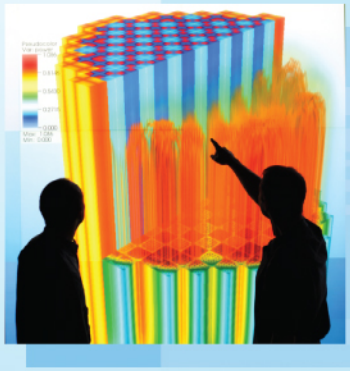
Power uprates
and plant life extension

CASL-U-2013-0283-000

Consortium for Advanced Simulation of LWRs



Engineering design
and analysis

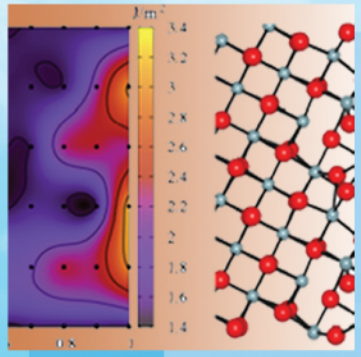
L3.VRI.CM.P7.01 Milestone Report

N.K.Crane

Sandia National Laboratories

September 25, 2013

Science-enabling
high performance
computing



Fundamental science

Plant operational data

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CASL Milestone

L3.VRI.CM.P7.01

Modal Dynamics Analysis Demo with Sierra

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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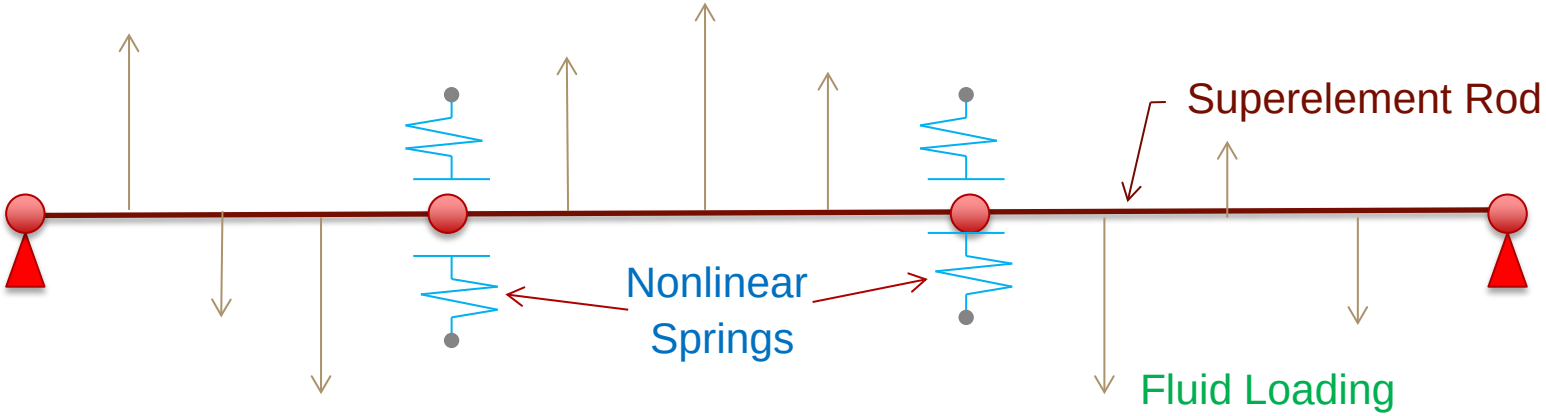
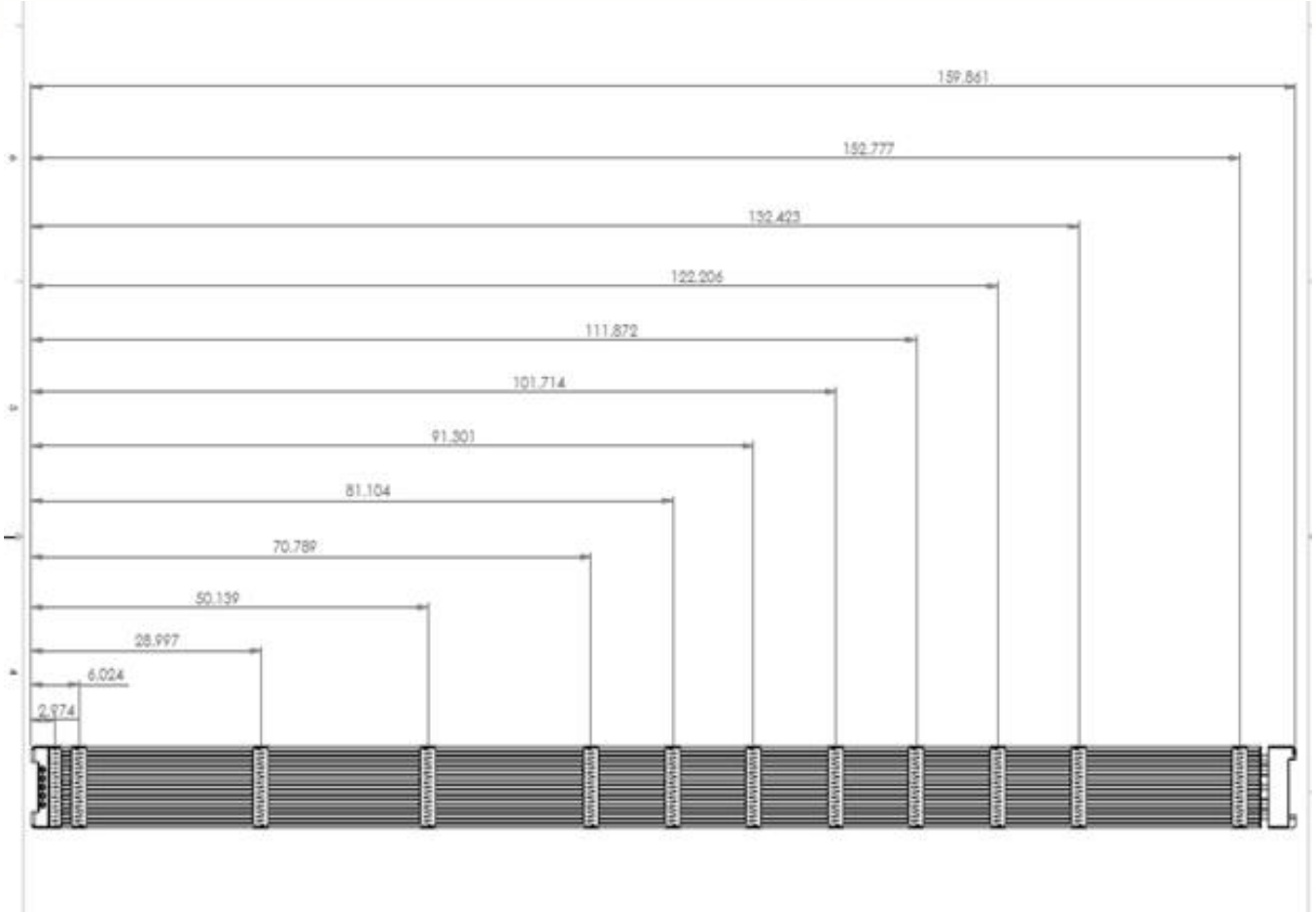
Analysis Methodology Overview

1) Create a modular script that will generate a fuel rod mesh based on desired geometry. Script will also create input deck for running Sierra calculation.
2) Build a full three dimensional model of a specific rod and pellet geometry. **(CUBIT)**
3) Reduce this model to a ~100 degree of freedom linear super-element with Craig Bampton reduction. **(Sierra/SD)**
4) Add non-linear springs representing grids. Run transient dynamics analyses for system vibration over a few seconds. **(Sierra/SM)**
5) Post process out wear rate based on spring forces and displacements



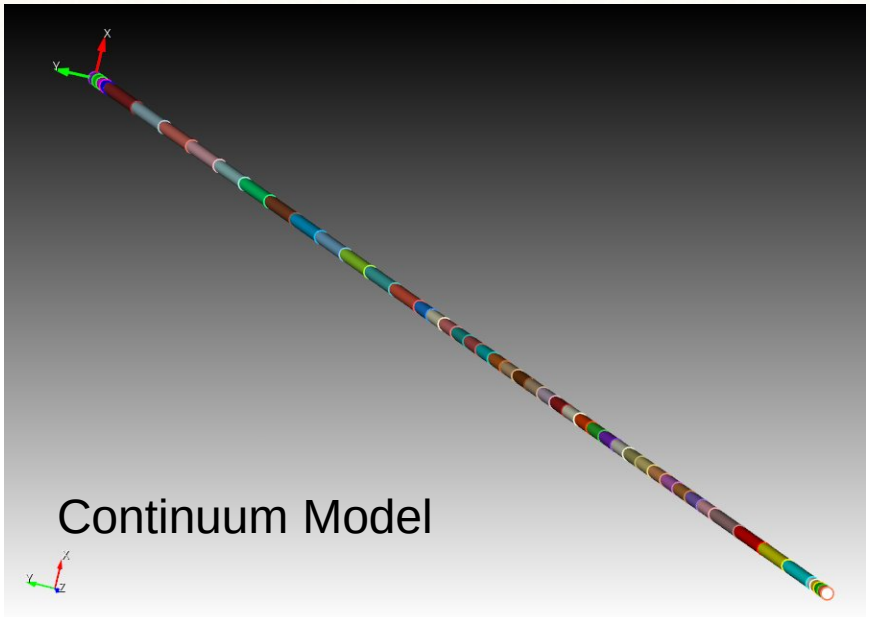
Rod/Grid Geometry Used for Test Case



Geometry of single Rod:

- Total Length 3.88 m
- Radius of fuel pellets 4.178 mm
- Clad inner radius 4.178 mm; outer radius 4.75 mm
- 12 spacers at various locations holding rod bundles

Building the Model, Stage 1, Superelement Creation



Solid model contains rod pellets and cladding. Pellets perfectly bonded to rod

Model size 167936 elements

- 12 spans with lengths matching rod spacer(gird) locations
- 13 spring locations corresponding to grid locations. 4 springs at +/- x and +/- y at each grid location.
- In each span, 3 “fluid” nodes where vibration forces are applied

Why generate a solid mesh and convert to a super-element (as opposed to direct use of beam elements to represent rod)?

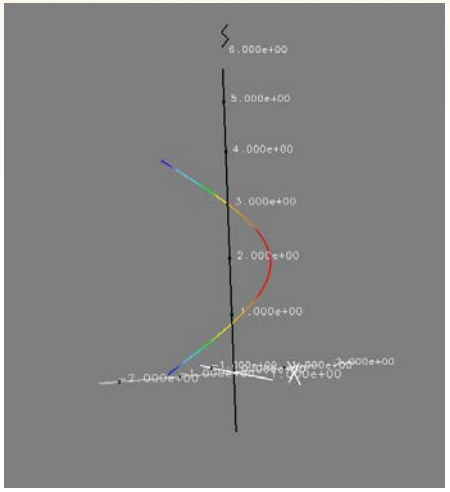
- Solid model can represent unevenly distributed geometry and material model changes due to radiation dose and temperature
- Reduced solid model can accurately represent stiffness effects of non-contiguous pellets (linearized contact)
- Internal pressurization of rod can be automatically taken into account into clad stiffness
- Solid model could potentially directly include effect vibration in water (wet modes). However, this was not done in this milestone.

Comparison of Superelement Eigenvalues

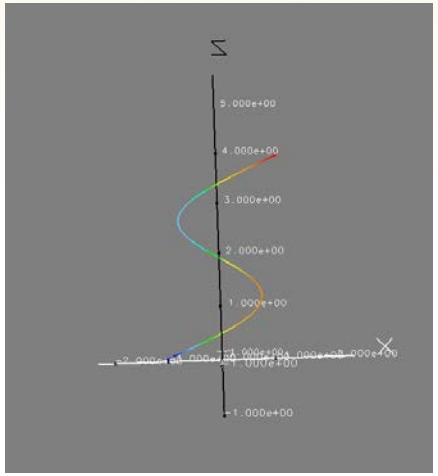
Comparison of calculated eigenvalues between Sierra/SD super-element and independent code shows good agreement. All differences are less than 3%. This confirms that the super-element generation is correct.

Mode number	Salinas	SLFFEA	% difference
1	1.46E+02	1.42E+02	2.86311
2	1.46E+02	1.42E+02	2.861738
3	1.11E+03	1.08E+03	2.864142
4	1.11E+03	1.08E+03	2.694894
5	4.28E+03	4.17E+03	2.34904
6	4.28E+03	4.17E+03	2.348723
7	1.17E+04	1.14E+04	2.12152
8	1.17E+04	1.14E+04	2.11738
9	2.61E+04	2.56E+04	1.956546
10	2.61E+04	2.56E+04	1.853087
11	5.08E+04	5.00E+04	1.706508
12	5.08E+04	5.00E+04	1.68594
13	9.01E+04	8.88E+04	1.500982
14	9.01E+04	8.88E+04	1.497091

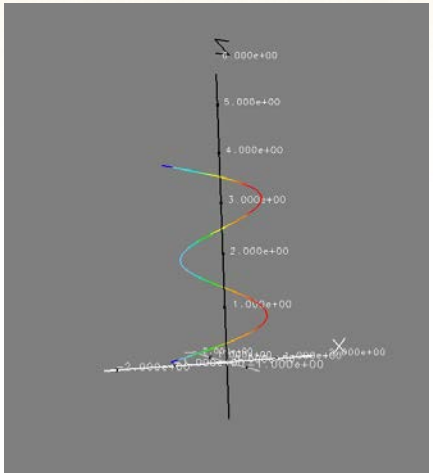
Superelement Rod Mode Shapes



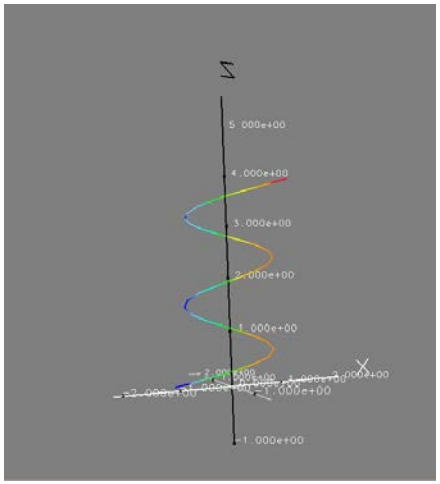
Mode 2



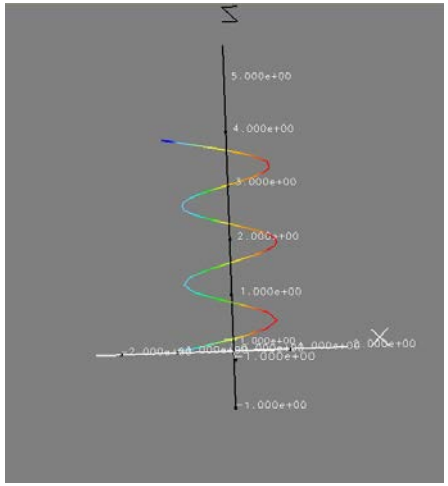
Mode 4



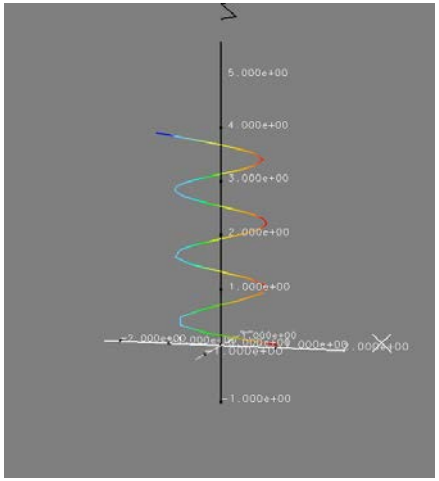
Mode 6



Mode 8



Mode 10



Mode 12

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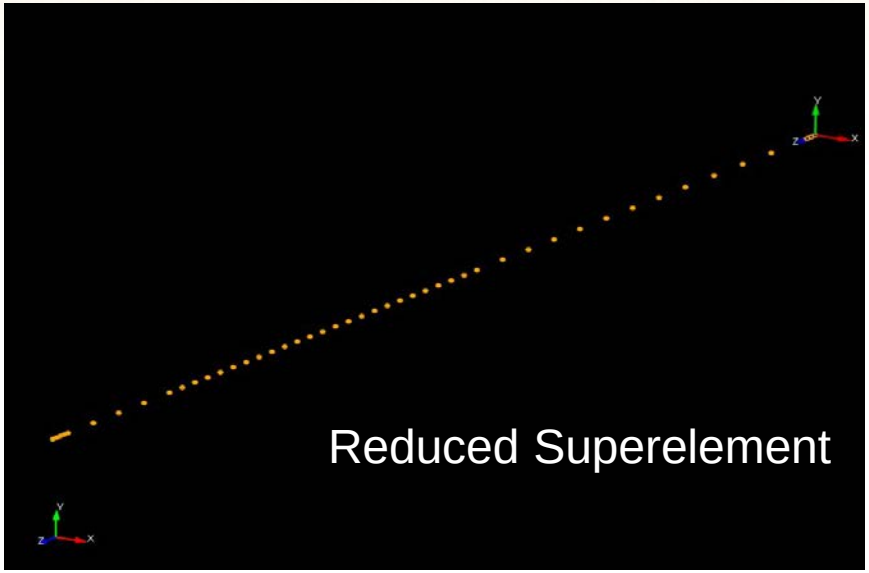
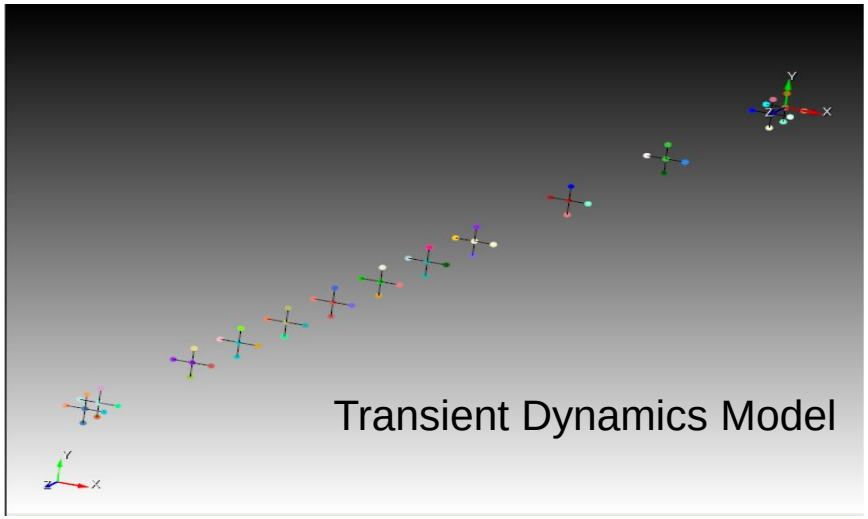
Building the Model, Stage 2, Transient Model



Reduced superelement contains one node at each grid plus several other nodes at which to apply fluid loading.

There are 147 Total Degrees Of Freedom (DOFs).

The Superelement contains all the nodes, both fluid and spacer nodes. The ordering of nodes is a spacer/grid node followed by 3 fluid nodes for the entire span.



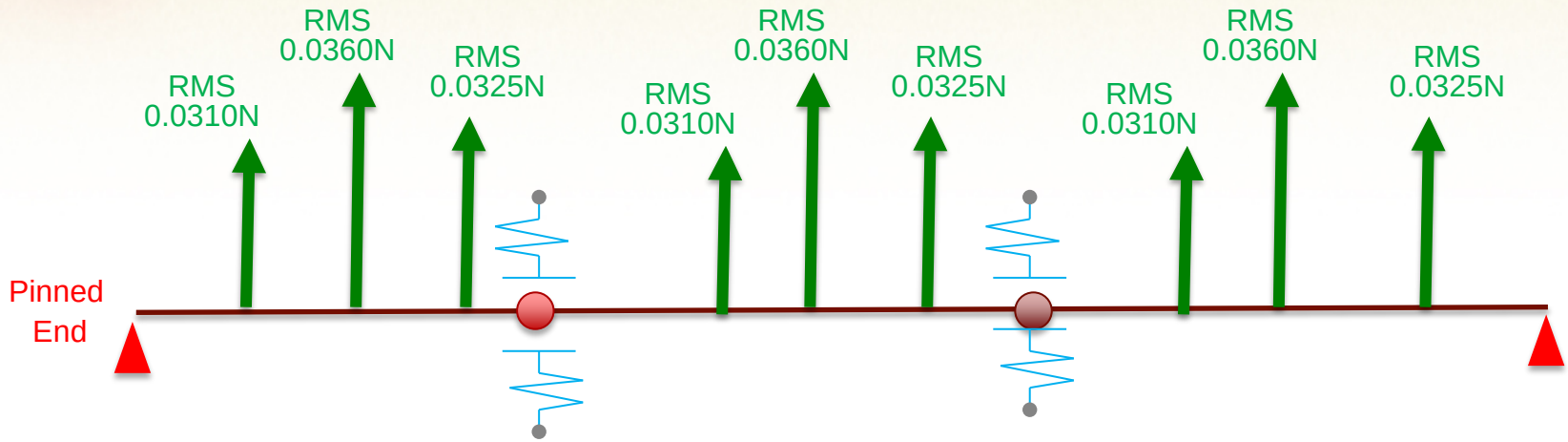
Transient model contains:

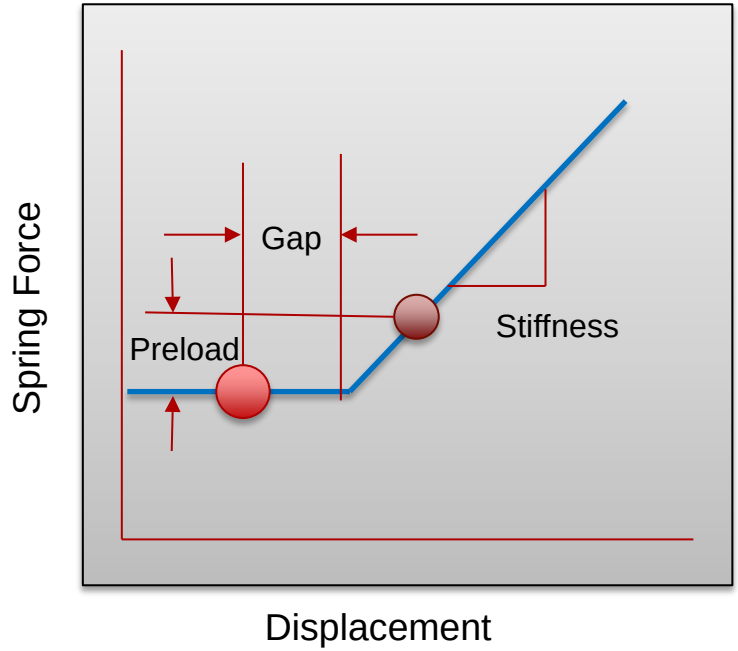
1 Linear Superelement (Rod)

52 Nonlinear spring elements (Grid Springs) with 4 springs at each of the 13 spacer grid nodes.

Transient model can accurately integrate spring nonlinearity. Low number of DOFs keeps timestep high and model running fast.

Transient Model Boundary Conditions





Fluid loads: Same as VITRAN, Realization of 5-100 Hz white noise with RMS load magnitudes provided by Hydra

Nonlinear Springs: Defined by force displacement function incorporating preload, stiffness, and gap in springs

Comparison with paper CASL-I-2012-0165-000:
General Comments:

Major deliverable with this milestone is comparison of Sierra approach here with VITRAN benchmark data for a nominally similar case (described in report: CASL-I-2012-0165-000). Known and unknown modeling discrepancies listed below. Due to these discrepancies we expect to show a close, but not precisely identical result.

Model Geometry:

- We model the 12 span geometry shown earlier. Span comparisons to the VITRAN data is given at the six nearly equal roughly 11 inch spans. This setup should be similar , but likely not identical, to the VITRAN benchmark.
- Though rod dimensions are fairly standard, may not be modeling precisely the same geometry used in the VITRAN benchmark.
- We were not completely sure what the spring state is in the VITRAN model. To bound uncertainty we modeled three cases.
    - Very stiff springs (pinned grid nodes)
    - Springs set with best guess to match VITRAN setup, nominal V5H springs with neither preload nor gap
    - Very loose springs (large initial gaps)

Model Assumptions:

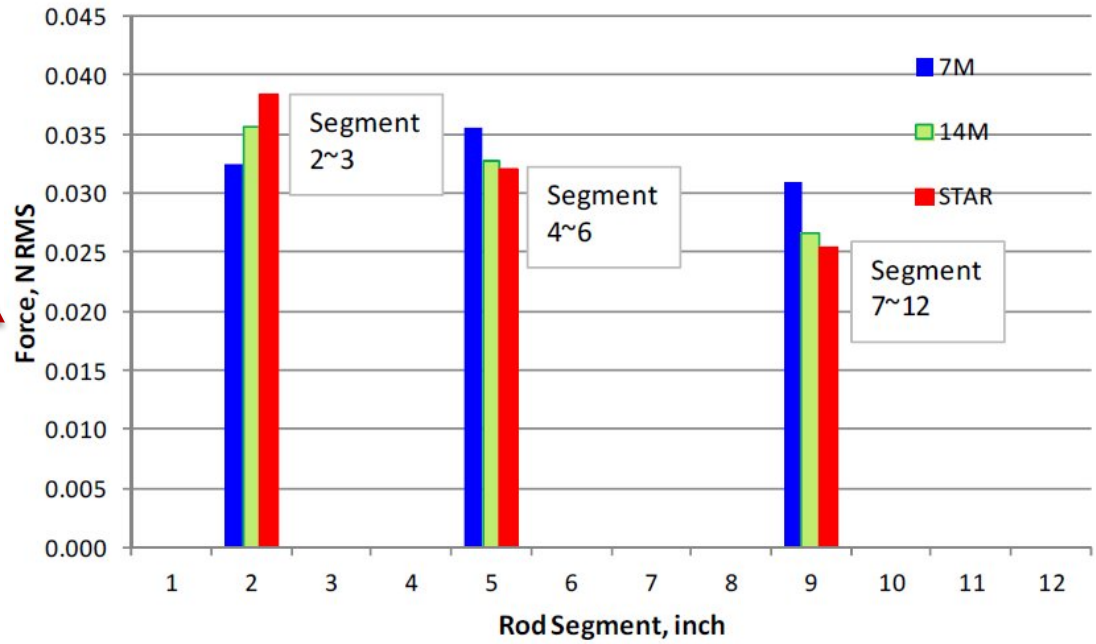
- Sierra is modeling spring vibration in vacuum. No correction made for additional mass or damping due to wet modes.
- In Sierra model rod fluid forces are modeled as completely un-correlated.
- In Sierra model a user subroutine is used to generate randomized forcing loads by summation of cosine functions. These forcing functions have the same spectral decomposition and RMS force magnitude as those used in VITRAN benchmark. However, force time history realizations generated in a different way may have subtlety different properties.

Comparison with paper CASL-I-2012-0165-000:

Loading conditions:

Fluid vibration RMS magnitudes taken directly from previous milestone report:

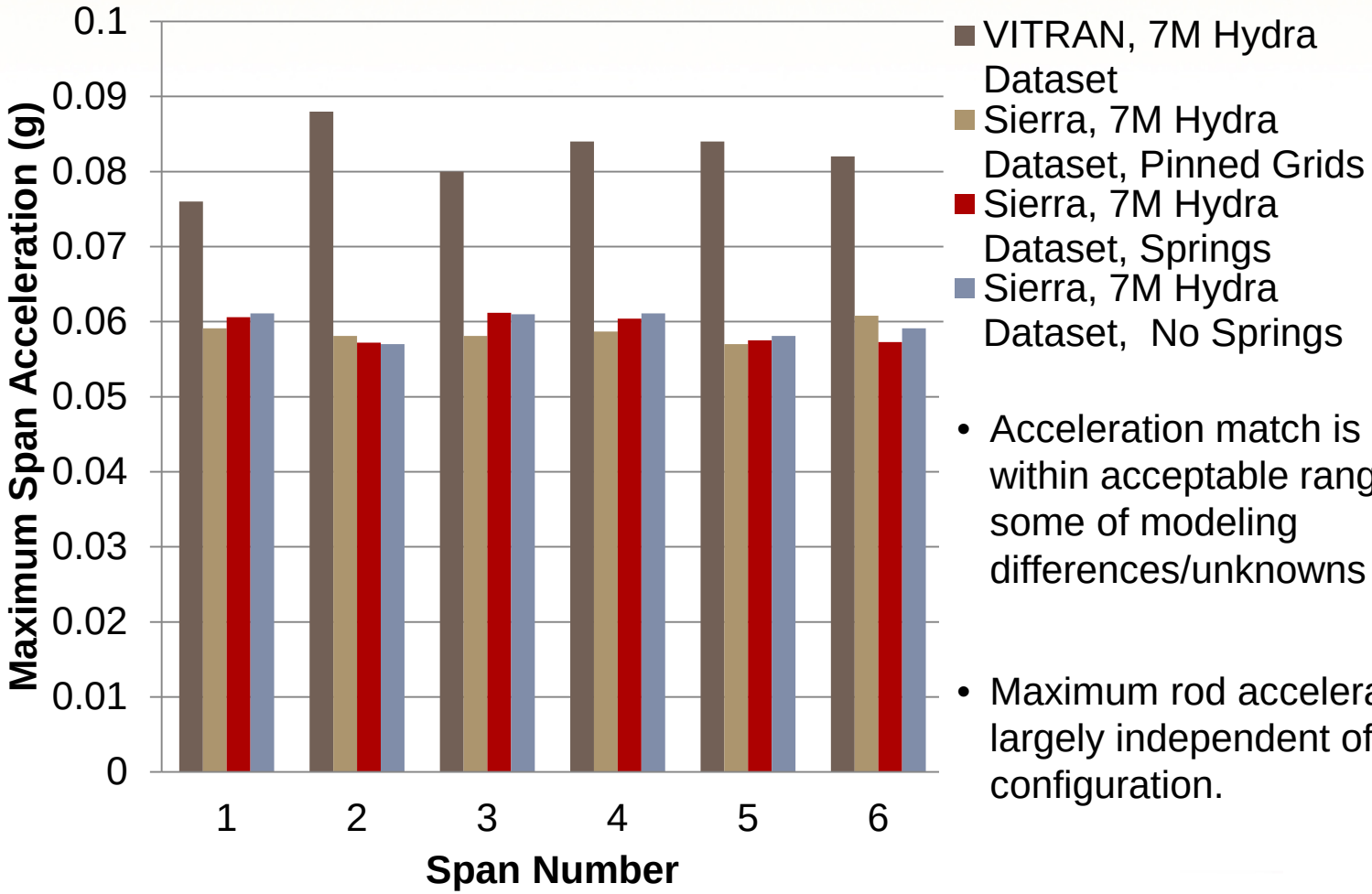
Force root-mean-squared magnitudes and locations provided by Hydra



The 7M, 14M are two different fluid loadings based generated by Hydra on different mesh refinements. We will compare both absolute magnitudes and the sensitivities of the results to the loading functions and spring conditions.

Comparison with paper CASL-I-2012-0165-000:

Span Acceleration



- Acceleration match is decent, within acceptable range given some of modeling differences/unknowns
- Maximum rod acceleration largely independent of spring configuration.

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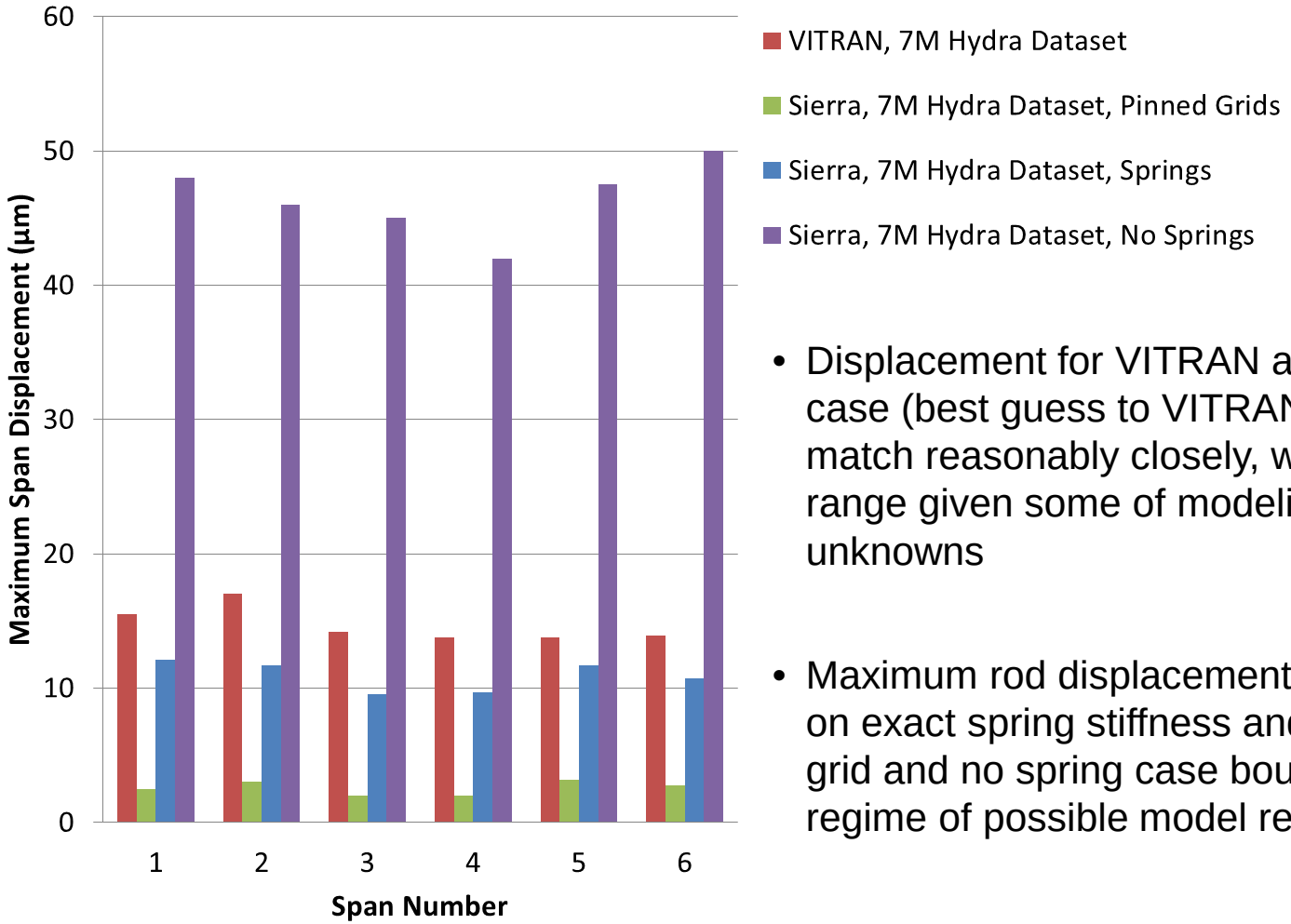
Comparison with paper CASL-I-2012-0165-000:

Span Displacement



- Displacement for VITRAN and Sierra "Springs" case (best guess to VITRAN model setup) match reasonably closely, within acceptable range given some of modeling differences and unknowns
- Maximum rod displacement heavily dependent on exact spring stiffness and gap. The pinned grid and no spring case bound the entire regime of possible model response.

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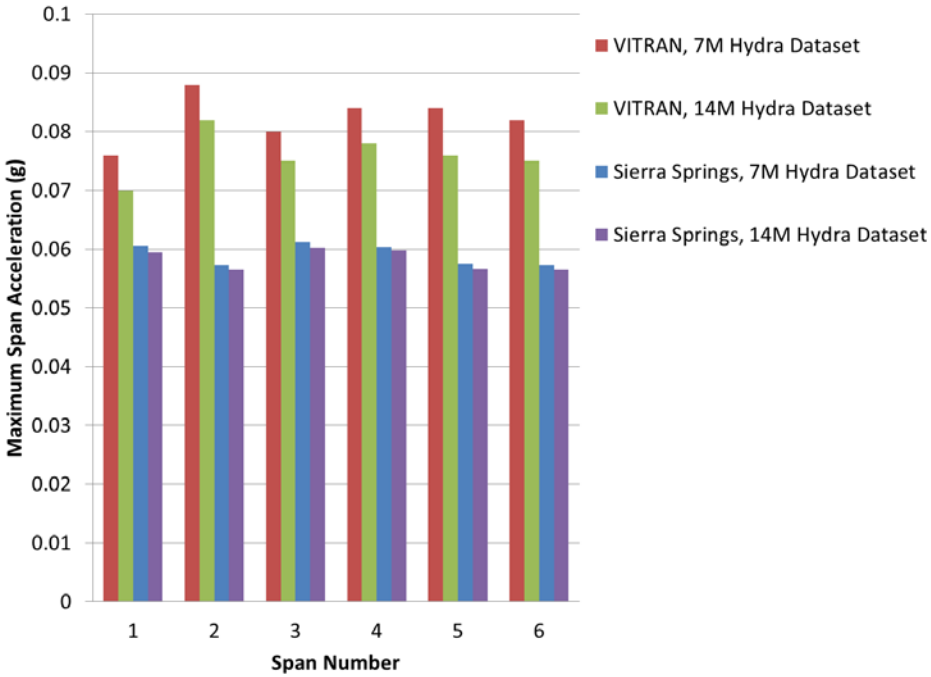
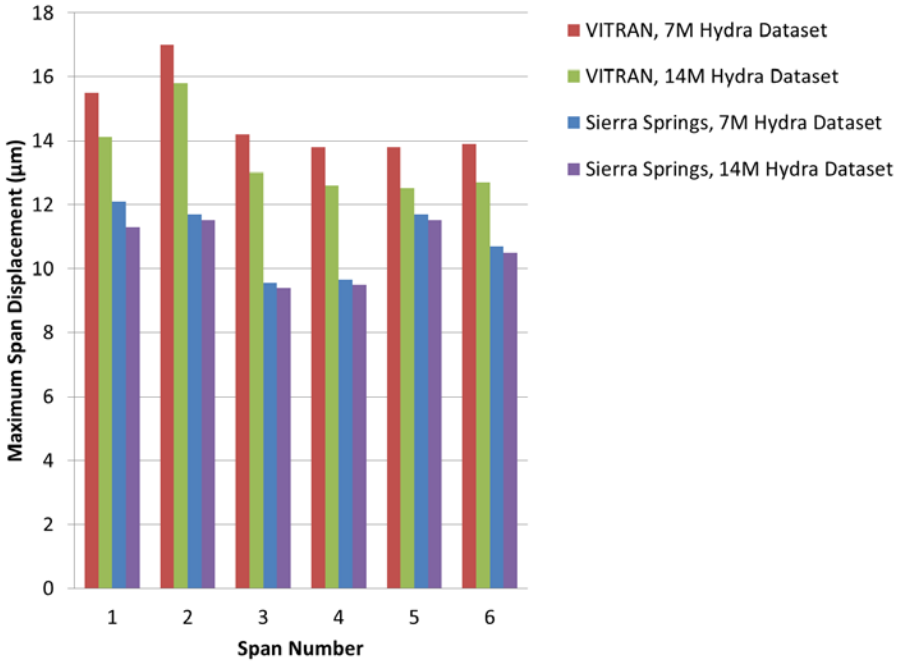
Comparison with paper CASL-I-2012-0165-000:

Sensitivity to Loading





- The Sierra based model shows a bit less sensitivity to the loading than does the VITRAN model, though the trends are the same.
- Discrepancy in sensitivity magnitudes most likely due to differences in model setup (span length and spring conditions)

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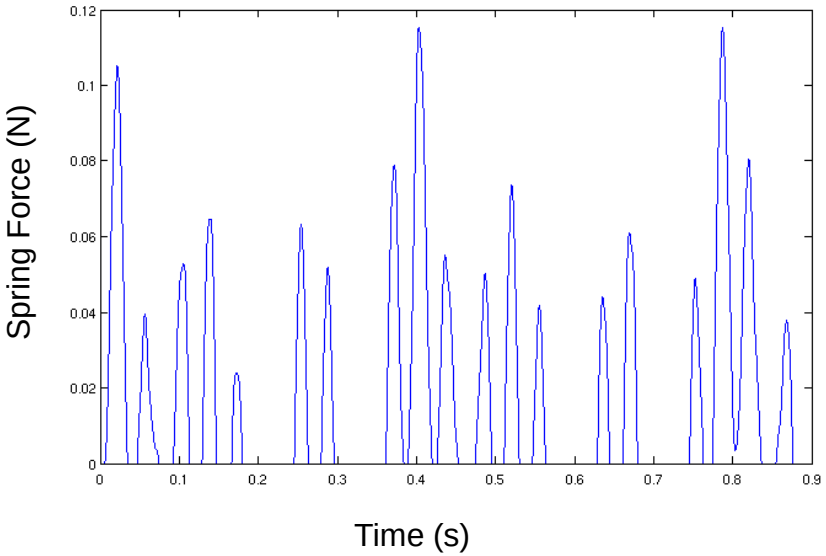
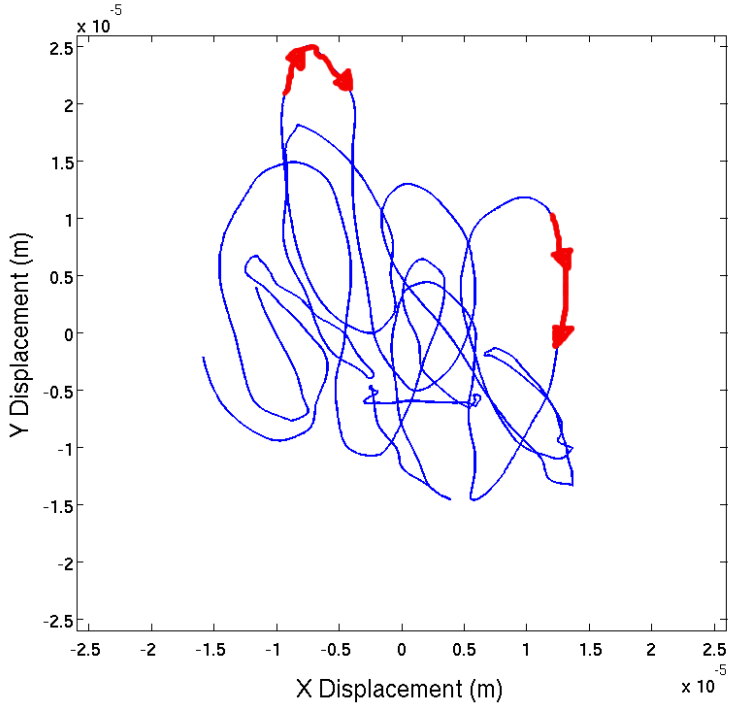
Wear Rate

- No wear rate algorithm has currently been integrated into Sierra. However, sufficient information is generated by the Sierra analysis to drive a physics based wear calculation.

Force in a specific spring as function of time. Analyses predicts ~20 impacts per second.



Motion of rod at a grid location from T=0.5s to T=1.0s. Highlighted sections of curve would generate significant wear due to combination of large spring load and lateral sliding of rod on spring.



Runtime

Phase	Runtime
Running script to create continuum rod element mesh	30 minutes
Craig Bampton Reduction of Superelement (Sierra/SD)	15 minutes on 8 processors
Transient analysis (Sierra/SM) [1 second analysis time]	40 minutes in serial

Conclusions

- The presented analysis results show that the Sierra coupled modal rod model with transient dynamics integration can successful model fluid induced rod vibration and wear in a reasonable time frame.

- The approach of directly tying rod representation to the full solid geometry allows the opportunity to directly model additional physics such as spatially variant rod conditions, wet modes, and different rod pellet interface conditions. Additionally mapping back to the full 3D model can enable considering more detail at the grid-rod contact points to for more accurate modeling of wear physics.

- We suspect if the Sierra analysis more exactly replicated VITRAN model boundary conditions we would get a closer match to VITRAN results. However, may be more productive to independently validate model.

Possible Follow On Work:

If this demonstrated approach is deemed viable, the following steps would be needed to create fully functional GTRF analysis tool.

- Add enhancements to structural dynamics model model to accurately take into account wet modes in superelement response.
- Add wear rate computation heuristics to automatically calculate wear from spring deformation history or include other science based wear physics computations.
- Directly apply the true lumped force time histories from Hydra. This would directly take into account any correlation of fluid force with distance and remove any approximation errors associated with white noise frequency band assumptions.
- Automatically hook model spring inputs to the spring force deflection curves produced in milestone L3.VRI.CM.P7.03, “Spring Relaxation Demo with Sierra”.
- Fully integrate vibration model with spring relaxation model to compute wear rates as the spring and rod state evolves. Integrate total wear during entire fuel cycle.
- Validate model versus experimental data.
- Create a more user friendly front end and post processing suite to facilitate production usage