Nonlinear Transient Response of Electromechanical Assemblies
SAND2021-8886 PE

Students:
Sarah Demsky, Nathaniel Goldberg, Abdelrahman Youssef

Mentors:
Steven Carter, Deborah Fowler, Nathan Jackson, Robert Kuether, Andrew Steyer
Introduction
Background

Low-amplitude vibrations
1. Long-duration random vibration
2. Linear responses produced
3. Classical modal analysis applicable

High-amplitude vibrations
1. Short-duration mechanical shock
2. Nonlinear responses produced
3. Classical modal analysis not applicable*

• Many electromechanical assemblies of interest to Sandia have sources of nonlinearity stemming from contact impacts
• This limits or invalidates the applicability of linear modal analysis techniques
Test Set Up

- Impact tip assembly
- Threaded hole for shaker attachment
- Access hole for direct beam excitation
- Impact beam
- Suspension springs
- Box tube
**Project Description & Goals**

**Description**
Understand how contact-impacts due to bearing clearances lead to nonlinear coupling between elastic and rigid body modes in rotor-bearing assemblies

**Method**
Study an idealized system that will imitate the essential physics

**Task 1**
Analyze physical test model
- Visualize the experimental linear modes
- Validate the linear modes via modal assurance criterion (MAC)
- Create a test plan to excite nonlinear modes
- Generate spectrograms for the nonlinear responses

**Task 2**
Develop detailed Sierra model
- Create simplified geometry and generate a hexahedral mesh
- Apply preload to the springs in Sierra SM
- Transfer the preload and run modal analysis in Sierra SD
- Replicate experimentally observed transient response

**Task 3**
Develop simplified FE model
- Write implicit, transient finite element code in MATLAB
- Correlate model parameters to experiment
- Replicate experimentally observed transient response
- Contextualize transient response with NNM calculations
Physical Test Model
Linear Test Instrumentation & Plan

• 6 accelerometers were placed on the beam, 5 accelerometers on the box tube

• 4 impact load cells

• The system was excited with an impact hammer at a variety of locations on the box tube to excite the system in three orthogonal directions

• The system was tested in two configurations:
  • Impact gaps fully open
  • Impact gaps fully closed – The preload is unknown, but it was sufficient to ensure that the tips were in contact with the beam for all ranges of excitation.
Preliminary Nonlinear Tests

- Experiments were performed to measure transient response with impacts
  - Gaps set to approximately 0.01”
  - Beam excited by impact hammer at midpoint
- Data show large amount of damping
  - Likely due to accelerometer cables
  - Questionable applicability of short-time Fourier transform
Computational Capabilities
MATLAB Finite Element Code

• Implicit transient, accepts any time integrator
• Planar, 3-DOF Euler-Bernoulli beam elements
• Accepts easy-to-write input files
• Extensive validation against analytical solutions
• Also developed related codes to analyze nonlinear normal modes and forced response
• Model parameters $k_g$ and $k_s$ meticulously correlated to physical system
Automated Generation of Geometry and Mesh

- Created versatile CUBIT journal file
  - Input: various dimensions of parts
  - Output: CAD geometry and high-quality hex mesh

- Mesh is highly symmetric and regular

- Useful for future optimization studies
Spring Modeling

Parameters:
1. Meshing
2. Simulation
3. Fidelity

Solid elements (hex or tet)
Beam elements
Spring elements w/ concentrated mass
Sierra Finite Element Model Workflow

Mesh (CUBIT) -> Preload (Sierra SM)

Nonlinear Transient (Sierra SM) -> Check

Linear Modal Analysis (Sierra SD) -> Check

Post-Processing (Paraview, EnSight)
Sierra Model Workflow

1. Simplified CAD
2. Mesh
3. Preload initial conditions
4. Preload results
Linear vs. Nonlinear Response

Linear Modal Analysis

Closed gap ~410 Hz

Open gap* (0.01 in.) ~709 Hz

*Springs not included in above animation

Nonlinear Transient

Open gap** (0.01 in.)

** Only beam represented in above animation
Outcomes
Pseudo-Rigid Body Mode Shapes (Fully Open Case)

- Longitudinal ~10.5 Hz
- Lateral ~11.25 Hz
- Yaw ~13.75 Hz
- Bounce ~18.5 Hz
- Pitch ~22.5 Hz
- Roll ~34.75 Hz
Rigid Body Mode Shapes – Fully Open Case

- Longitudinal: 10.92 Hz
- Lateral: 11.66 Hz
- Yaw: 15.08 Hz
- Bounce: 19.94 Hz
- Pitch: 24.11 Hz
- Roll: 33.69 Hz
Spring and Box Tube Mode Shapes

Spring Mode Shapes

Spring buckling ~241-244 Hz

Spring barreling ~288 Hz

Box Tube Mode Shapes

Matchboxing ~441-454 Hz

Buckling ~716 Hz
Coupling of Springs with Bending Modes

First bending mode

- ~709 Hz
- ~724 Hz
MAC for Linear Response of the Beam Accelerometers Only

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<th>Mode Name</th>
<th>MAC Value</th>
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<td>Roll</td>
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MAC for Linear Response of the Full System

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<td>Roll</td>
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</table>
Transient Response - Experimental

- Hit beam with impact hammer at mid-span
- Gap size 0.01”
- Several hammer hits with varying force
- Data is preliminary (damping due to cables, malfunctioning load cell, etc.)
Transient Response - Linear Regime

- Emulate weak excitation with hammer
- 5-N pulse for 4 ms at middle node
- Best estimate of model parameters
- Light Rayleigh damping
Transient Response - Nonlinear Regime

- Emulate strong excitation with hammer
- 50-N pulse for 4 ms at middle node
- Best estimate of model parameters
- Light Rayleigh damping

\[ k_g, r, E, I, A \]

No impacts

Pitch mode

Bounce mode

Spontaneous symmetry breaking (chaos?)
Outcomes

• Computational capabilities developed
  • Transient finite element code for simplified model
  • Multi-harmonic balance input files for nonlinear periodic response (free and forced)*
  • CUBIT input files for parametric CAD and hexahedral mesh generation
  • Sierra SD linear modal analysis input files
  • Sierra SM nonlinear transient input files

• Key conclusions
  • Linear modal testing and modal analysis techniques can successfully characterize the system when no impacts occur
  • Modal coupling may be difficult to observe due to instabilities and/or chaos
  • Highly discontinuous nature of contact complicates both modeling and experimentation
**Future Work**

**Task 1**
Analyze physical test model
- Generate a MAC for the linear closed-gap case
- Clarify testing plan to excite the nonlinear modes
- Possibly modify apparatus to decrease damping

**Task 2**
Develop Sierra model
- Vary the load type, and location
- Vary the gap size
- Change impact tip material

**Task 3**
Develop simplified FE model
- Incorporate more realistic damping mechanism
- Investigate potential instability/chaos
- Study nonlinear normal modes with MHB code

Get a clearer picture of the nonlinear normal modes and the effect of contact impacts

Relate this research back to the electromechanical assemblies of interest at Sandia
Acknowledgements

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Rigid Body Mode Shapes – Closed Gap Case

200.8 Hz
220.8 Hz
225.3 Hz
275.3 Hz
283.3 Hz
287.8 Hz
295.1 Hz
326.9 Hz
331.3 Hz
Mode Shapes – Closed Gap Case

200.8 Hz
220.8 Hz
225.3 Hz
275.3 Hz
283.3 Hz
287.8 Hz
295.1 Hz
326.9 Hz
331.3 Hz
377.0 Hz
527.4 Hz
546.9 Hz
554.2 Hz
602.7 Hz
Protruding spring, requiring preload
Automated Generation of Geometry and Mesh (cont’d)