Development of Multi-Physics Dynamics Models for High-Frequency Large- Amplitude Structural Response Simulation

Armen Derkevorkian, Lee Peterson, Ali R. Kolaini, Terry J. Hendricks, and Bill J. Nesmith

Jet Propulsion Laboratory
California Institute of Technology

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Outline

- Background and Motivation
- Computational Modeling Approach
- Analyses and Results
- Conclusions

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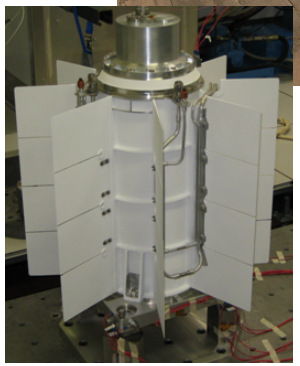
Mars Science Laboratory (MSL) Testing

- A series of pyroshock tests were performed on MSL's Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) Engineering Unit
- Temporary power drop was observed during the qualification test. The power fully recovered after the shock signature subsided
- An effort is underway to understand the root causes of the temporary power drop

Image Credit: NASA/JPL-Caltech/Malin Space Science Systems



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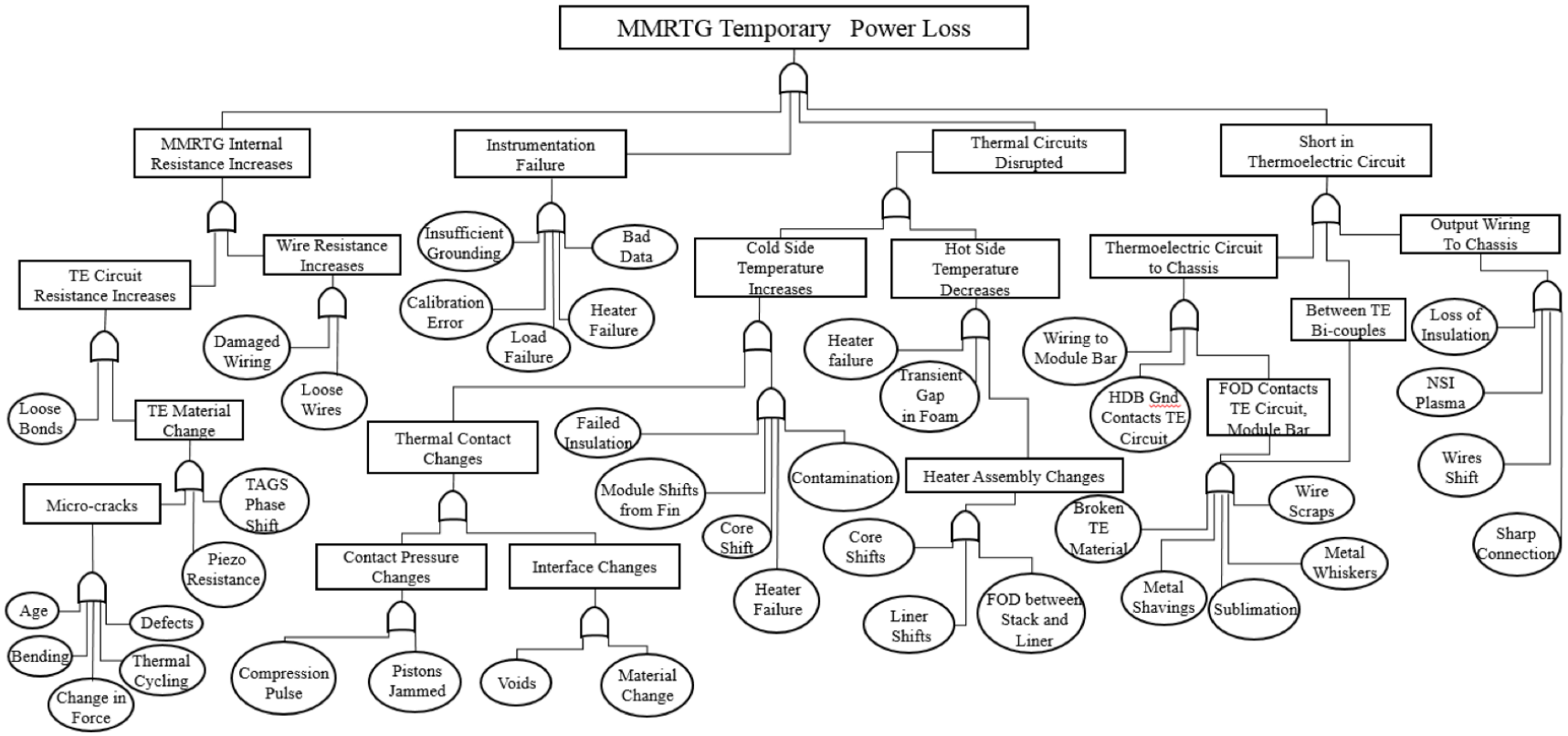
Fault Tree for Power Drop Root Causes



Derkevorkian, A., et al., "Pyroshock Induced Loads Driving Electrical, Thermal, and Structural Impacts in Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs)," *Proceedings of NETS Conference*, Albuquerque, NM, 2015.

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Scope

- Dynamic Analysis of the MMRTG key components to predict structural responses due to shock wave propagation
- Assess the viability of a suite of numerical tools to simulate transient, non-linear solid mechanics and structural dynamics problems, such as shock wave propagation
- Validate the numerical results by performing tunable beam shock tests on a representative test article

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Challenges with Shock Response Prediction

- The activation of pyro-shock devices such as explosives, separation nuts, pin-pullers, etc. produces high frequency transient structural response, typically from few tens of Hz to several hundreds of kHz.

- Lack of reliable analytical tools makes the prediction of appropriate design and qualification test levels a challenge.

- In the past few decades, several attempts have been made to develop methodologies that predict the structural responses to shock environments.

- Currently, there is no validated modeling approach that is viable to predict shock environments over the full frequency range (i.e., ~100 Hz to 10 kHz).

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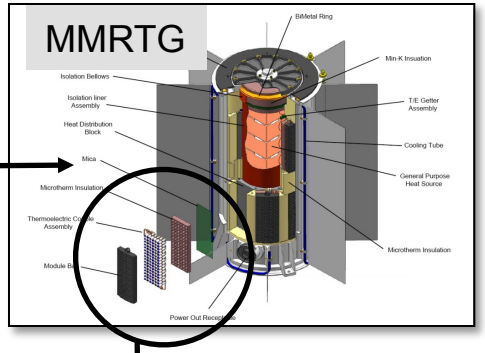
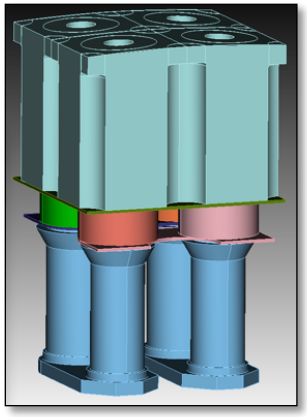
Computational Modeling Approach

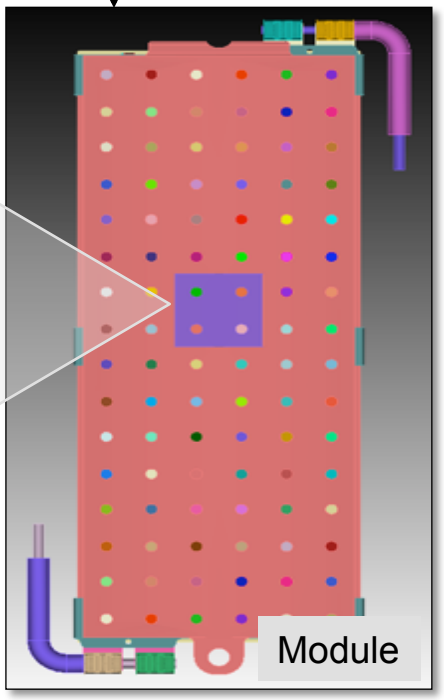
- A high-fidelity finite-element based computational models were developed for key MMRTG components
- An explicit dynamic solver was used to capture the various contact mechanisms and predict the shock response
- The parallel supercomputing capabilities at JPL and NASA Ames Research Center were utilized

Image Credit: NASA/JPL-Caltech





Mini-Module



Module

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Computational Tools Used for this Study

- **Cubit** (Pre-processor)
  - Geometry and Mesh Generation Toolkit
  - Robust generation of 2D and 3D Finite Element meshes
  - Geometry Power Tool to help detect and repair problems
  - Efficient algorithm for large hex meshes of complicated assemblies

- **Sierra/Solid Mechanics** (Solver)
  - Adagio (implicit) and Presto (explicit) are part of the Sierra multi-physics codes developed by Sandia National Laboratory
  - Lagrangian, three-dimensional code for finite element analysis of solids and structures
  - Efficient and robust solution of models with extensive contact subjected to large, suddenly applied loads

- **Paraview** (Post-processor)
  - Stands for “Parallel Visualization Application”, open-source, multi-platform
  - Designed to visualize data sets of varying sizes from small to very large

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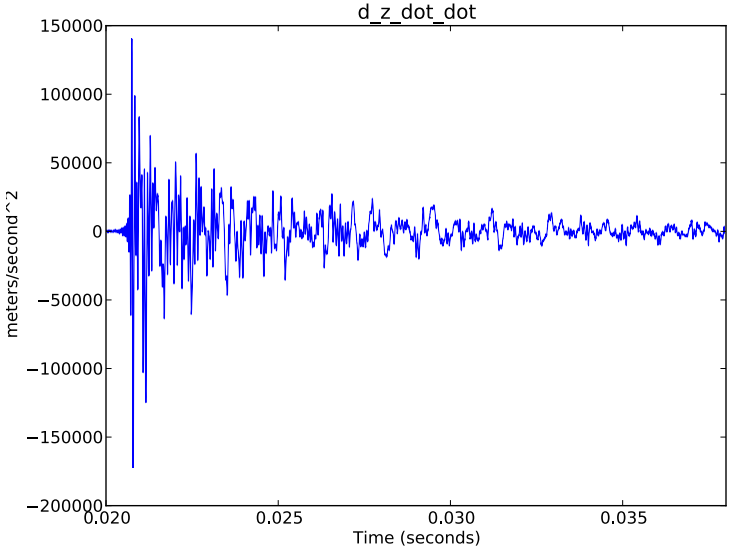
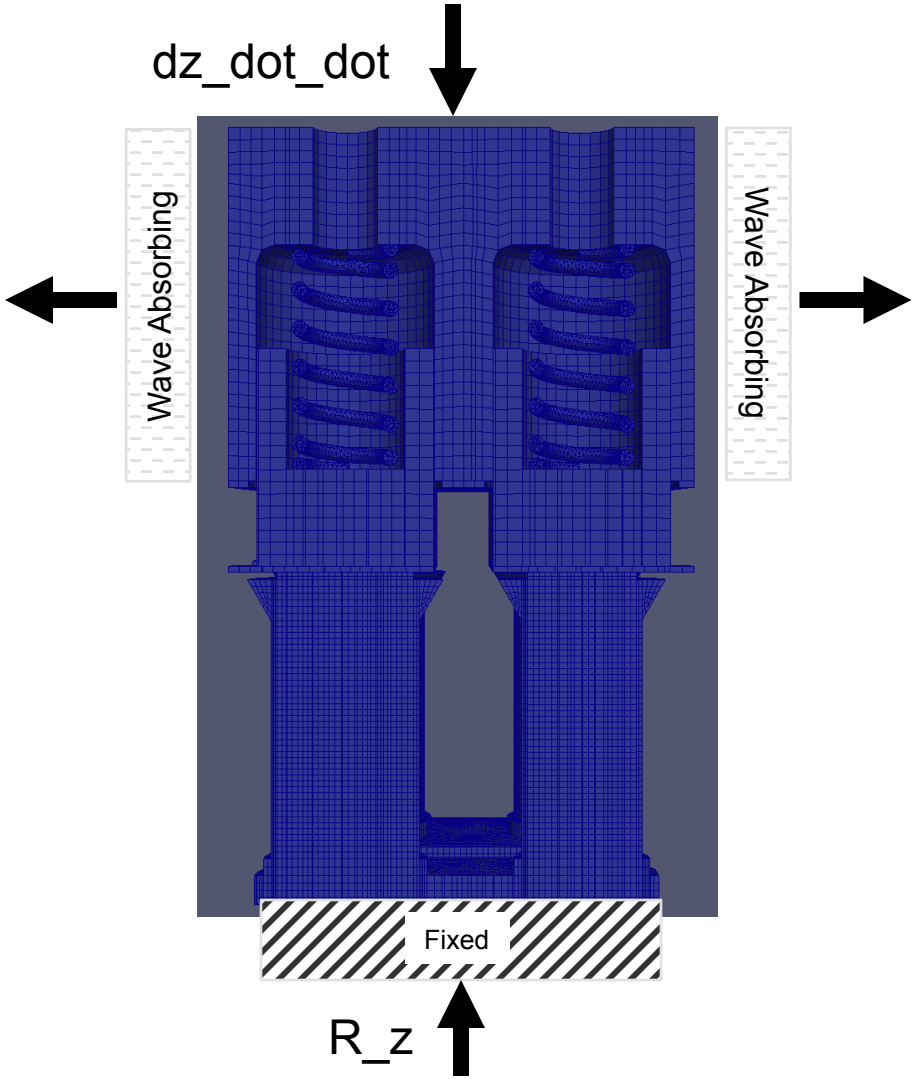
Simulation of the Mini-Module

- Applied preload with the explicit solver
- After preload, acceleration shock input was applied



  - Running time ~ 50 hours using 150 processors on JPL Supercomputer
- Silent (absorptive) boundaries on housing sides
- Hot shoes constrained (no sliding)
- Sliding contact with friction elsewhere



Derkevorkian, A., et al., "Advanced Computational Modeling Approaches for Shock Response Prediction," *Proceedings of the 29th Aerospace Testing Seminar*, Los Angeles, CA, 2015.

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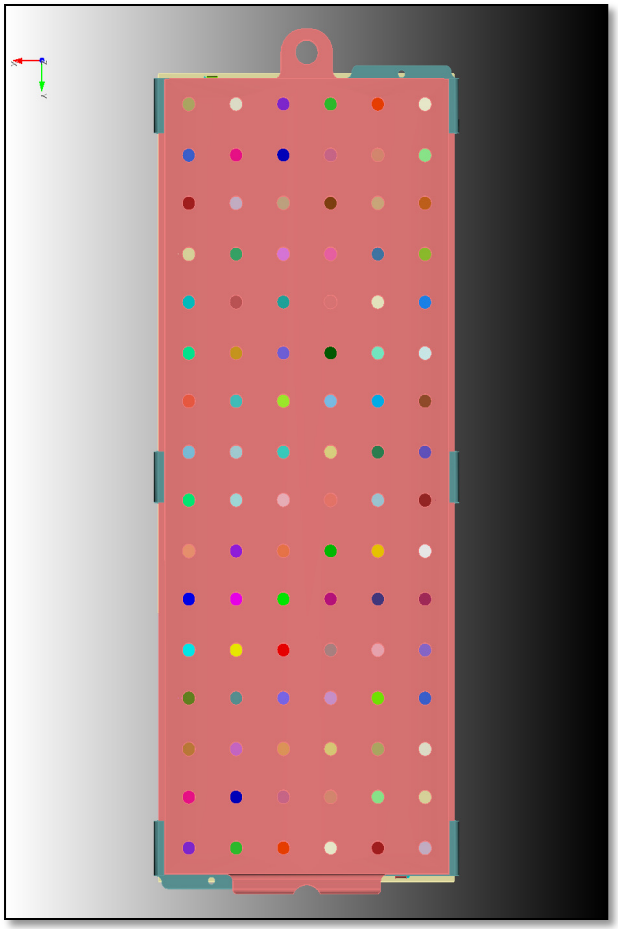
Simulation of the Module-Bar

Computational Resources for the Analysis:

1. 60 hours – 3000 processors at NASA Ames Super Computers
2. The FE model was created and assembled using Cubit
3. Analysis was performed using Presto explicit solver
4. Post-processing was performed using Paraview
5. FE model has ~ 30M degrees-of-freedom (DOF)

Module



Assumptions for the Analysis:

1. Inputs are used from MSL MMRTG measured pyro-shock acceleration (de-trended, numerically integrated to get displacement, and band-pass filtered 500-10000 Hz)
2. Pyro-shock loads were applied on the top plate edges in all 3 directions, simultaneously. All other edges on the top plate were assumed to be silent (absorptive) boundaries

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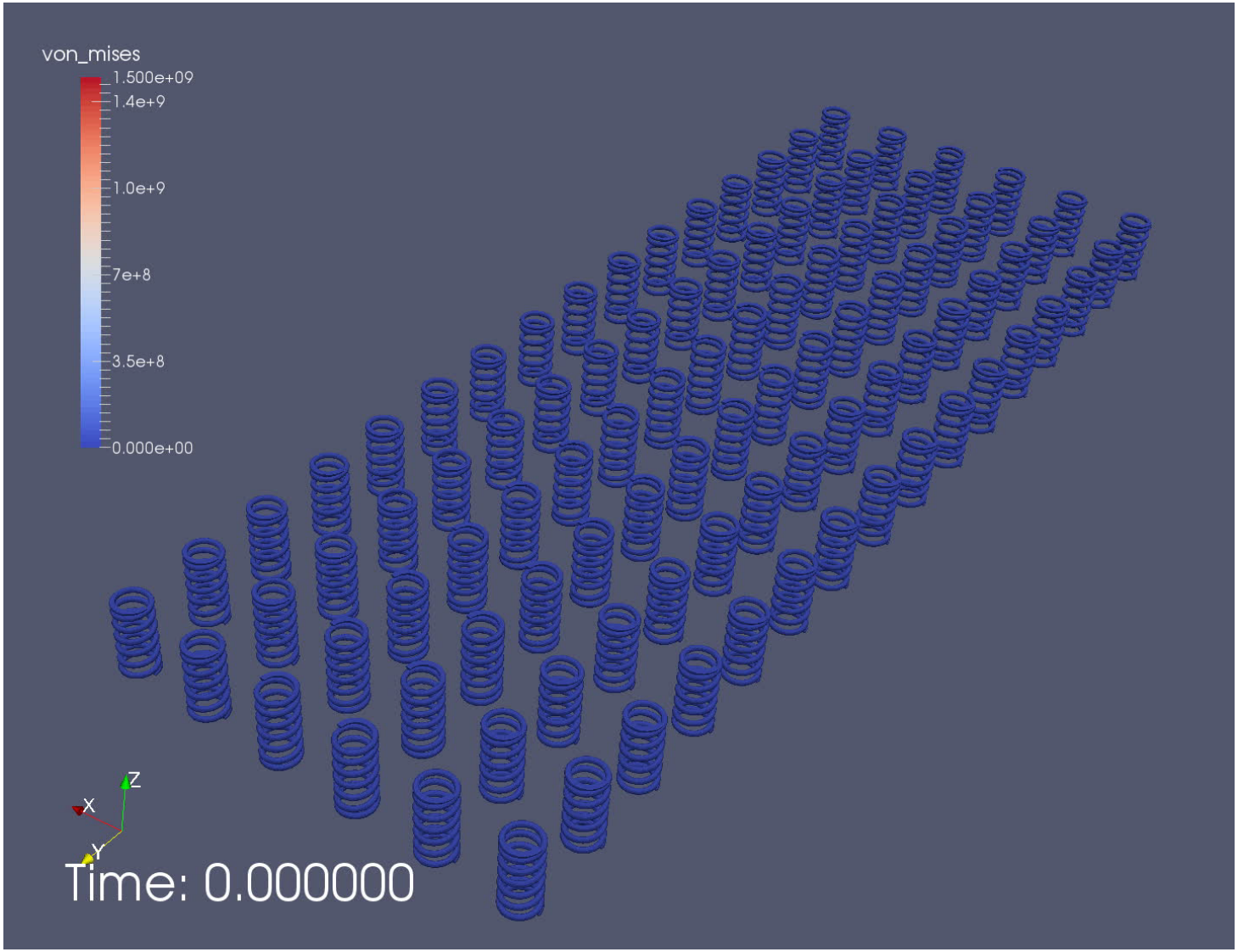
Springs – Resonating Freq. at about 3000 Hz



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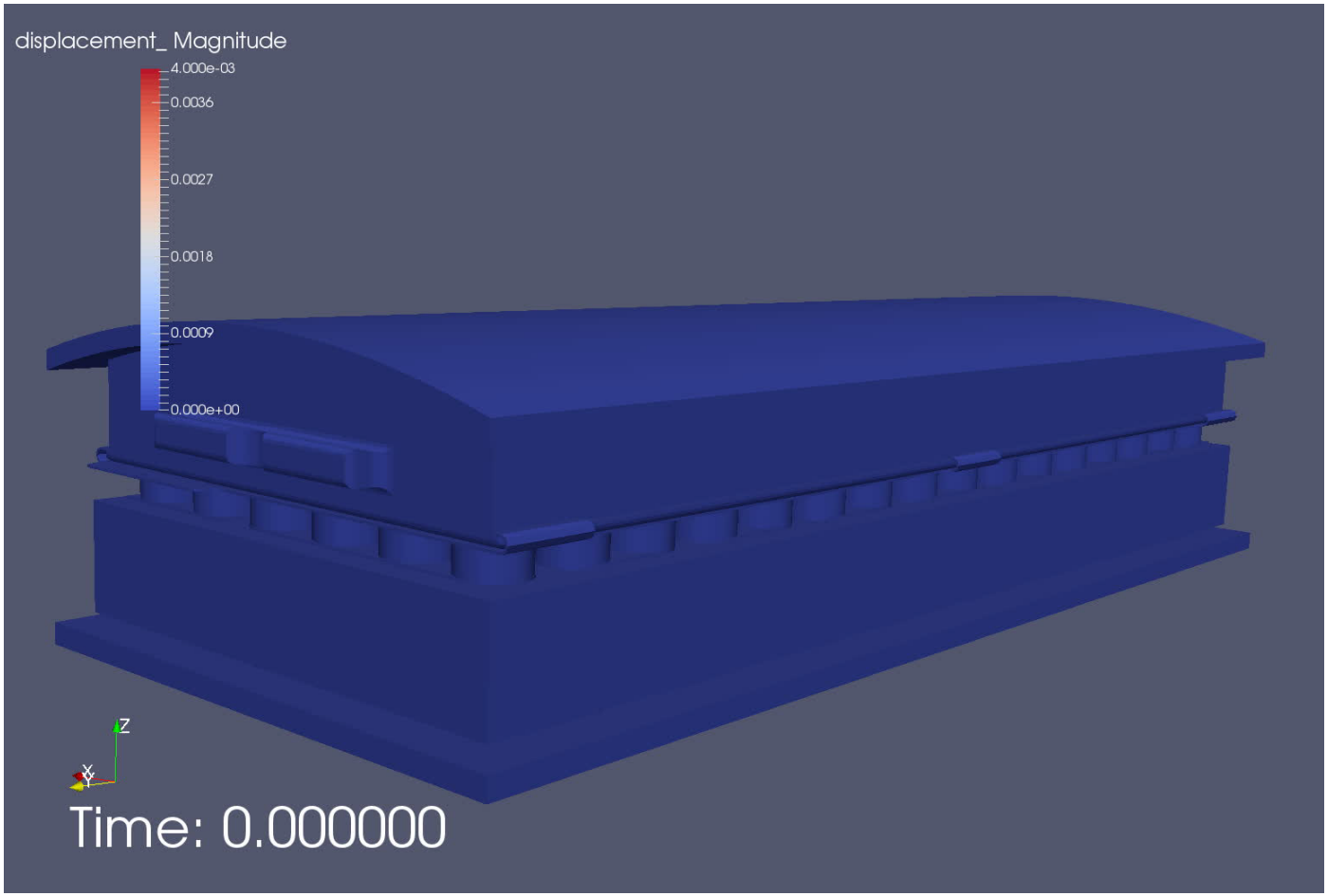
Displacement for all Blocks (note the insulation sheet)



Derkevorkian, A., "Shock Response Prediction Using High-Fidelity Computational Tools," *NASA Young Professionals' Forum for Structures, Loads, and Mechanical Systems (SLaMS)*, Jet Propulsion Laboratory, Pasadena, CA, September 2015.

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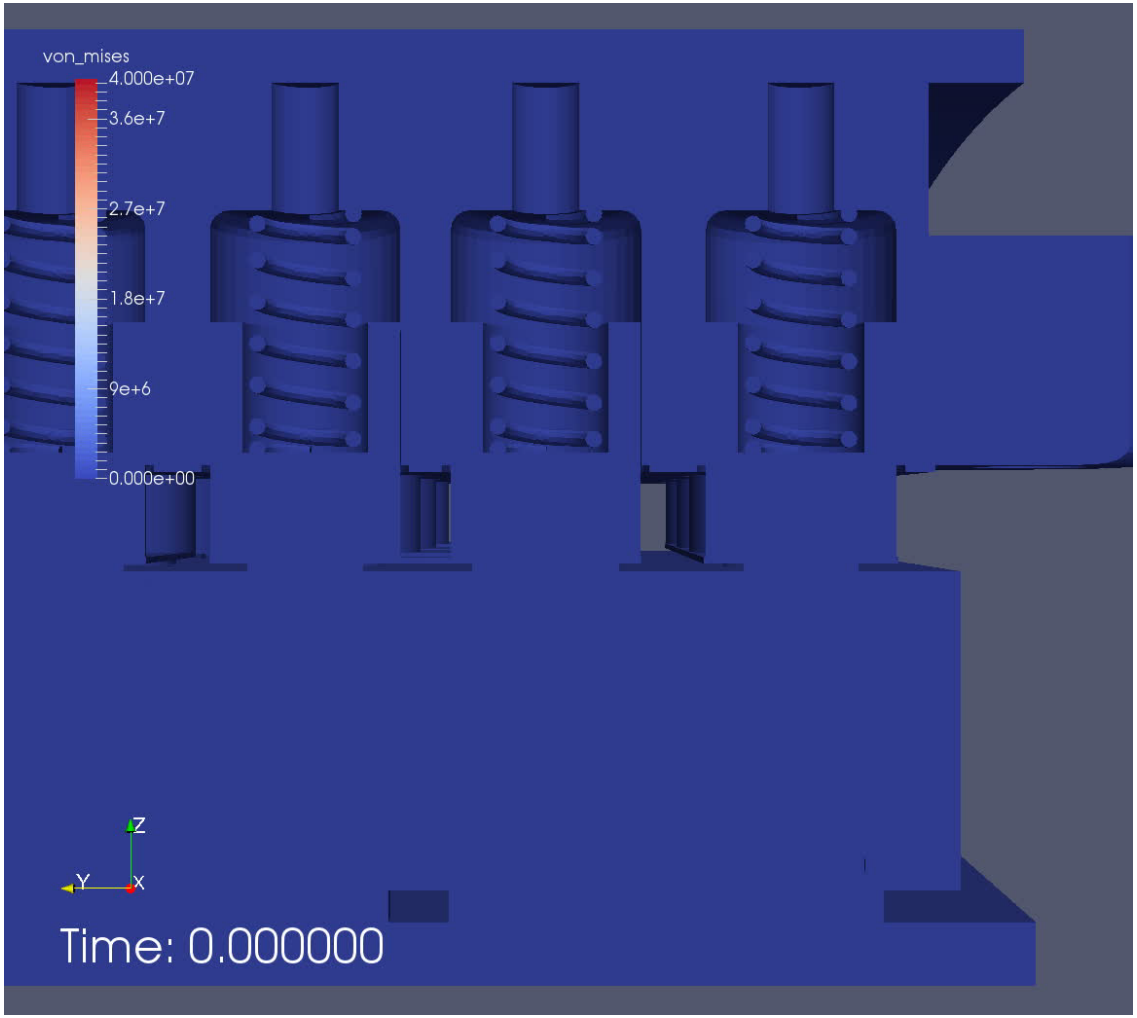
Shock Response Animation (Zoomed Von Mises Stress)

- Springs tilting after the preload
- Springs exhibiting strong wave response at about ~3KHz
- Contacts between springs and piston edges at some locations were observed



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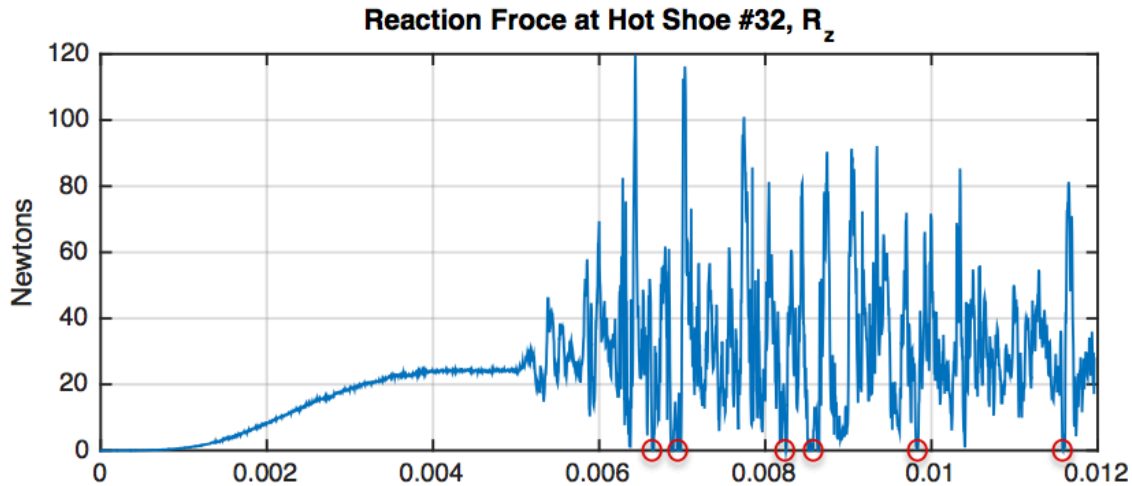
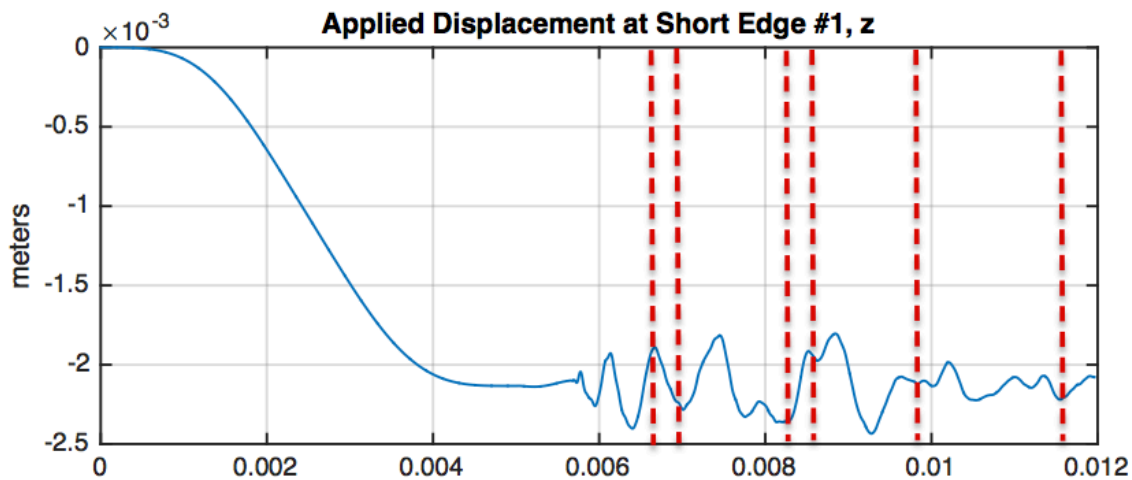
Pyro-shock Response in the Vertical Z-Direction

- Unloading of the shoes were observed at multiple locations



- Preload was initially applied to the springs/ pistons and then shock environments were applied



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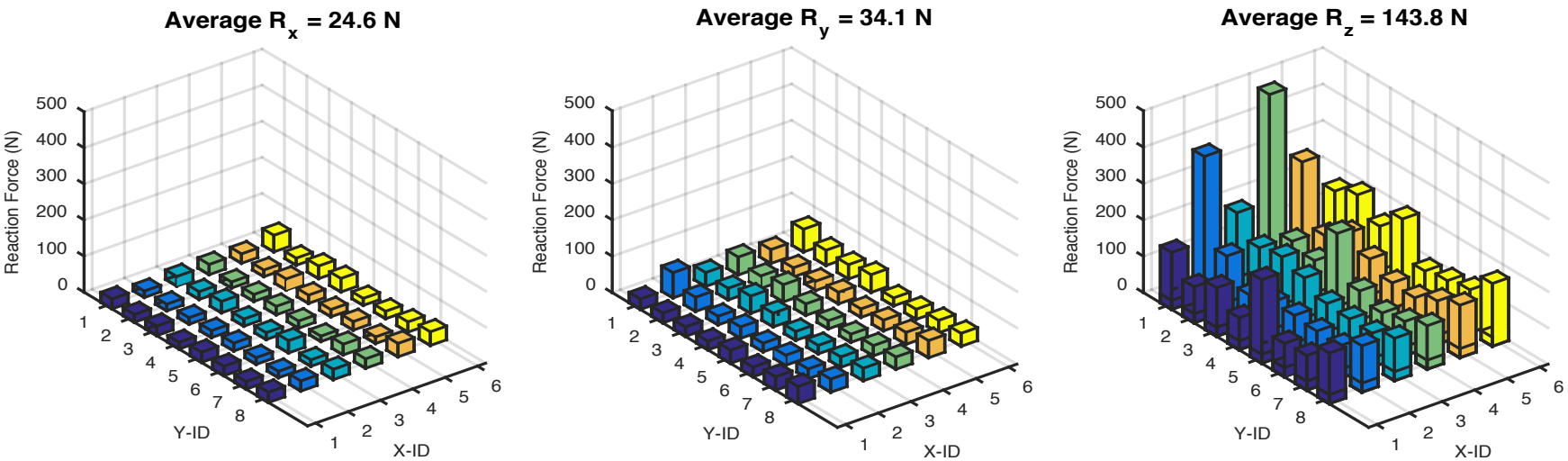
Average Maximum Reaction Forces at the Bottom of the Module



- Large peaks are observed in the vertical (Gravity) Z-direction

Hendricks, T.J., et al., " Pyroshock Dynamic Loading Impacts on Thermoelectric Module Assemblies and Bi-Couples in Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs)," *Proceedings of NETS Conference, Huntsville, AL, February 2016.*

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Comparison of Computational Effort

	Mini-Module (Sierra/SM)	Module Bar (Sierra/SM)	Full Model (Nastran)
Number of Elements	0.4 million	11.5 million	0.05 million
Number of Processors	150	3000	4
Run Time	50 hours	60 hours	0.1 hours
Applied Load	1D (vertical)	3D (simultaneously)	1D

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Conclusions

- The computational tools used in this study can potentially become a viable method to predict shock response in complex structures
- These numerical tools can detect details of the structural response and wave propagation in high frequency ranges
- Large-scale cases can be solved using parallel processors. However, this leads to significant computational cost
- Just like other numerical analysis, the results shown in this study need to be validated with experimental test results
    - Experimental tunable beam shock test is in progress
- Given the intricate details of the sophisticated tools one has to be very careful in the modeling, interpretation, and the choice of the inputs that go in the model

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Future Work

- Development of an innovative hybrid data-driven methodology for computational shock response prediction
- Utilize the large amounts of shock data sets to develop non-parametric reduced order models
- The proposed models promise to be more accurate and computationally less expensive
- Ongoing research collaboration between University of Southern California (USC) and JPL

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