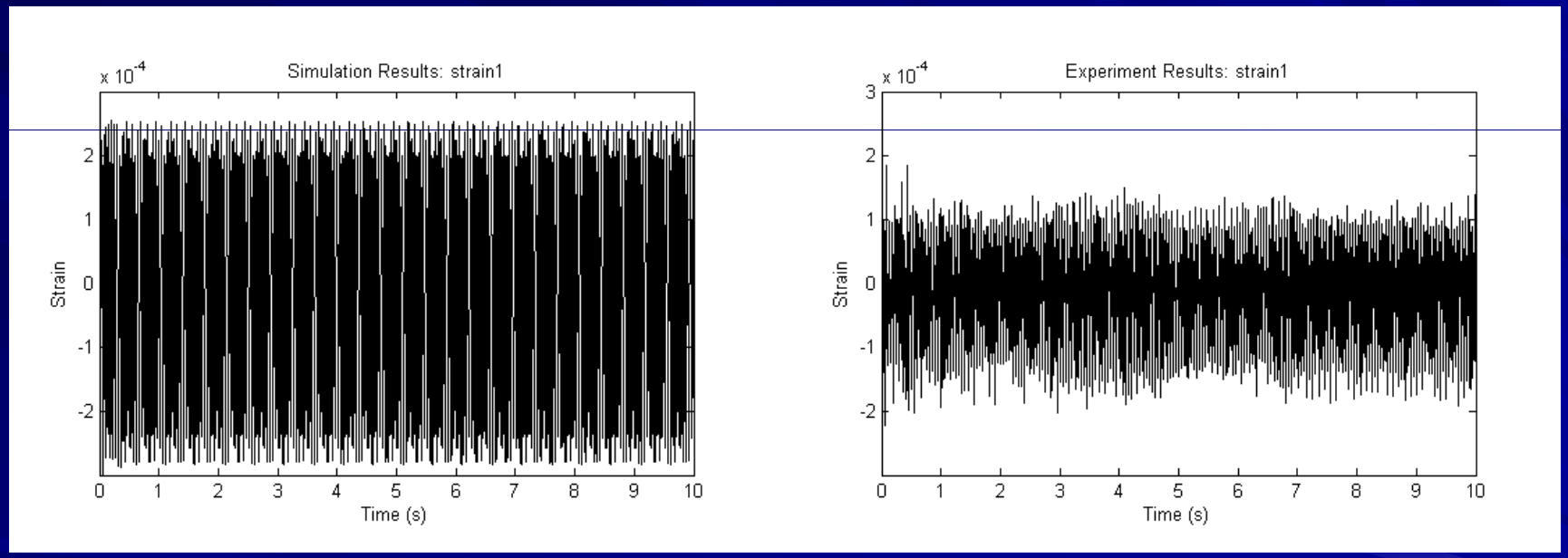
Power Spectrum - Acceleration

- Only good for periodic signals
- Shows nonlinearities via super and sub harmonics
- Frequency content matches well
- Power off by order of magnitude

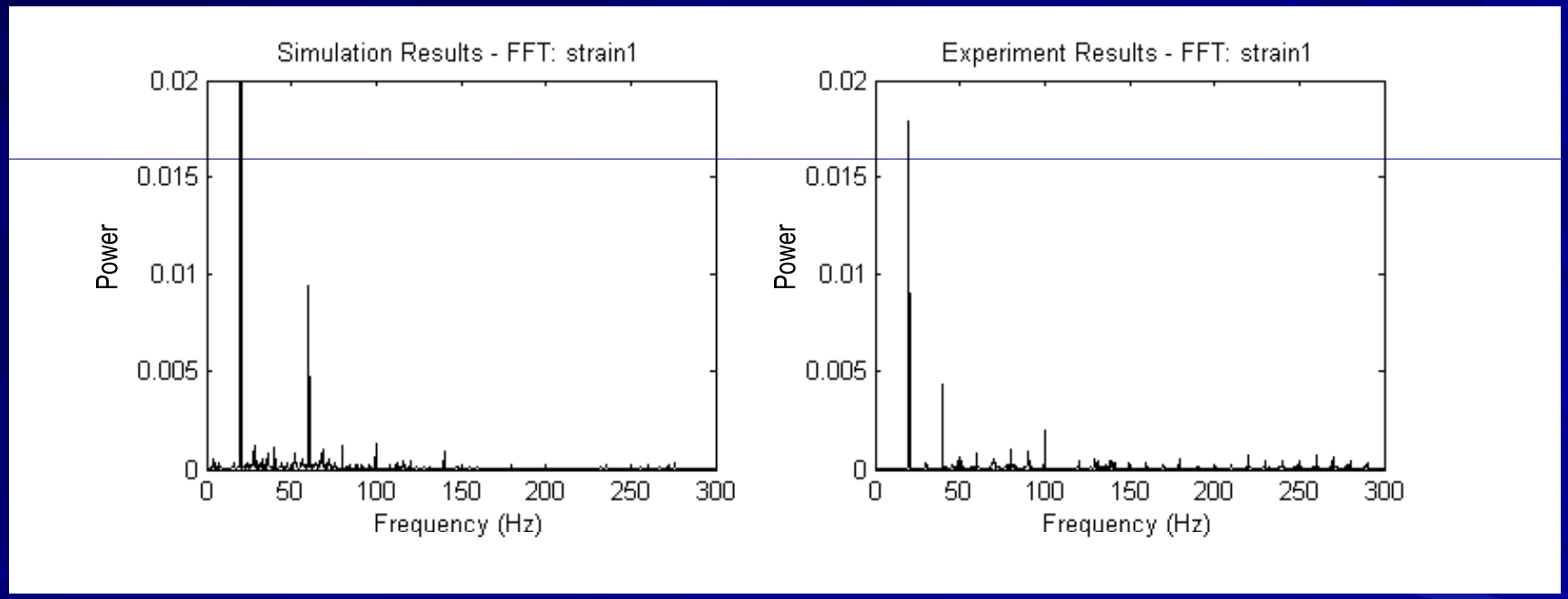




Time Domain Analysis - Strain

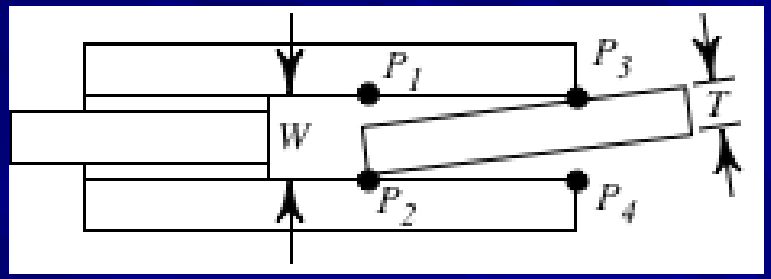


Power Spectrum - Strain

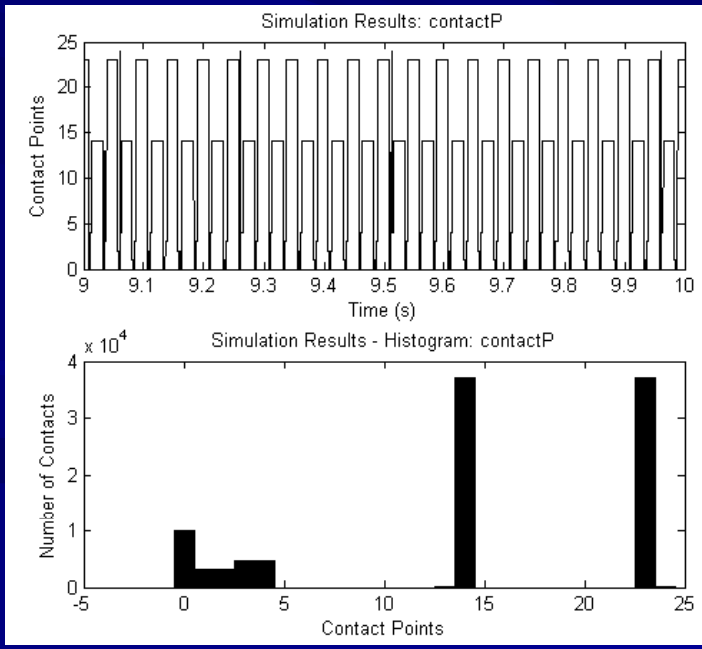


Contact Point

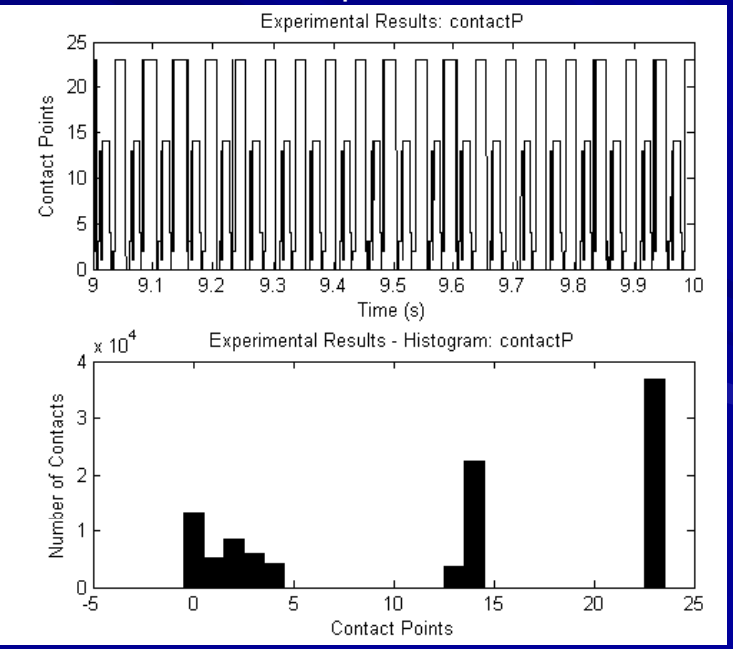
- Best match
- Shows the switching dynamics work well
- Skew in experimental data from friction and joint geometry



Simulation

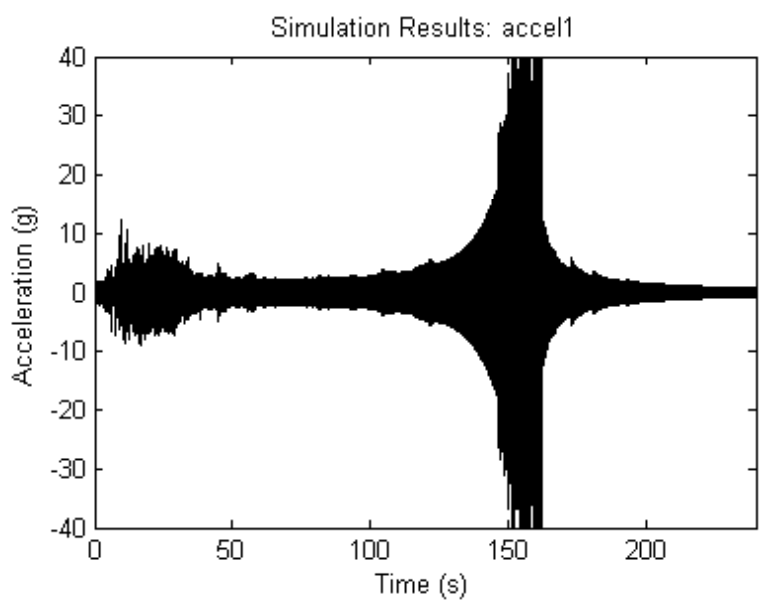


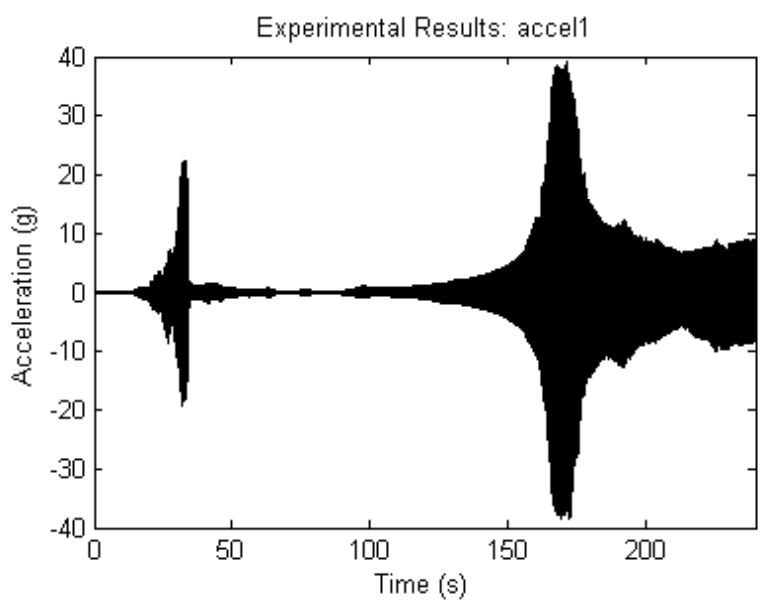
Experiment



Sine Chirp

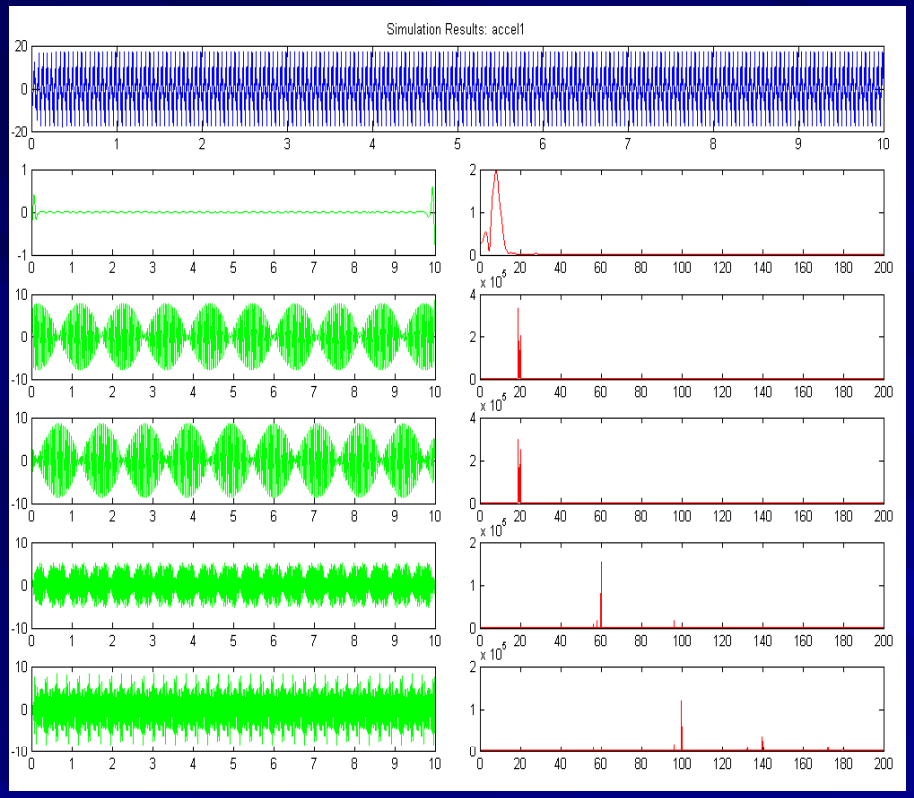
- Frequency Range: 5 – 60 Hz
- Total Time: 4 mins.



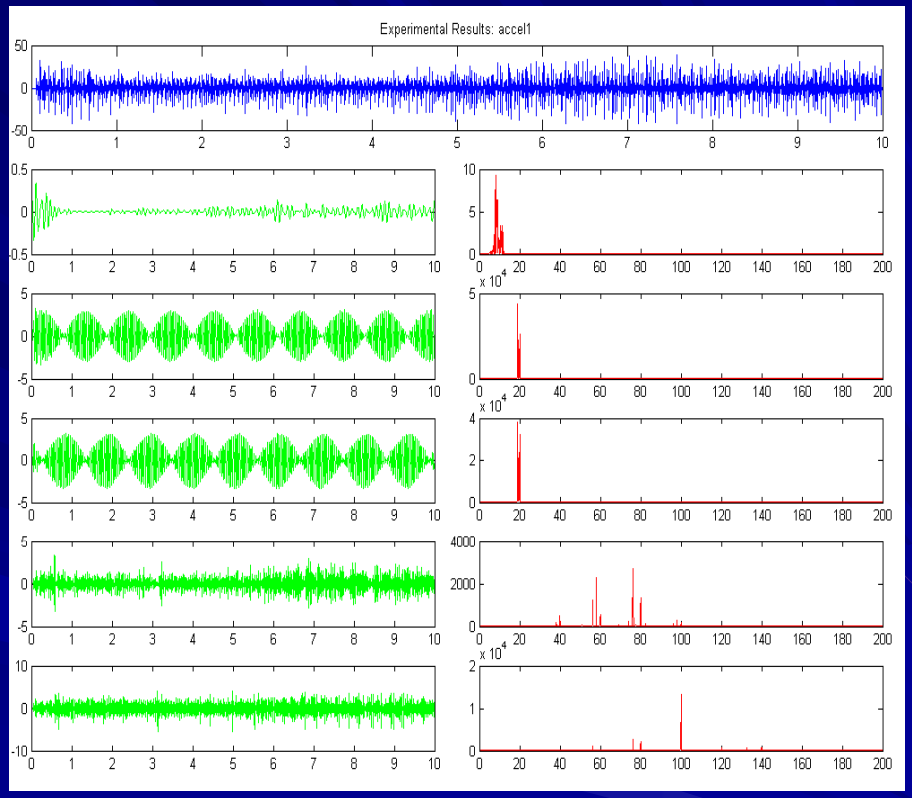


Wavelet Analysis

Simulation

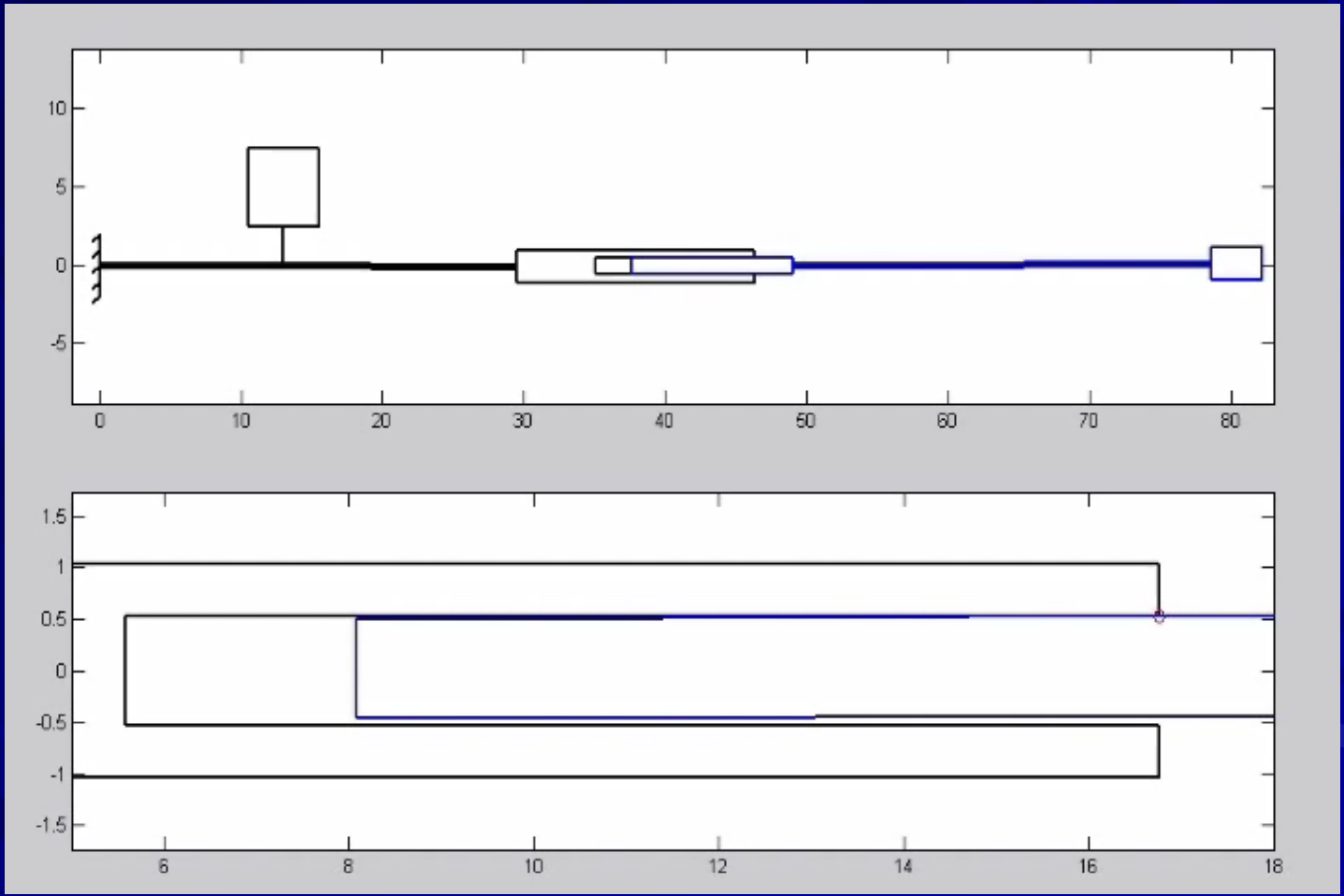


Experiment



- Overall shape of first 3 levels good
- Frequency content good
- Amplitudes off

Simulation Animation



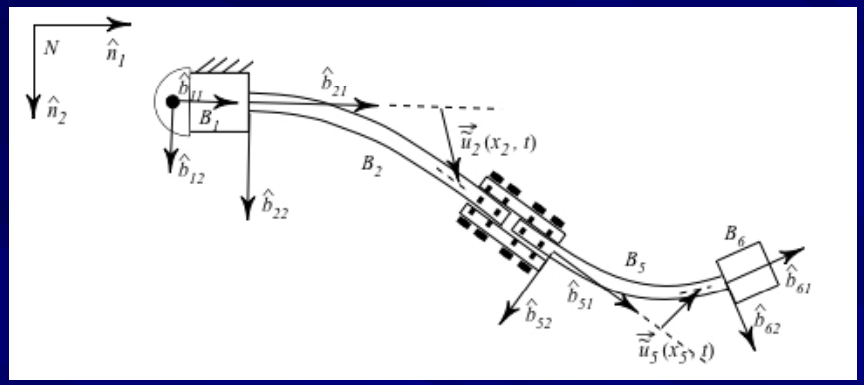
Conclusion

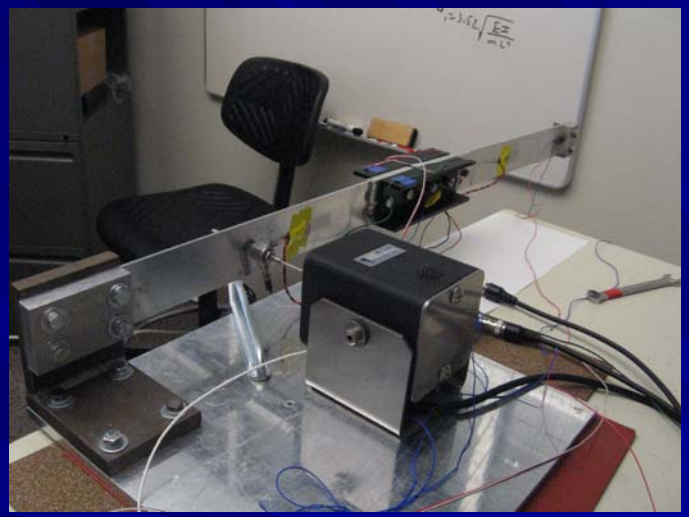
- Low order model
- Parameter identification
- Experiment setup
- Positive results given extent of nonlinearities
- Can handle the switching dynamics caused by impact
- Damping and energy loss still a problem

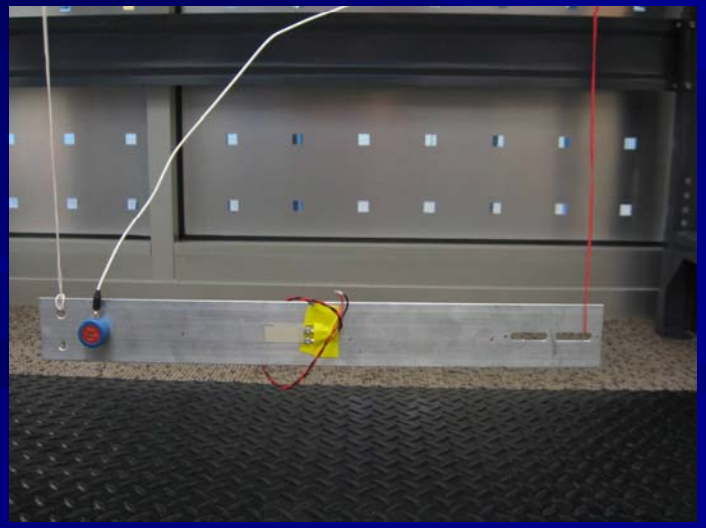
Acknowledgements

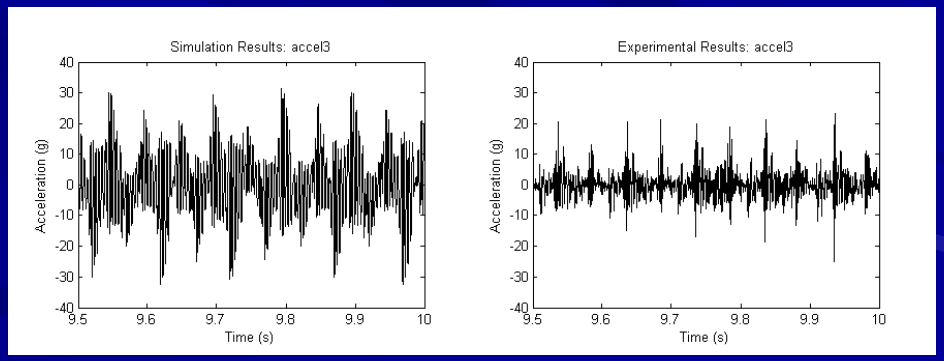
- The Los Alamos National Laboratory – University of California Engineering Institute for hosting the Los Alamos Dynamics Summer School
- Funding support from Los Alamos National Laboratory
- Vibrant Technologies (ME Scope software)
- The Mathworks, Inc. (Matlab, Simulink, XPCTarget)
- ABAQUS Inc. (ABAQUS finite element analysis software)
- The support from our mentor Alan Barhorst

Questions?


N
$\hat{n}_1$
$\hat{n}_2$
$\hat{b}_{11}$
B_1
$\hat{b}_{12}$
$\hat{b}_{22}$
$\hat{b}_{21}$
B_2
$\vec{\tilde{u}}_2(x_2, t)$
B_5
$\hat{b}_{51}$
$\hat{b}_{52}$
$\vec{\tilde{u}}_5(x_5, t)$
B_6
$\hat{b}_{61}$
$\hat{b}_{62}$






Simulation Results: accel3
Acceleration (g)
Time (s)
Experimental Results: accel3
Acceleration (g)
Time (s)