PIRAT - An Analytical Tool for Insertion Reliability Assessment of Reactivity Control Systems - Progress and Applications to Sodium Fast Reactors

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PIRAT - An Analytical Tool for Insertion Reliability Assessment of Reactivity Control Systems - Progress and Applications to Sodium Cooled Fast Reactors

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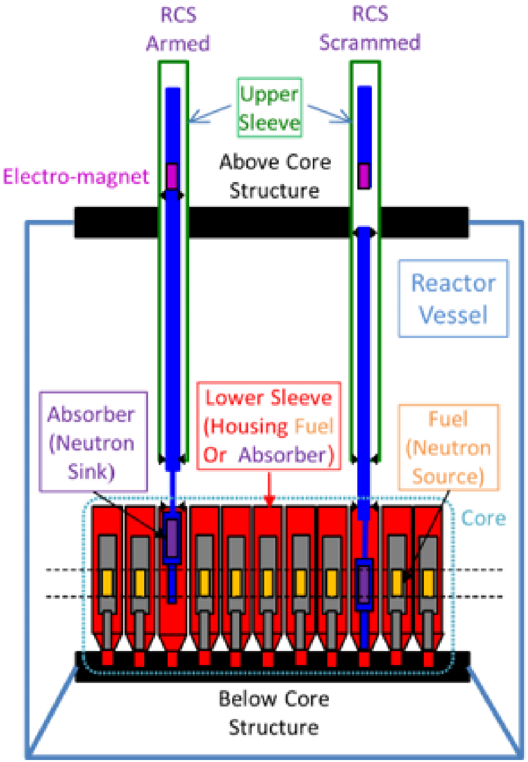
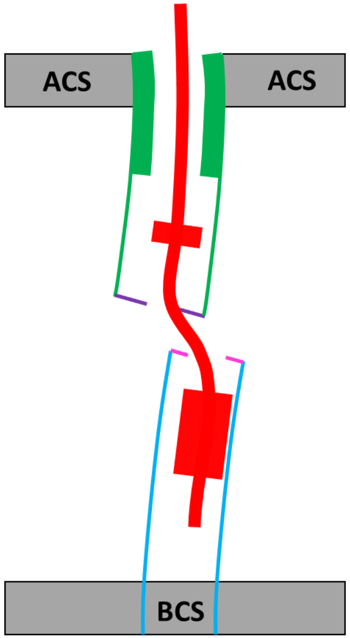
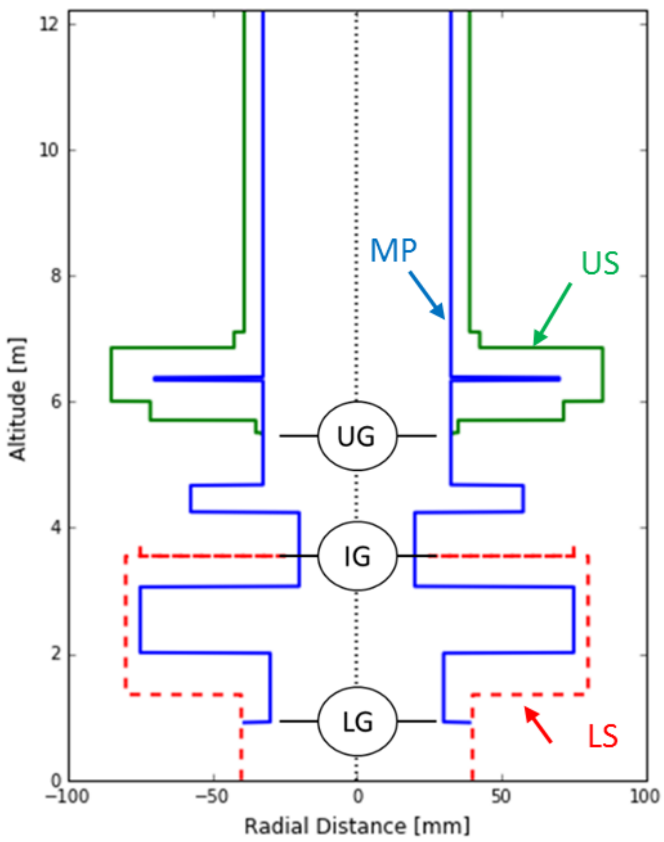
Motivation

- A Reactivity Control System (RCS) is a critical component for a reactor
- Seismic vibrations represent the most challenging situation for RCS design
- Earthquakes produce low-frequency excitation via large displacements
- Specifically, produces large displacement on the below core structure (BCS)
- Can impede operation when misalignment of 3 subsystems
- Previous studies typically use static representation
- This work focuses on dynamic effects and differences between Static and Dynamic simulations of the same event to demonstrate progress in development of PIRAT

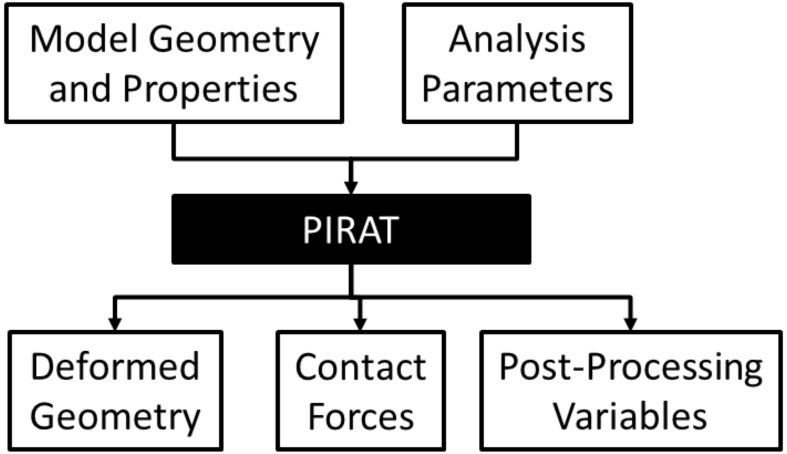




- A typical RCS is comprised of 3 main components:
  - A Mobile Part (MP) that embeds neutron absorbing material
  - A Lower Sleeve (LS) that is considered a rigid boundary (due to core compactness)
  - An Upper Sleeve (US) that is considered a quasi-rigid boundary (slender, clamped to ACS)
- To test seismic situations, use the Model System Configuration (MSC)
  - Results shown in this work has unrealistic US mass to emphasize nonlinear effects
- Modeled after the past French SFR studies
- Contains 3 main points of interest
  - The Lower Guide (LG) is a moving contact at the end of MP
  - The Intermediate Guide (IG) is the main point of excitation
  - The Upper Guide (UG) is the main response point

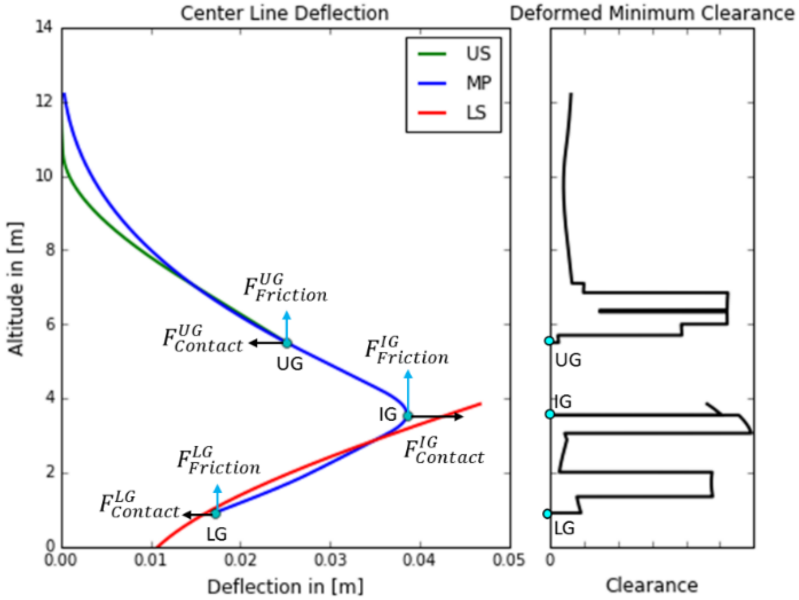


- PIRAT – Python Implementation for Reliability Assessment Tools
- Toolbox currently in development at CEA to study insertion reliability
- Based on analytical (continuous) modeling
- Comprised of 3 main tools
  - StaBI – Statically enforced boundary
  - DEBSE – Dynamic boundary enforcement (Main aspect of this work)
  - SIKI – Kinetic insertion to model drop-time (Currently not implemented, planned future work)
- User inputs model properties and analysis parameters, PIRAT outputs deflections and contact forces



Dynamic Effects – Static baseline

- Goal of work is to characterize differences between static and dynamic analyses
- Static analysis uses StaBI
- StaBI uses Bresse' formulations for beam deflection
- Main output is deflection of UG + reaction forces (not covered in this talk)
- Deflection of UG ≈ 25 mm (for considered conservative seismic scenario)
- For reference on Force:
  - Weight of MP ≈ 2400 N
  - In-Phase (25mm) UG force ≈ 300 N
  - Total friction force (with assumed μ=0.6) ≈ 20% of weight



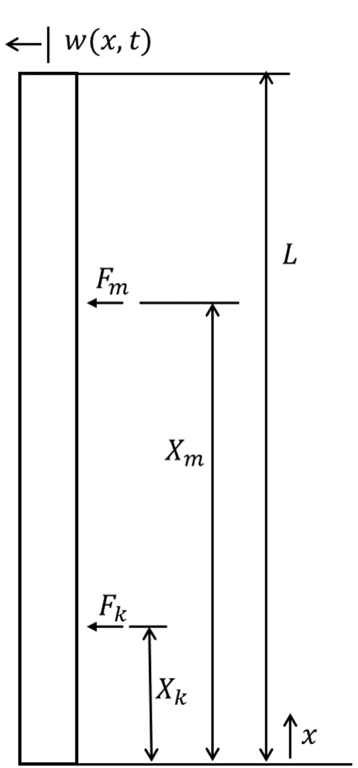
- Based on Euler-Bernoulli beam segments

$$EI\frac{\partial^4 w(x,t)}{\partial x^4} + cI\frac{\partial^5 w(x,t)}{\partial x^4 \partial t} + \rho A\frac{\partial^2 w(x,t)}{\partial t^2} = \sum^{N_k} F_k(t)\delta(x - x_k) + \sum^{N_m} F_m(t)\delta(x - x_m)$$

- Contact as external forces
- Segments transitions are continuous for displacement, slope, shear force, and bending moment
- Natural frequencies & mode shapes based on boundary and continuity conditions
- Use mode shapes to generate ODEs in modal space with a change of variable
- Contact forces are based on 2 stage spring (represents anti-friction coating and fluid compressibility)

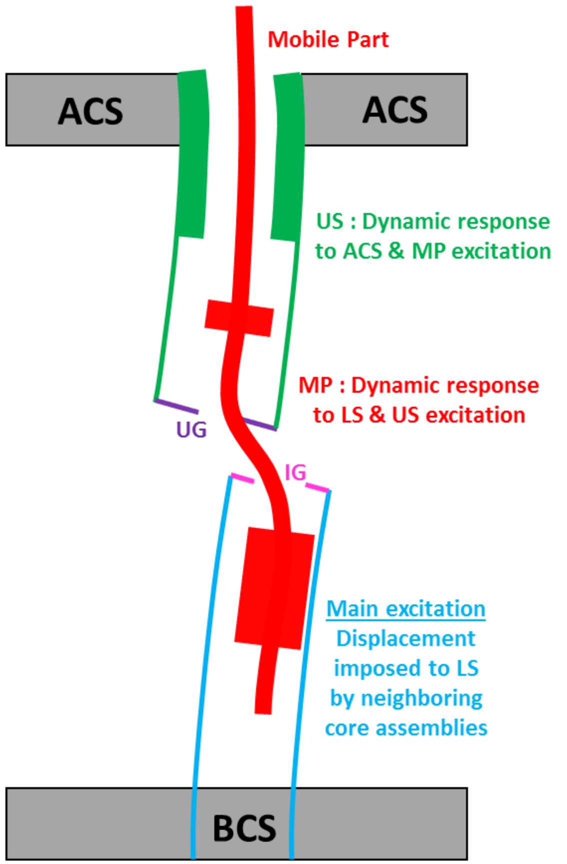
$$F_s = \frac{K_{coat}}{2}(r_1 + |r_1| + r_2 - |r_2|) + \begin{cases} \frac{K_{mat}}{2}((r_1 - g_k) + |r_1 - g_k|) & if\ r_1 \geq g_k \\ \frac{K_{mat}}{2}((r_2 + g_k) - |r_2 + g_k|) & if\ r_2 \leq -g_k \\ 0 & else \end{cases}$$

- r_1>0 for contact on right side and r_2<0 for contact on left side

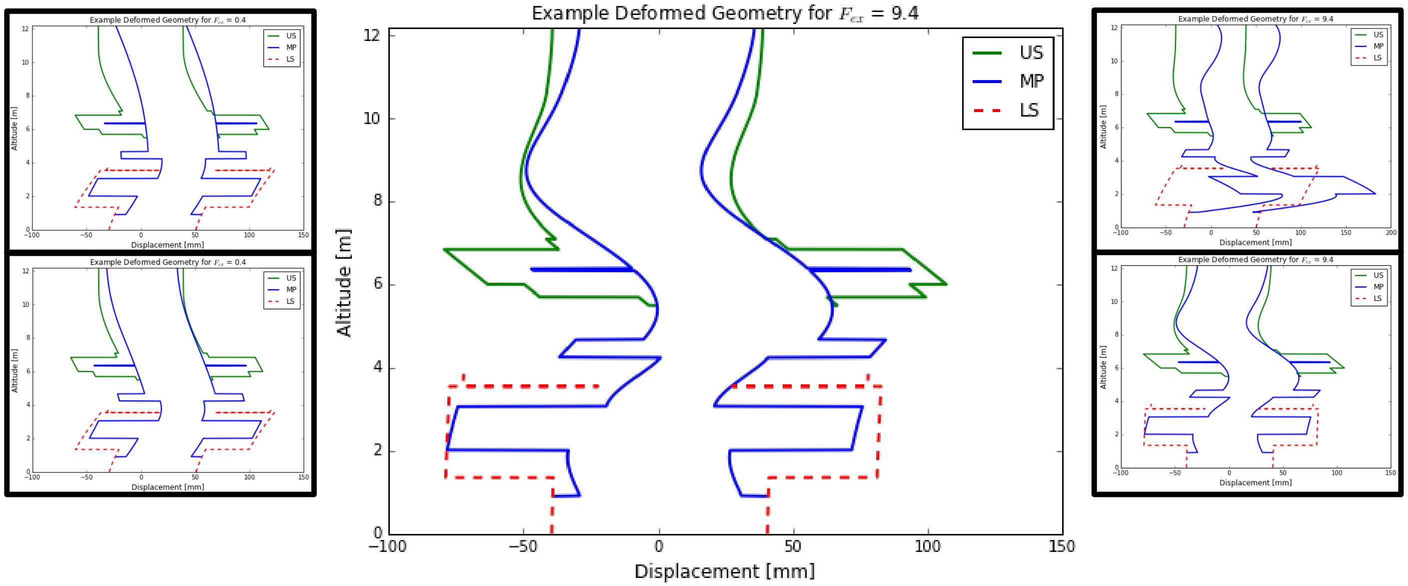


- Dynamic effects will be reported using 2 metrics
  1. Dynamic Amplification Factor (DAF) is measured as the largest amplitude normalized by static deformation. Used to show resonance effects and compare static results to enveloped dynamic results
  2. Phase lag is measured as the time difference between the largest amplitude and the peak of the excitation. Used to show relationship between LS and US.
- Excitation as harmonic motion of LS in range [0.4,10] Hz
- 3 Major differences between static and dynamic simulations

1. Parasitic Contact
2. Dynamic Amplification
3. Relationship between LS and US

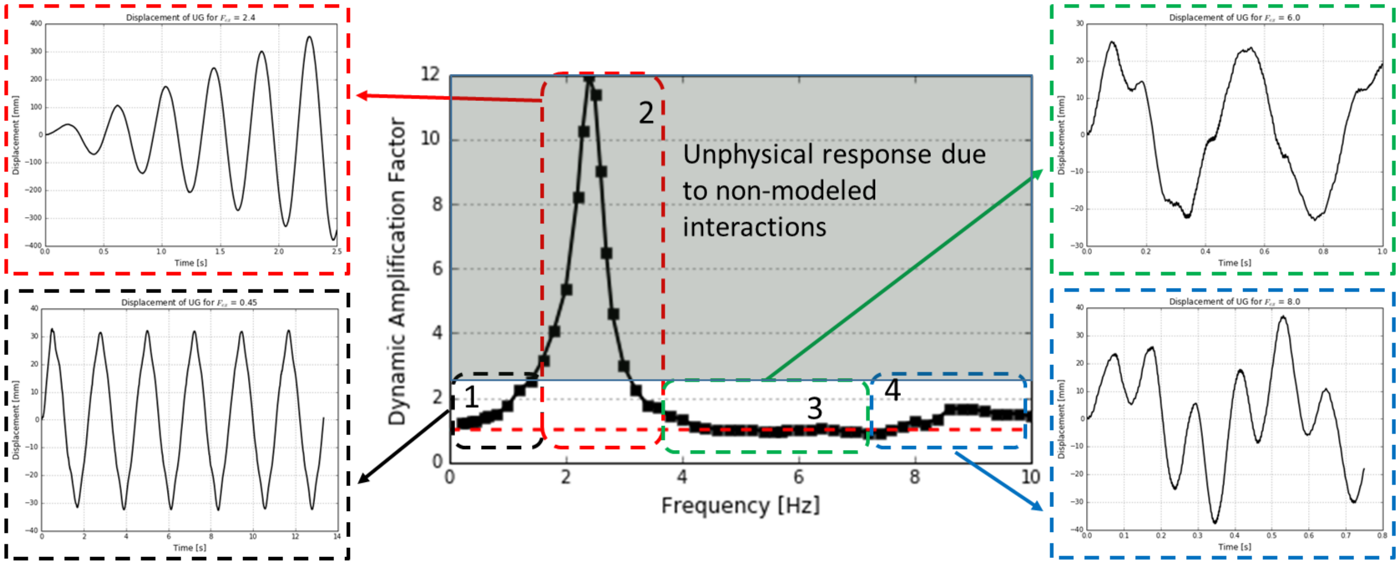


DEBSE – Parasitic contacts



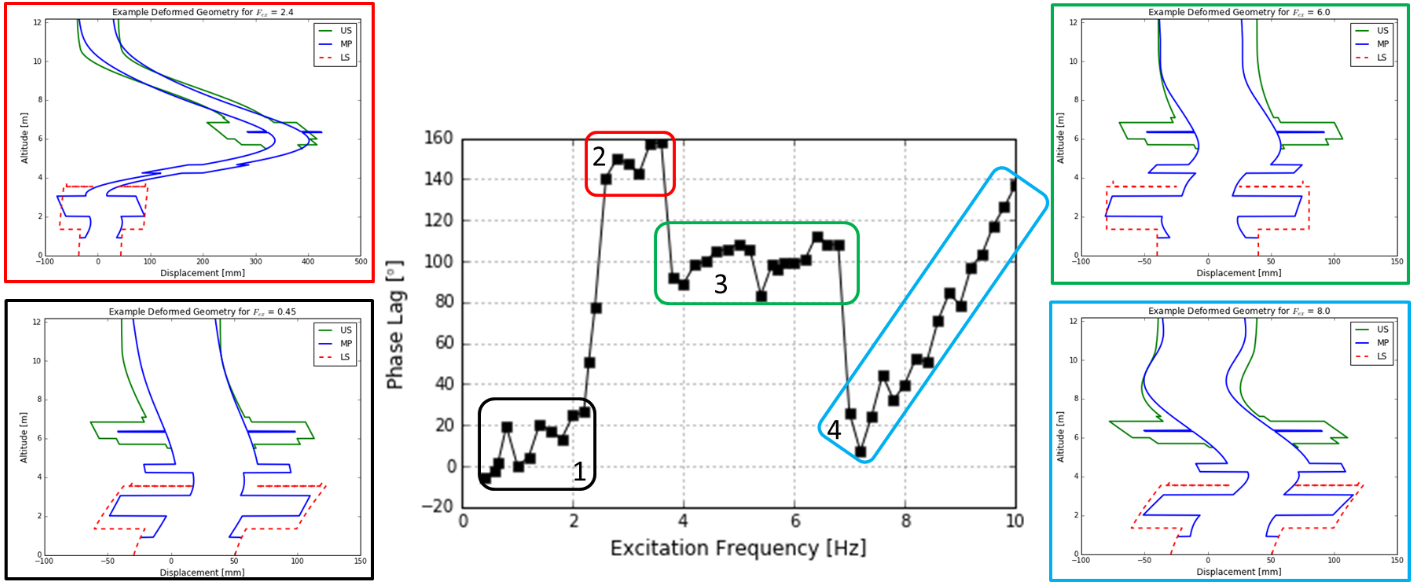
- Parasitic contact is unwanted contact/ contact at not specified guide sections: because they can lead to excess friction and possible damage
- Additional points of contact were required to produce realistic deformations (manually inputted)
- Seen at all frequencies tested, but more predominate at higher frequencies
- Parasitic contacts seen for both US and LS (Shorter duration of contact compared to guide regions)

DEBSE - DAF



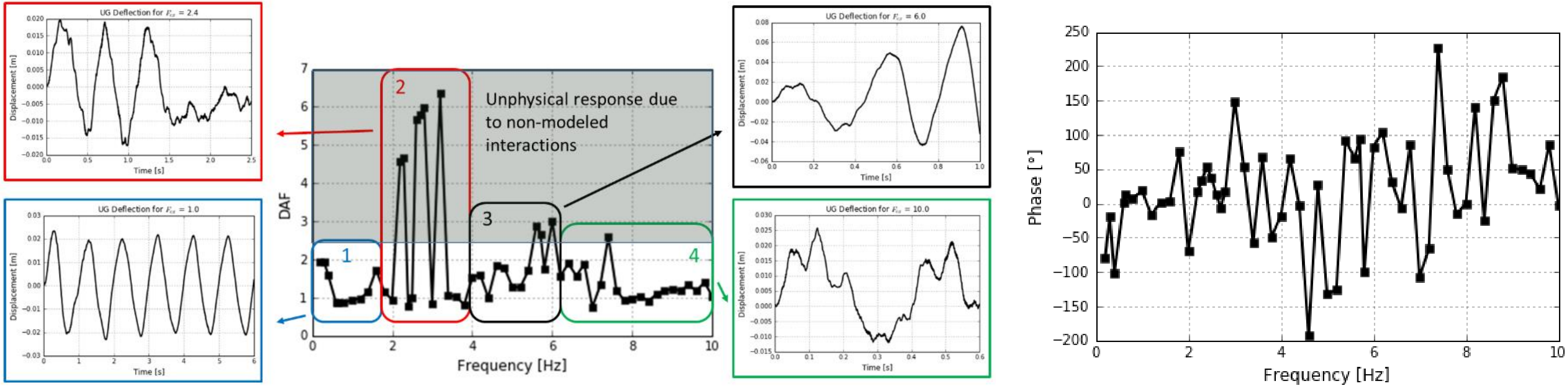
- Visually identify 4 distinct regions (further refined by phase lag) based on excitation frequency
- Large resonance effects near second bending mode (2.3 Hz)
- In the physical system, some aspects are not modeled and start to interact at “large” DAF values (ranges from 1-3 in realistic systems)
- Higher excitation (3+ Hz) shows reasonable displacement with DAF of 0.8-2

DEBSE – Phase lag



- Better defines same distinct phase groups (DAF inspection made by visual estimation)
- Demonstrates relationship between US and LS
- Only group 1 has LS and US consistently in-phase
- Group 4 incorporates 2nd bending in US (9.0 Hz)

Comments about system realism



- Leading up to final submission, a more realistic model of the US was created
- An difference in the density caused the mass of the US to be about 10x that of MP in this work
- Typically this ratio is around 2x
- Only effects the mass of US, all other properties are realistic
- For adjusted system:
  - Same general trends in amplitude, but no trends in phase lag
  - Resonance effects can cause ill-conditioning for realistic system (2.1 & 2.3 Hz)

Conclusion / Remarks

- PIRAT (in development at CEA) is currently able to perform both static and dynamic simulations for a stationary RCS
- DEBSE treats contact as external forces (Springs or Material Contact)
- Purpose of this work is to show advances of DEBSE and differences between static and dynamic simulations
- Showed 3 main differences

1. Parasitic Contact
2. Dynamic Amplification
3. Difference in Phase between LS and US

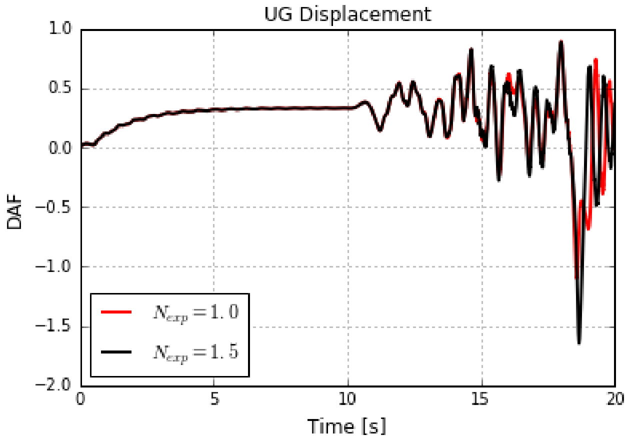
- These differences lead to an increase in contacts that create friction, possibly impeding the operation of the RCS
- Deformations might be unrealistically large (treats full static+dynamic as only dynamic). Recent work indicates that more realistic simulations might not experience the amplification and phase differences
- Future work to investigate dynamic reaction forces, dynamic deformation on statically deformed system, and implement SIKI for kinetic insertion studies

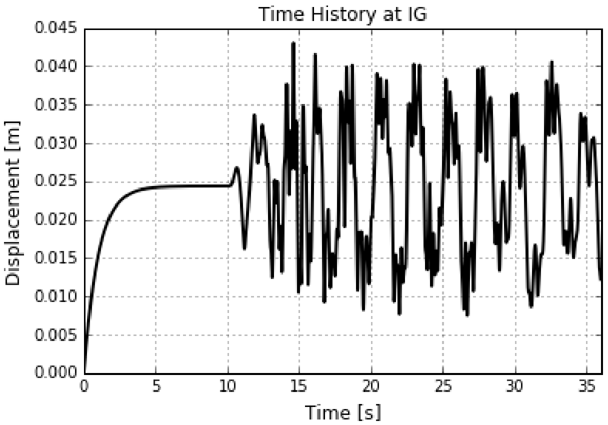
Thank you for your time and attention

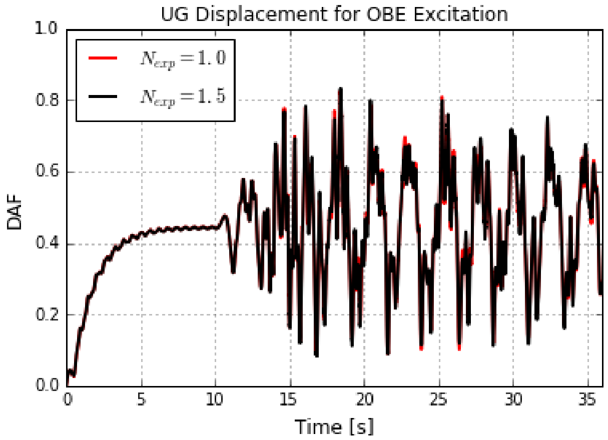
- Extra Slides

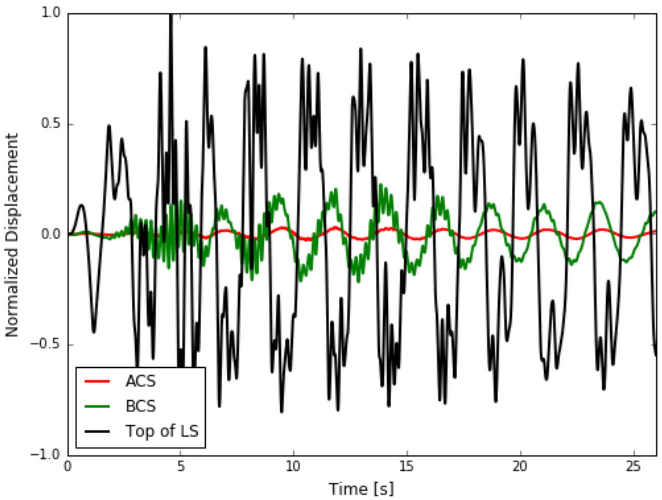
Static + Dynamic Excitation

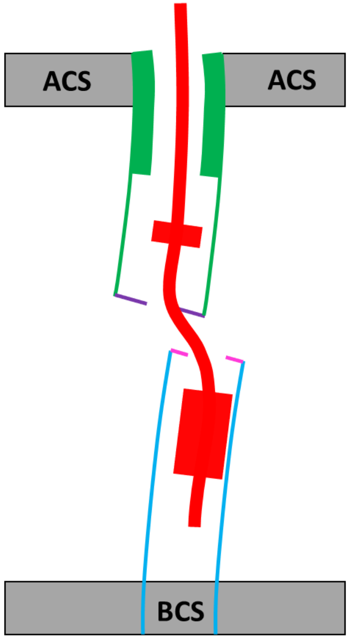
- DEBSE only requires time-history of excitation
- Misalignment caused by static deformations and dynamic excitation
- For SSE, about half static & half dynamic (about 20mm each at IG)
- Start to see nonlinear effects with large negative DAF
- For OBE, same static deformation with ½ dynamic excitation
- Little to no nonlinear effects – expected results







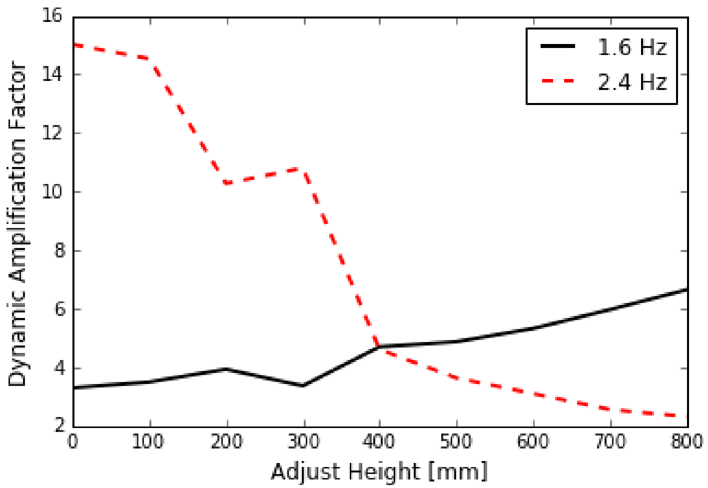


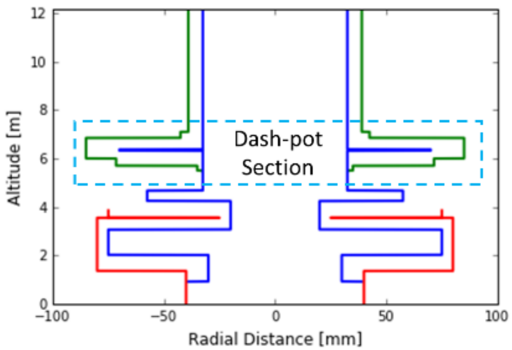


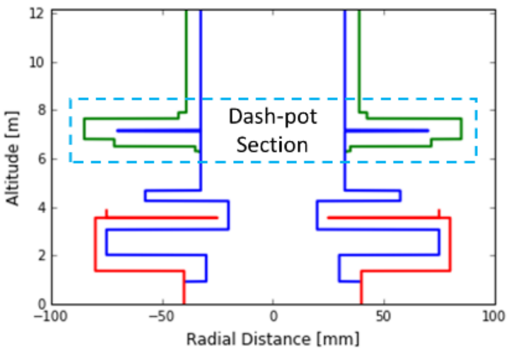
- LS motion dominated by BCS excitation
- US motion dominated by MP interaction
- Motion of US by ACS excitation is small, thus neglected in this work
- PIRAT is able to account for ACS excitation, but neglected for simplicity

Design modification

- Vertical adjustment of Dash-Pot section of US/MP
- Adjust up to 800 mm
- DAF for 2.4 Hz from 15 to 2
- Adjustments of 400+ mm made convergent result
- While decrease at 2.4 Hz, increase for 1.6 Hz
- Reduces effect of 2nd resonance, but increases effect of 1st resonance







Modeling extended

- $$F_s = \frac{K_{coat}}{2}\left(r_1 + |r_1| + r_2 - |r_2|\right) + \begin{cases} \frac{K_{mat}}{2}\left((r_1 - g_k) + |r_1 - g_k|\right) & if\ r_1 \geq g_k \\ \frac{K_{mat}}{2}\left((r_2 + g_k) - |r_2 + g_k|\right) & if\ r_2 \leq -g_k \\ 0 & else \end{cases}$$
- r_1>0 for contact on right side and r_2<0 for contact on left side
- Change of variables + modal decomposition
- For LS
- $$r = \phi_0 \frac{L - x_k}{L} + \phi_L \frac{x_k}{L} + \sum_N \psi_n q_n - V_c \pm \delta_k$$
- For US
- $$r = \phi_0 \frac{L - x_m}{L} + \phi_L \frac{x_m}{L} + \sum_N \psi_n q_n - \sum_\Gamma \Psi_\gamma Q_\gamma \pm \delta_m$$
- Use mode shape orthogonality and contact model to generate set of dependent modal equations of motion