# Implementation and Comparison of Contact Models within PIRAT for Nuclear Reactivity Control Systems

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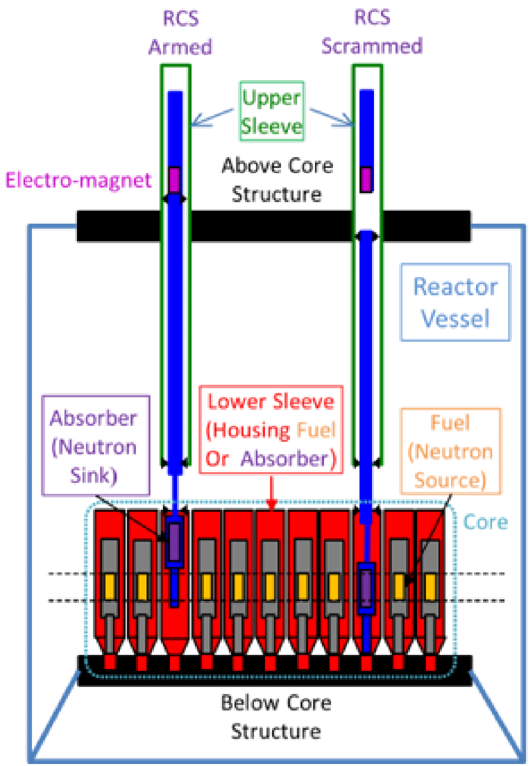
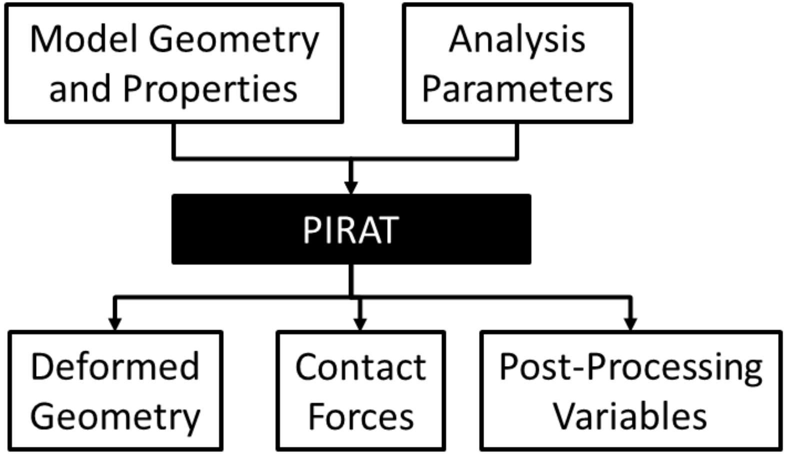
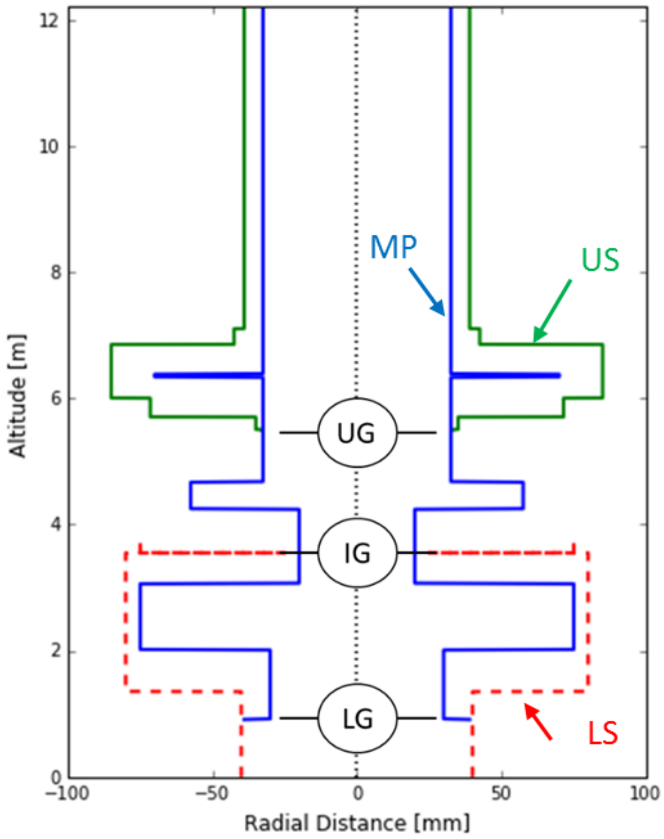
- CEA is focused on the development of next generation nuclear reactors
- Current development for Reactivity Control Systems (RCS)
  - Main use: Control output of reactor
- Exhibit difficult case of forced excitation and multi-body interactions with frictional contacts
- Desire: a simplified tool for early design phase simulations for safety during seismic event
  - Easy to modify/adjust test system



- To study these systems, PIRAT (Python Implementation for Reliability Assessment Tools) is currently being developed
- Based on 3 main tools:
  - StaBI – Statically enforced boundary
  - DEBSE – Dynamically enforced boundary (Focus of this work)
  - SIKI – Kinetic insertion to measure drop-time
- Uses analytical (continuous) modeling approaches
  - Opposed to FE



- RCSs control the output of the reactor
  - Primarily during earthquake
- Comprised of 3 main subsystems
  - Mobile Part (MP) containing the absorbing material
  - Lower Sleeve (LS) that enforces the dynamic excitation caused by the core
  - Upper Sleeve (US) that is more rigid than MP but has relatively free movement
- To study these systems, the Model System Configuration (MSC) system is used
  - Modeled after past French fast reactors



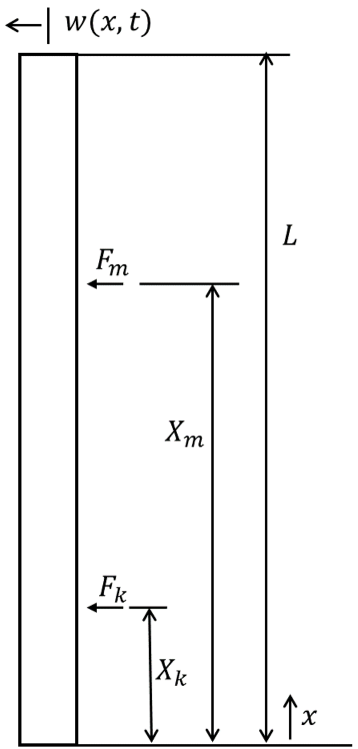
- Based on Euler-Bernoulli beam segments

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

- Treat contact as externally applied, point-force
  - $k$ for contact with LS and $m$ for contact with US
- Contact forces and deformation relationship described by contact models (focus of this work)
- Due to excitation (fixed displacement), simple BC with change of CS is used to simplify analysis

$$w(x,t) = \phi_0(t)D_0(x) + \phi_L(t)D_L(x) + \sum^{N} \psi_n(x)q_n(t)$$

- Same type of analysis for US, assumed to be cantilever



- 2 models considered
- Both are regulation based and depend on relative penetration of MP and the sleeves

$$\Delta_i^b = \left(\frac{p_r + |p_r|}{2}\right)^b - \left(\frac{|p_l| - p_l}{2}\right)^b = \begin{cases} + & Contact\ on\ Right \\ - & Contact\ on\ Left \\ 0 & No\ Contact \end{cases}$$

- First model: a mass-less, two-stage linear spring with a gap

$$F_i = K_c\Delta_i + \frac{K_m}{2}\begin{cases} (p_r - g_i) + |p_r - g_i| & if\ p_r \geq g_i \\ (p_l + g_i) - |p_l + g_i| & if\ p_l \leq -g_i \\ 0 & else \end{cases}$$

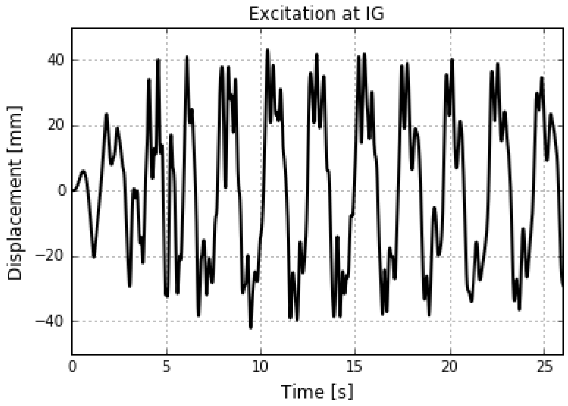
- Second model: Lankarani and Nikravesh (L&N) contact model

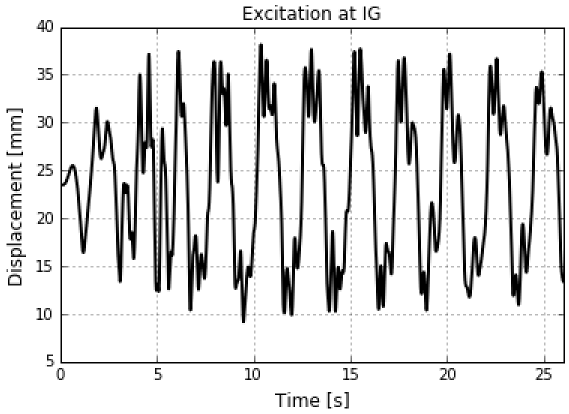
$$F_i = \frac{4}{3}\pi E_i^* \sqrt{R_i^*}\, L_i \Delta_i^b \qquad b \in [1.0,1.5]$$

- Both characterize different aspects and simplifications for these types of systems

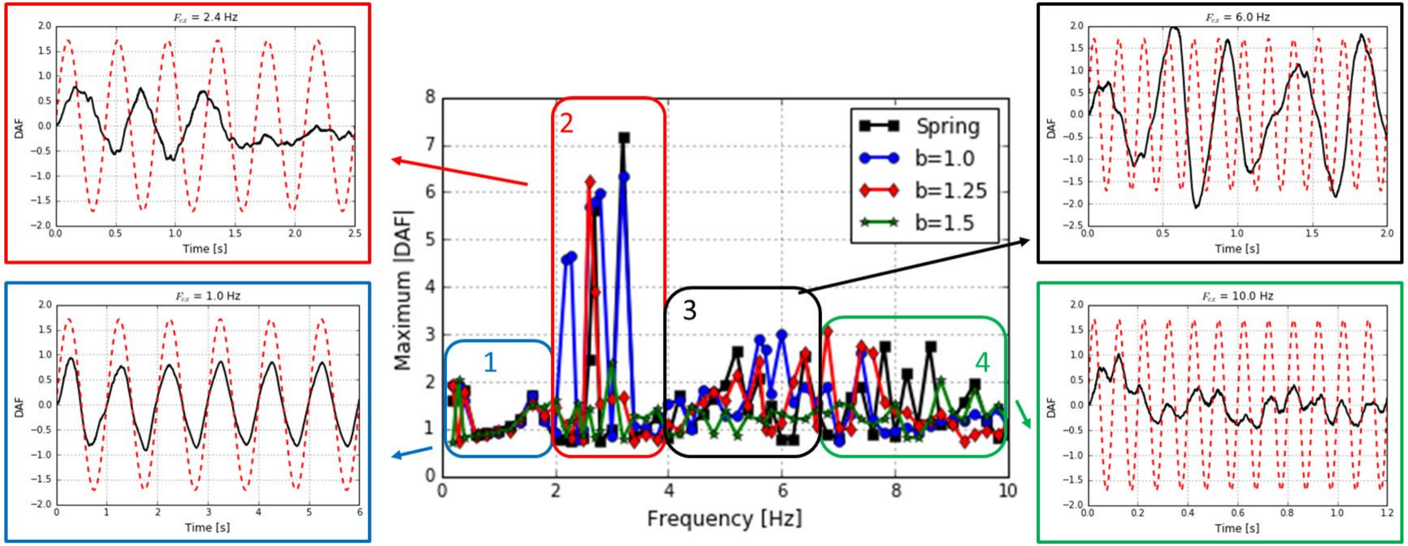
# Simulation Results

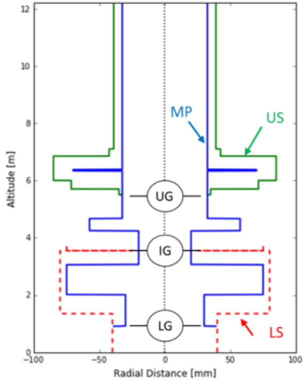
- 3 types of excitations considered
  - Nearly same maximum displacement of excitation locations
  - Safe Shutdown Earthquake (SSE) magnitude
- 1st – Stepped-Sine excitation
  - Easier to understand interactions
  - Adjust applied frequency
  - Identify resonance behavior
- 2nd /3rd – Realistic excitations
  - Generated from whole-core simulations
  - Reactor is not expected to restart
    - Focus on early time



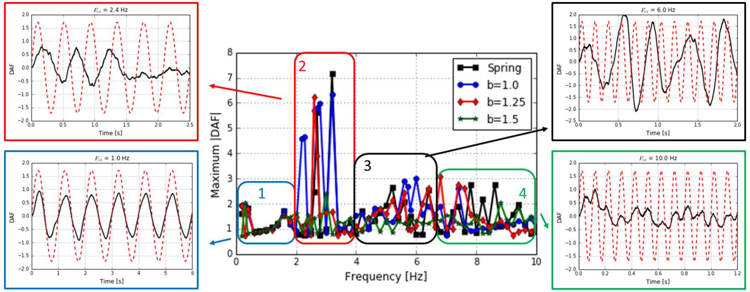



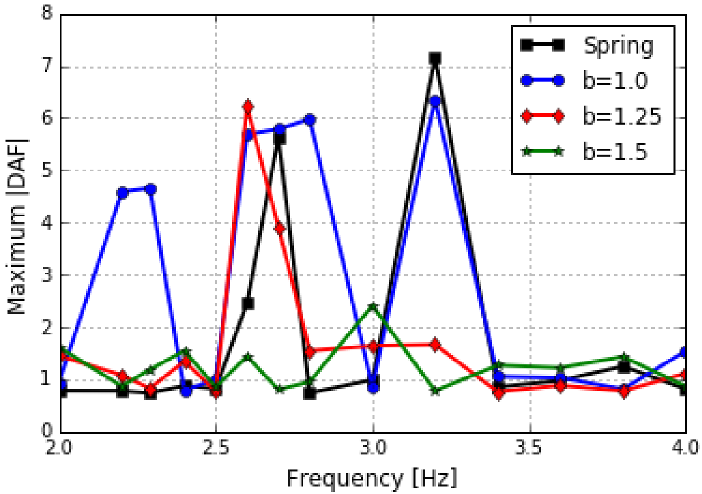
- The first result is for LS motion via Sine wave with variable frequency
- Plot shows maximum displacement magnitude of Upper Guide (UG) normalized to static deformation estimate – Dynamic Amplification Factor (DAF)
- Shows 4 distinct regions based on frequency



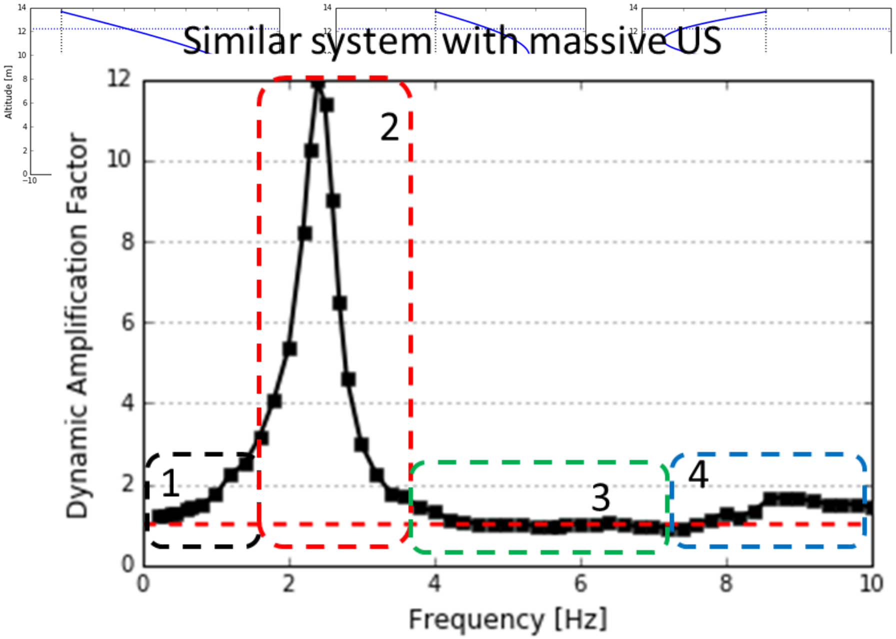



- Low frequency region
  - Nearly identical results
  - Some numerical issues at very low frequencies
- Resonant region
  - MP mode at 2.3 Hz and US mode at 2.1 Hz
  - Causes numerical instabilities
- Mid frequency region
  - Large variability
  - Response dominated by low frequency motion, not excitation
- High frequency region
  - Multi-mode response

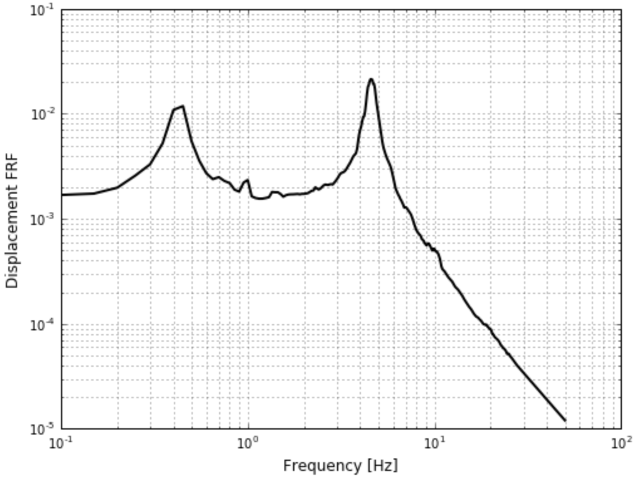


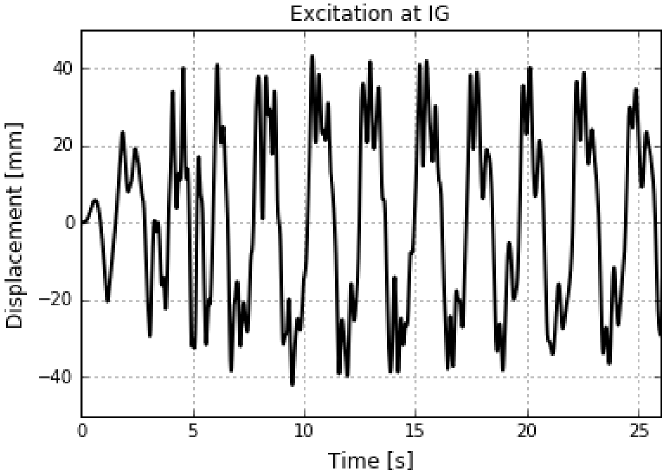



- 2 Aspects of resonance effects
  - Variability (partially due to numerical conditioning)
  - Increase in response
- Increase in response due to imposing large displacement at mode shape max
  - Large energy due to resonance, but fixed amount of energy in 2nd mode due to fixed displacements
  - Energy transferred to 1st mode where UG has large displacement

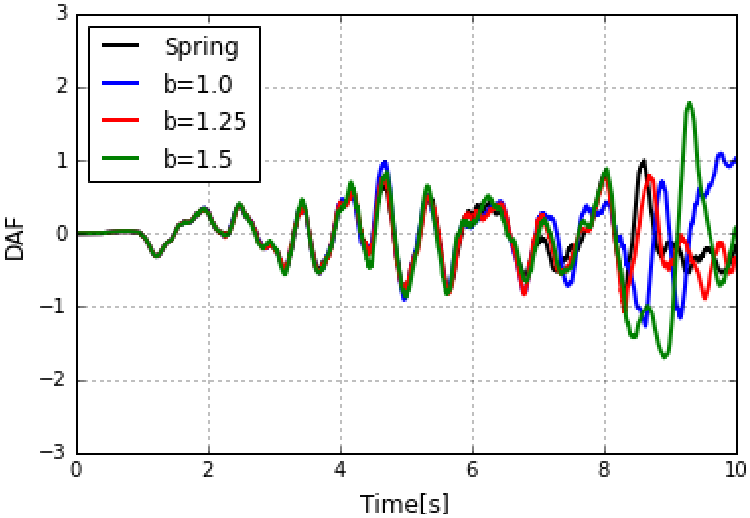


- To mimic more realistic excitation, response of whole core simulation of seismic event is used (From BASILIQ$^{CAST3M}$ a CEA code)
- Uses dynamics of fuel rods, RCS, and core
- Based on realistic seismic spectrum to get deflection of LS



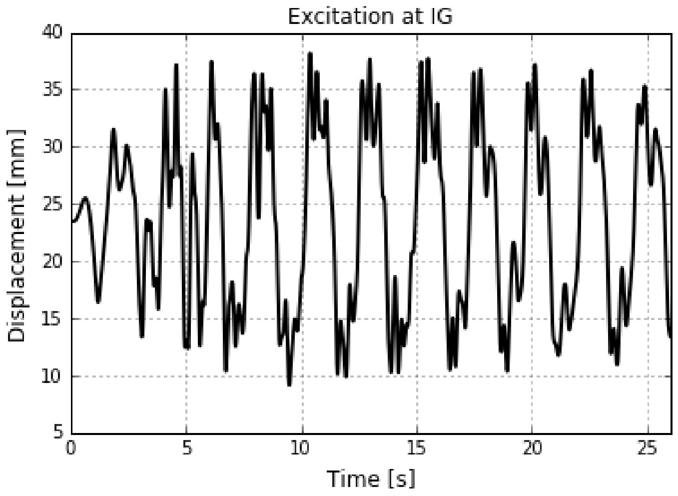



- For short-time (<8 seconds), little variability
- In general for this excitation only focused on short-time
  - Reactor is not expected to restart after this level of earthquake
- Within short-time, |DAF|<1 suggesting that static estimate might be conservative

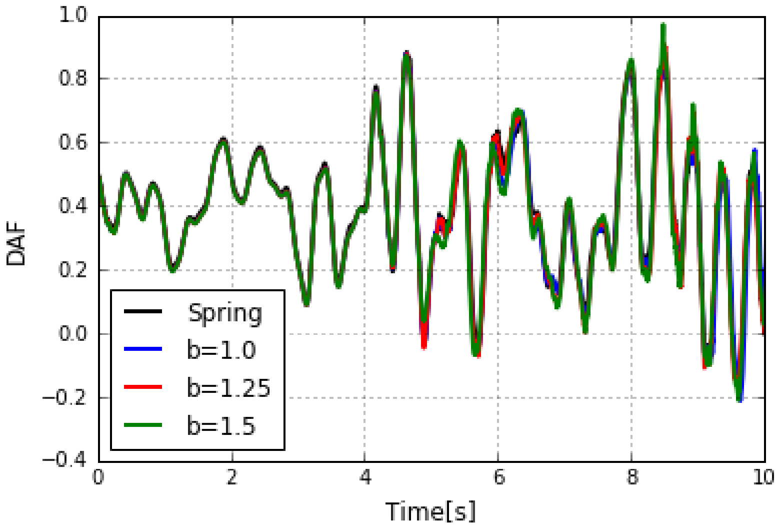


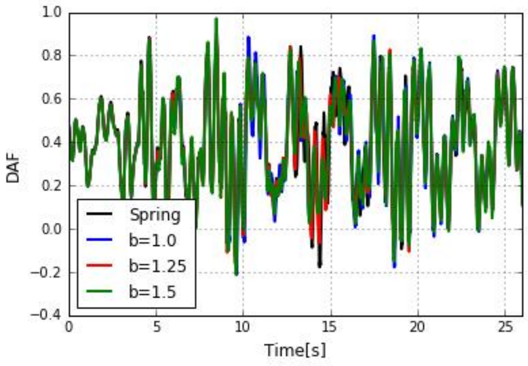
# Realistic Excitation – Dynamic Excitation on Statically Deformed System

- In actuality, the deformation is comprised of several components, some static and some dynamic
- Static contributions:
  - Installation misalignment
  - Fabrication uncertainty
  - Irradiation
- Dynamic contributions:
  - Primarily seismic activity
- To simulate this, apply dynamic excitation to statically deformed system
- Nearly same maximum deformation



- Almost no variability in short time (<10 seconds)
- Largest DAF <1
- Some instances where IG is positive (at all times) and UG is negative
  - Induces large shear forces that hinder the safety function of RCS



# Conclusions

- CEA is developing tools to study Reactivity Control Systems that consist of multiple sub-systems
- One of the most difficult aspects is the interaction between sub-systems
- For the dynamic tool DEBSE, 2 candidate contact models are compared
  - 2-stage spring, L&N contact model (with various exponential values)
- Both are implemented and can produce similar results
- Differences were noticed for both higher frequency (especially resonance range) sine excitation and parts of more realistic excitation
- Large dynamic excitations shows variability in contact models
- But for the scope of early design phase/excitations of interest, current modeling is sufficient
  - Just needs experimental validation

# Thank you for your attention

- Tonight at 6pm, Early Career Researcher Social
- At Valhalla Bar [6100 Main St, Houston, TX 77005]
  - Next to Engineering Building
- Meet other early career researchers (Grad-students, post-docs, entry professors/lecturers, etc.)
- Drinks & Food provided
  - Torchy's Tacos for food and Valhalla for drinks

FREE!!!

Come hang out!

# Extra-Slides

$$\Delta_i^b = \left(\frac{p_r + |p_r|}{2}\right)^b - \left(\frac{|p_l| - p_l}{2}\right)^b = \begin{cases} + & Contact\ on\ Right \\ - & Contact\ on\ Left \\ 0 & No\ Contact \end{cases}$$

- $p_r > 0$ for contact on Right, and $p_l < 0$ for contact on Left
- Depends on US or LS
- For LS:

$$p_r = \phi_0(t)D_0(x_k) + \phi_L(t)D_L(x_k) + \sum^{N} \psi_n(x_k)q_n(t) - V_k(t) - \left(R_{LS}(x_k) - R_{MP}(x_k)\right)$$

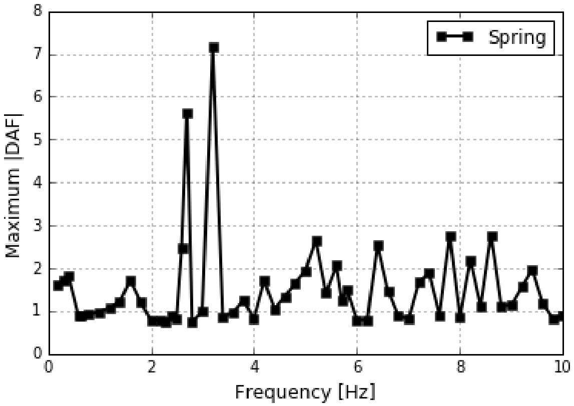
$$p_l = \phi_0(t)D_0(x_k) + \phi_L(t)D_L(x_k) + \sum^{N} \psi_n(x_k)q_n(t) - V_k(t) + \left(R_{LS}(x_k) - R_{MP}(x_k)\right)$$

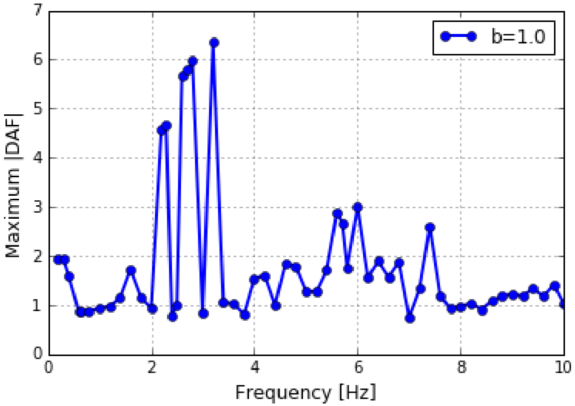
- For US:

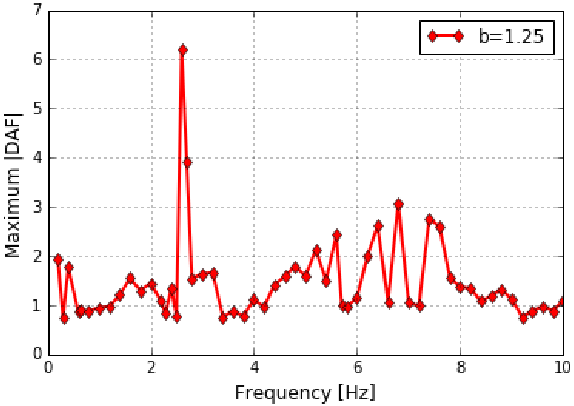
$$p_r = \phi_0(t)D_0(x_m) + \phi_L(t)D_L(x_m) + \sum^{N} \psi_n(x_m)q_n(t) - \sum^{\Gamma} \Psi_\gamma(z_m)Q_\gamma(t) - \left(R_{US}(z_m) - R_{MP}(x_m)\right)$$

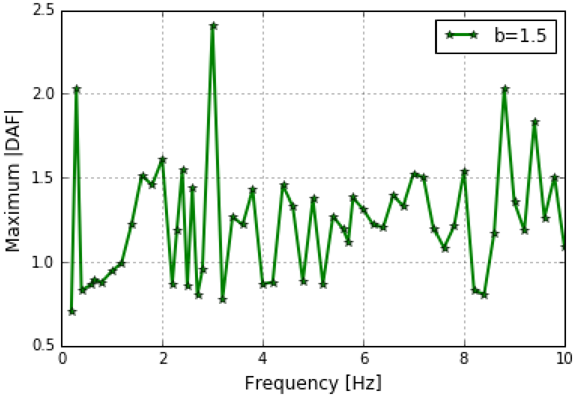
$$p_l = \phi_0(t)D_0(x_m) + \phi_L(t)D_L(x_m) + \sum^{N} \psi_n(x_m)q_n(t) - \sum^{\Gamma} \Psi_\gamma(z_m)Q_\gamma(t) + \left(R_{US}(z_m) - R_{MP}(x_m)\right)$$

# Extra Slide – Stepped-Sine DAF



# Extra Slide – Separate Time Histories