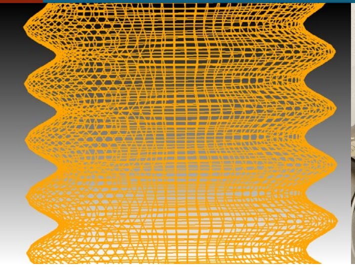
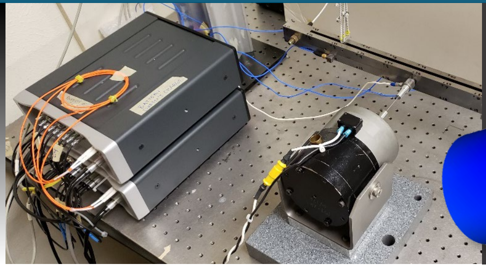
N-O-MAD Research Institute

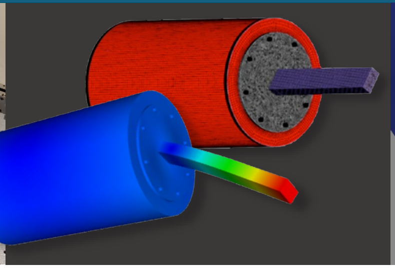
Sandia National Laboratories

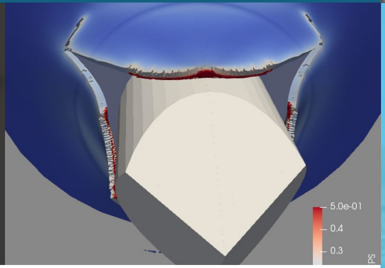
THE UNIVERSITY OF NEW MEXICO

Investigating the Potential of Electrical Connection Chatter Induced by Structural Dynamics









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Agenda

Project Motivation

Summary of Previous Work

Goals for NOMAD 2021

Reality Check for NOMAD 2021

Pin-Receptacle Modelling

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Project Motivation

All modern systems rely on electrical components to function as designed.

Therefore, it is critical to ensure that electrical connections are **reliable** and **maintain electrical continuity** in **all operating environments**.

Under sufficiently large vibrations, the **resistance** between two components may rise such that **electrical signals can no longer be transferred.** This phenomenon is called **electrical chatter**.

Chatter is extremely **application specific** and it is defined differently depending on the system. A typical definition for chatter is when resistance exceeds 125 Ω for more than 25 ns.

Chatter is a complicated phenomenon whose root causes are **not well understood** and which spans **several engineering disciplines**.

Goal: Investigate the influences of structural dynamics on electrical chatter and develop/validate a reduced order model to accurately simulate chatter events.

Chatter is Complicated!

Several Engineering Disciplines

- Structural Dynamics
- Contact Mechanics
- Tribology
- Electrostatics

+

Wide Time Scale Range

- Short Duration Chatter Events (ns)
- Extended Duration Vibration Environments (s)

+

Wide Length Scale Range

- Surface Features (μm)
- Structural Length Scale (m)

= Chatter

Previous Work

NOMAD 2019:

- Designed a test bed to measure electrical chatter
- Complicated test fixture which did not fully allow chatter to be isolated

Ben Zastrow et al. (1556):

- Developed and simulated a high-fidelity pin-receptacle in SIERRA/SM
- Simulation duration: **1-3 ms**
- Runtime on HPC's: **4 days**

Takeaway 1: A test fixture which does not influence the pin-receptacle structure is needed.

Takeaway 2: Although the high-fidelity model is powerful, it is too expensive to run. A simpler model which preserves accuracy is needed.

Goals for NOMAD 2021

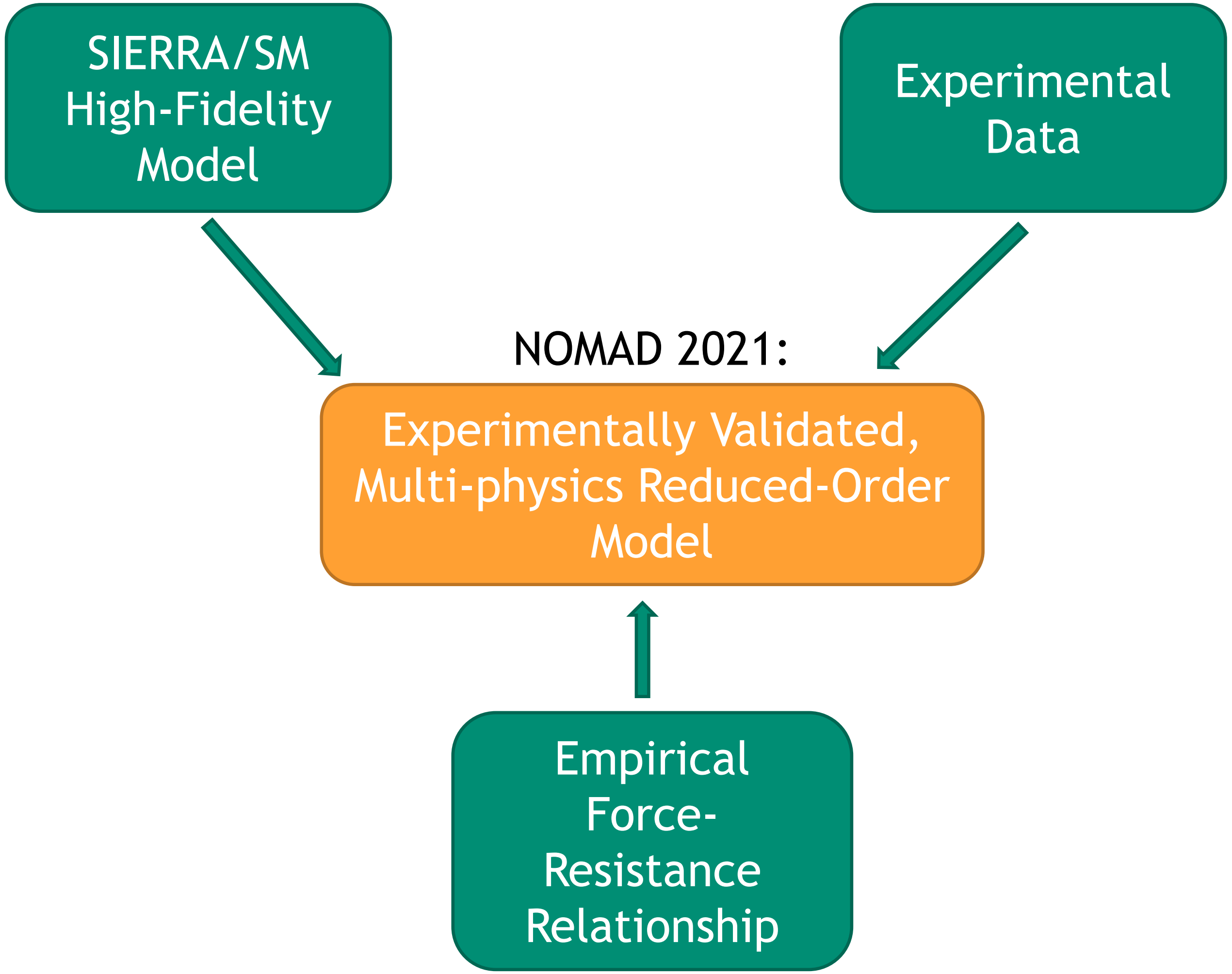
Use a new test fixture design to excite a pin and receptacle, try to induce chatter.

- Modal hammer tests
- Shaker random vibration tests

Develop a Hurty/Craig-Bampton reduced-order model which can accurately simulate chatter events

- Validate the model against B. Zastrow's SM simulations and experimental data
- Test different contact formulations in the reduced-order model
- Significantly reduced computational cost

Determine an empirical relationship between contact force and electrical resistance with AFM measurements and incorporate this into the reduced-order model



Reality Check for NOMAD 2021

Challenges associated with experimental setup – no data available.

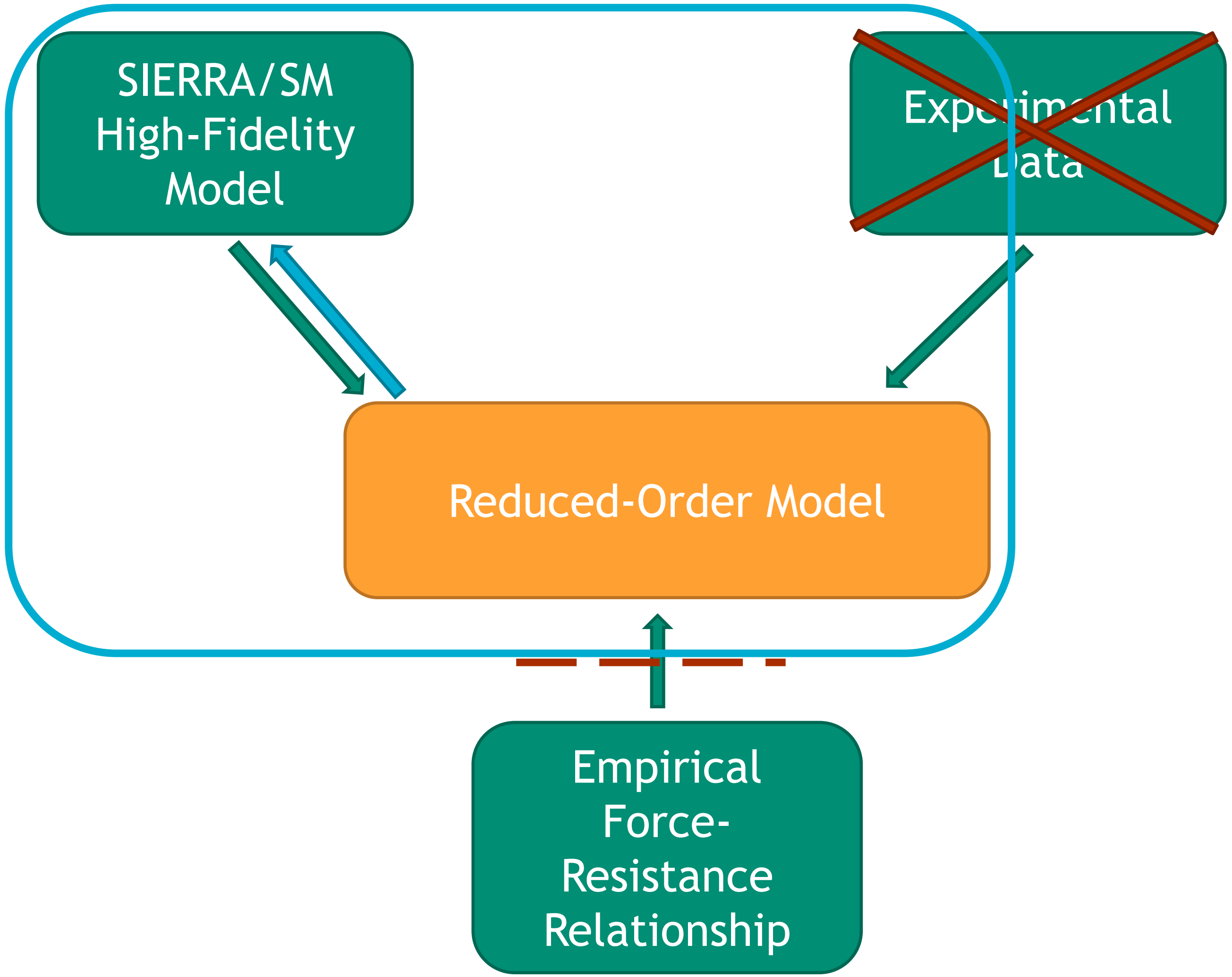
- Resulted in a pivot to computational analysis only

Developed a Hurty/Craig-Bampton reduced-order model which can accurately simulate chatter events

- Validated the model against B. Zastrow's SM simulations
- Tested different contact formulations in the reduced-order model

Determined an empirical relationship between contact force and electrical resistance with AFM measurements, but did **not** incorporate this into the reduced-order model

Focus of NOMAD 2021:



Developing a Reduced Order Model for the Pin-Receptacle

Pin-Receptacle Reduced Order Model

<u>Goal: Develop a model which can be solved much faster while maintaining physical accuracy as much as possible.</u>

Approach: Use the Hurty/Craig-Bampton reduction method, whose code is built into SIERRA/SD.

Basic Idea: Divide model into interface set and fixed-interface mode shapes.

$$\boldsymbol{u} \rightarrow \begin{Bmatrix} \boldsymbol{u}_{\text{interface}} \\ \boldsymbol{u}_{\text{leftover}} \end{Bmatrix} = \boldsymbol{\Phi}_{CB} \begin{Bmatrix} \boldsymbol{u}_{\text{interface}} \\ \underbrace{\boldsymbol{q}}_{\substack{\text{fixed-interface} \\ \text{mode shapes}}} \end{Bmatrix}$$

Can specify BC's at the interface nodes as required

Significantly reduce size of model

Number of interface mode shapes is arbitrary, depending on quantities of interest in analysis

Pin-Receptacle Reduced Order Model

SIERRA/**SD** used to perform reduction. Outputs are the system mass and stiffness matrices.

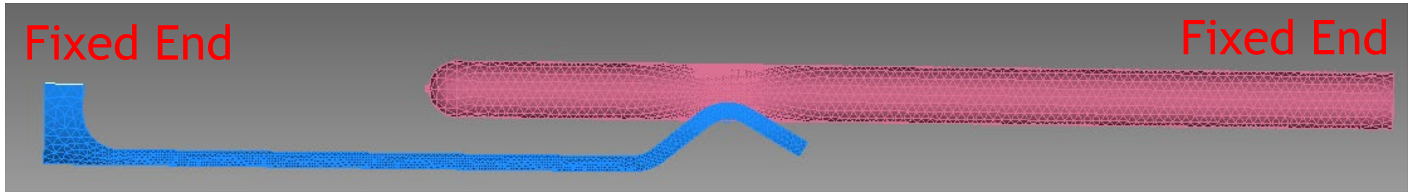
After reduction, the system is propagated in time using MATLAB and a Newmark-Beta ODE solver

But, developing a reduced-order model is not as simple as typing "cbr" in the input file…

Critical questions for any reduced model:

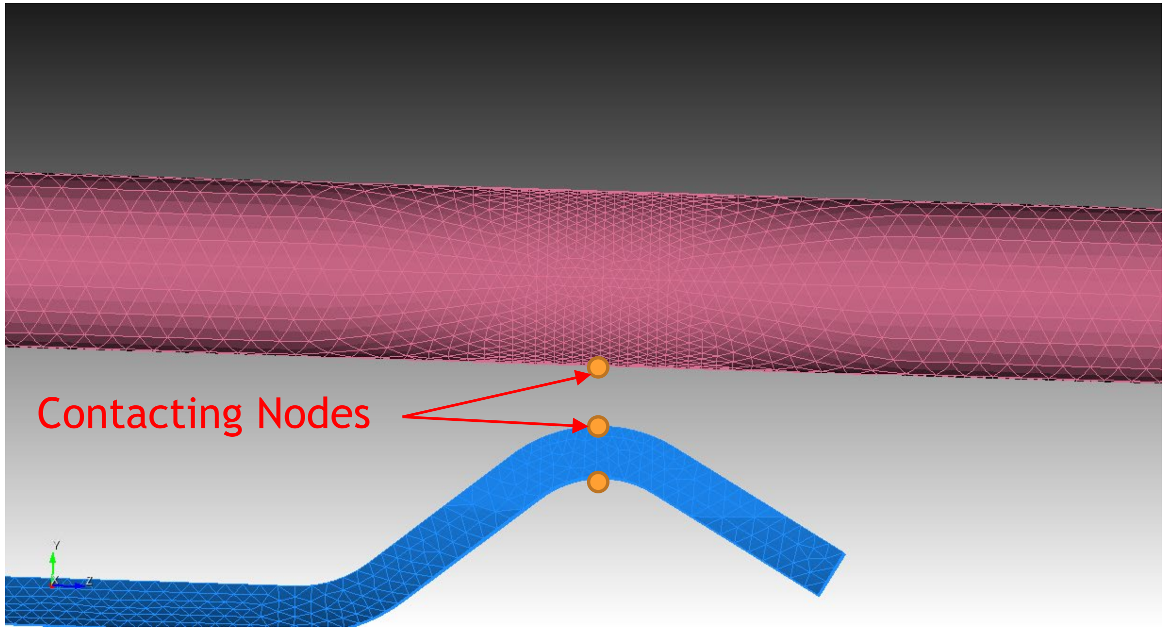
1. How many **modes** do we need to include?
2. Which nodes should be placed in the **interface set**?
3. How do we model the **contact interaction** between the pin and receptacle?
4. What are the relevant **boundary conditions**?

Pin-Receptacle Reduced Order Model



Modes:
- First 20 modes of the structure are used

Interface Set:
- Seven nodes in the interface set, four are subjected to BC's, leaving three nodes (9 DOF)
- Physical significance of three interface nodes:
  - One node on the inner surface of the receptacle arm
  - One node on the outer surface of the pin
  - One node on the outer surface of the receptacle arm



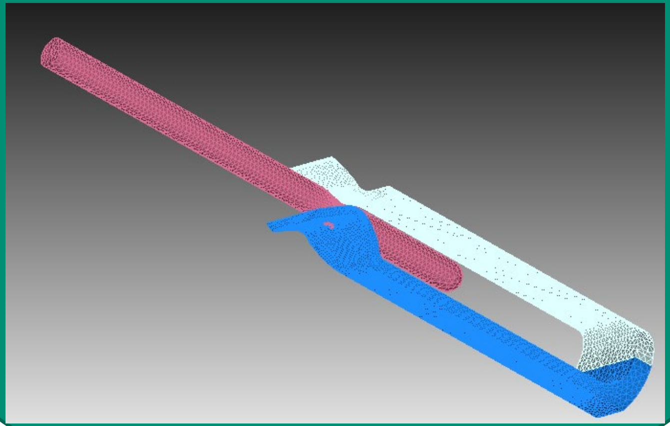
Boundary Conditions:
- Fixed at the ends of the structure

Contact Formulation
- Initially a linear penalty spring
- More to come…

Pin-Receptacle Reduced Order Model

SIERRA/SM High-Fidelity Model:

215,773 Elements
Time to simulate: 4 days



Reduces to:

MATLAB CB Model:

Number of Modes: 20
Number of Interface Nodes: 7

Total System Size: 29 x 29

$$M_{CB} = \begin{bmatrix} \cdots & \cdots \\ \cdots & \cdots \end{bmatrix};\ K_{CB} = \begin{bmatrix} \cdots & \cdots \\ \cdots & \cdots \end{bmatrix}$$

Time to generate reduced matrices: 5 min
Time to simulate: 25 min

We go from 4 days on the HPC to 30 min on a basic workstation…**230x** reduction in computing time!

Contact Model Fitting

Goal: To most accurately model the contact force interaction between the pin and receptacle.

Approach: Using SM data, fit an expression for contact force, $F_c(x) = F_c(x)(1 - H(x))$ where x denotes the gap distance between nodes in contact and $H(x)$ is the Heaviside step function.

Several candidate forms for the contact interaction:

Linear: $F_c = Kx$

Polynomial: $F_c = K_0 + K_1 x + K_2 x^2 + \ldots + K_n x^n$

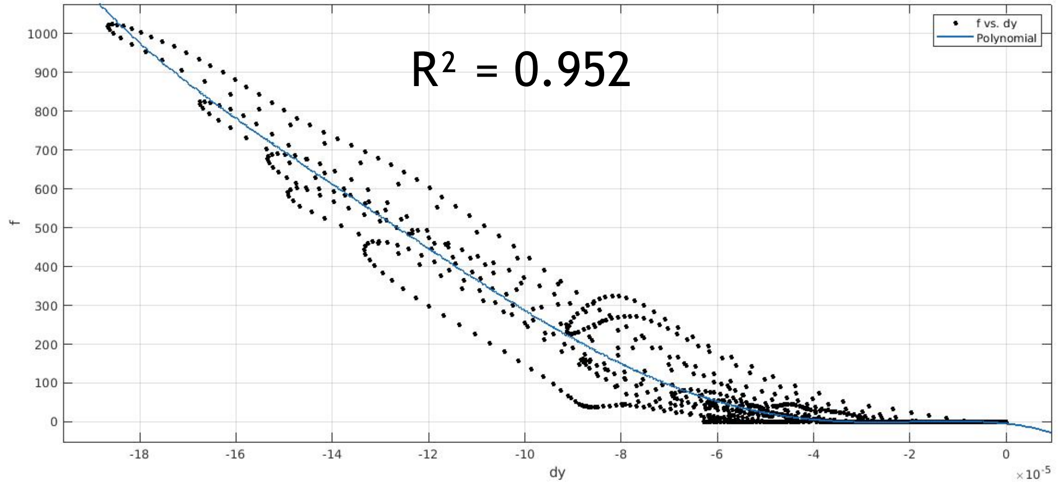
Rational:
$$F_c = \frac{a_n x^n + a_{n-1} x^{n-1} + \ldots + a_2 x^2 + a_1 x + a_0}{b_m x^m + b_{m-1} x^{m-1} + \ldots + b_2 x^2 + b_1 x + b_0}$$

Piecewise Linear:
$$F_c = \begin{cases} m_1 x + b_1 & x < a \\ m_2 x + b_2 & x \geq a \end{cases}$$

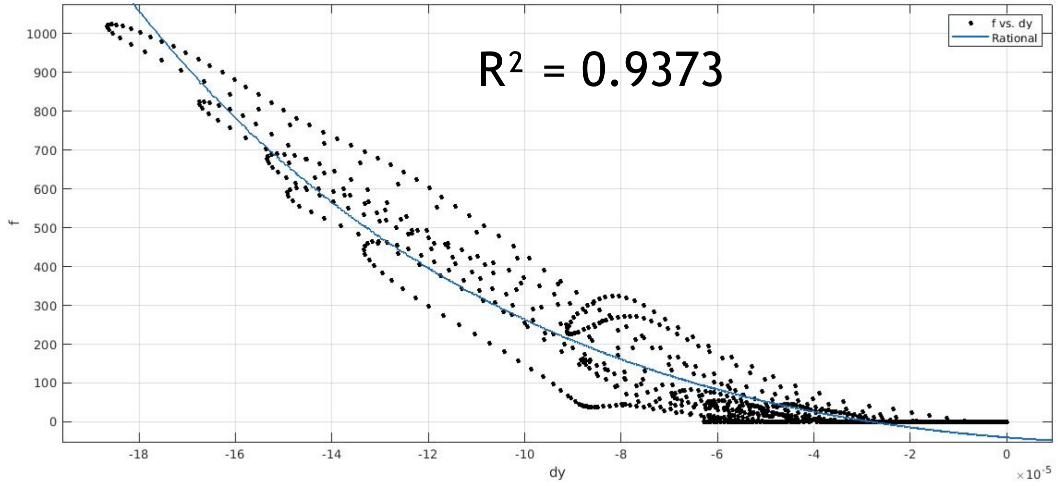
Exponential: $F_c = ax\exp(bx)$

Contact Model Fitting

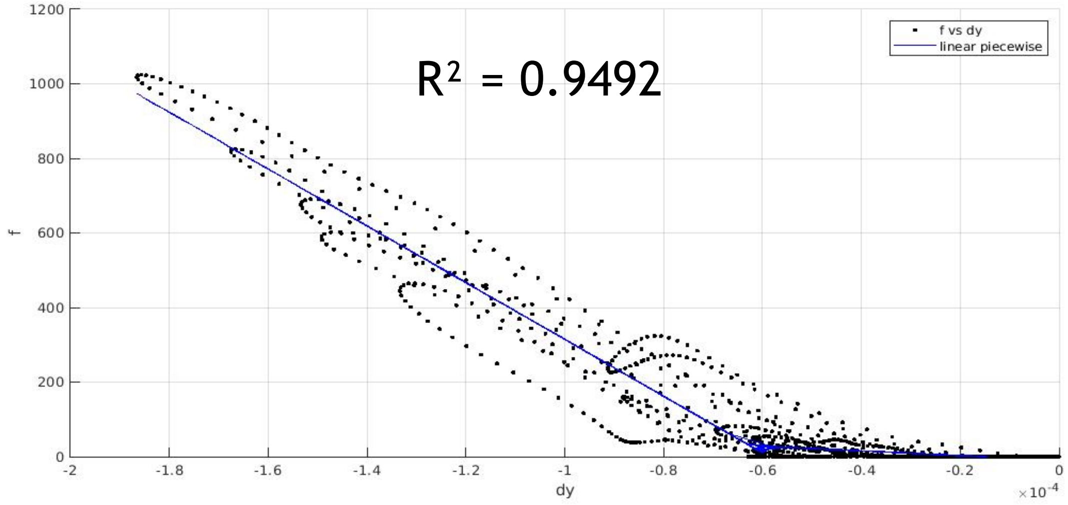
Polynomial:



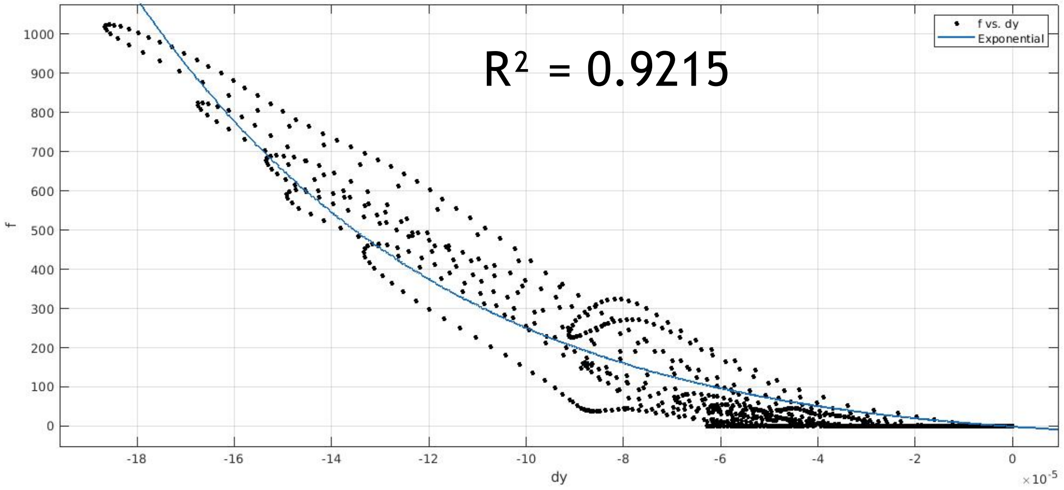
Rational:



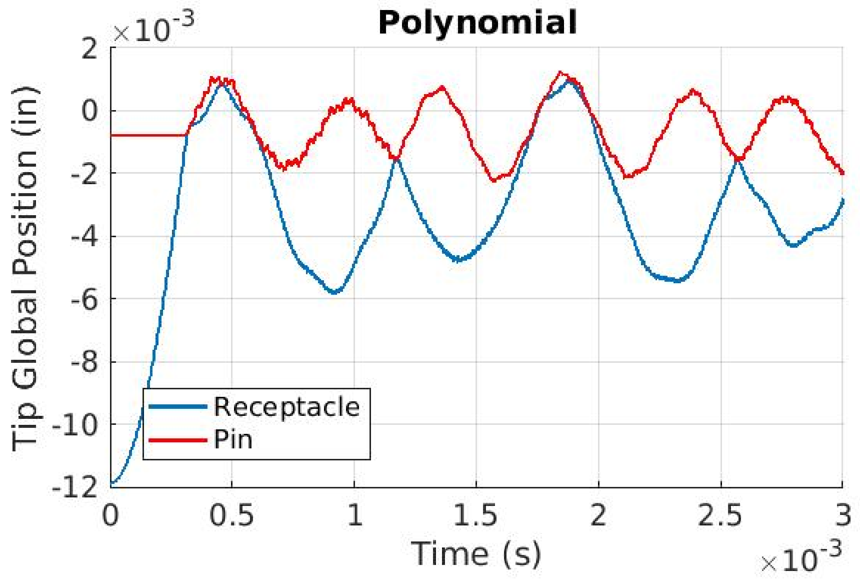
Piecewise Linear:

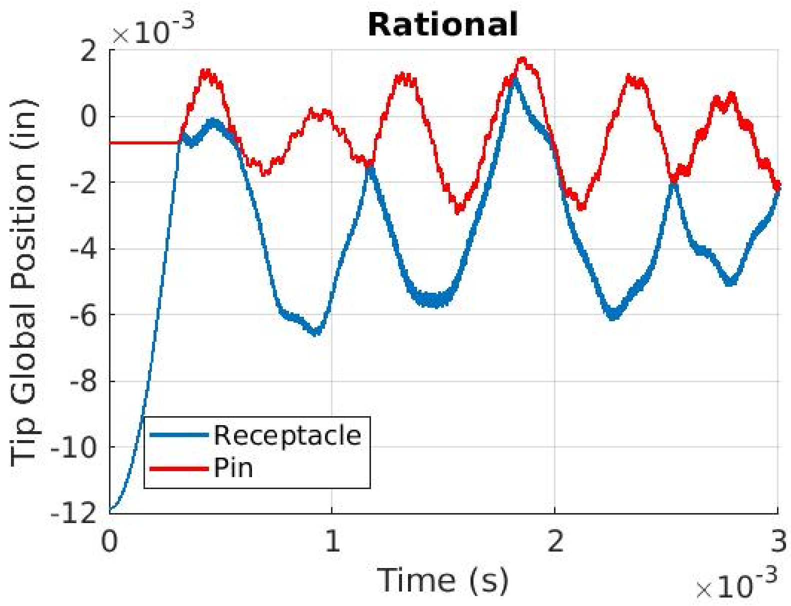


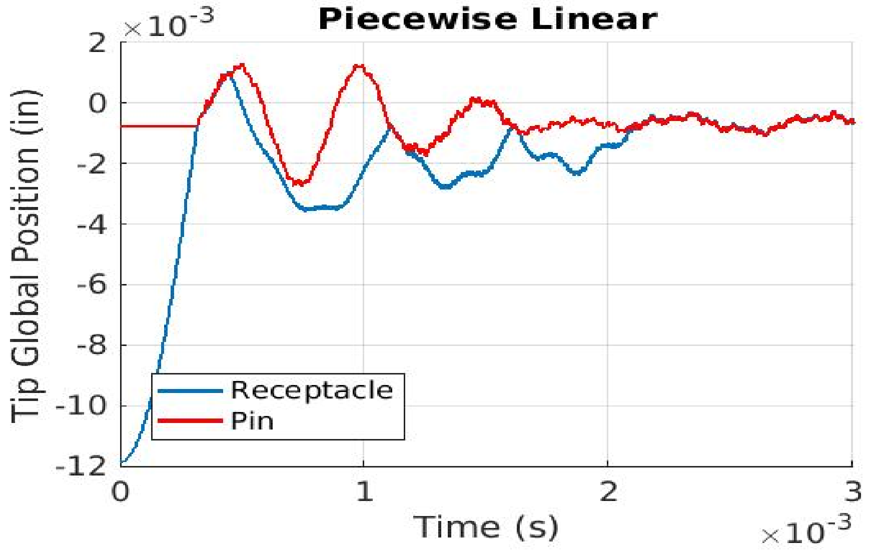
Exponential:

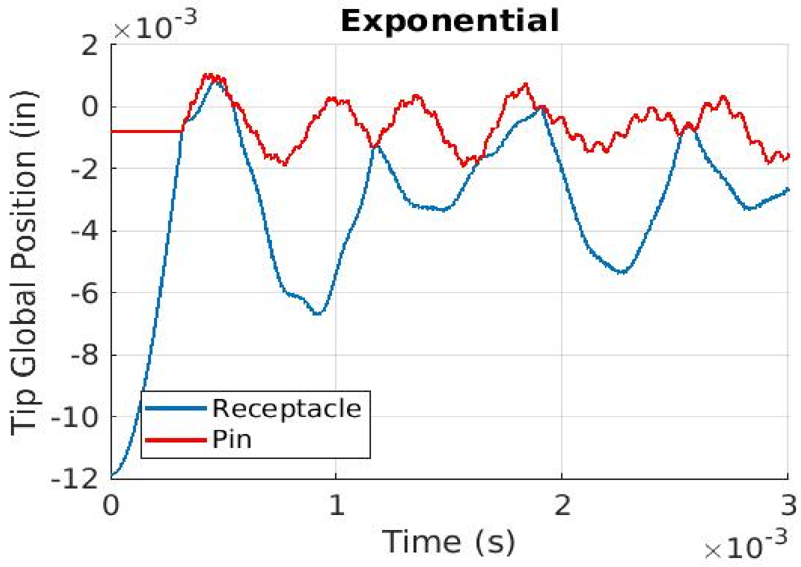


Contact Model Fitting



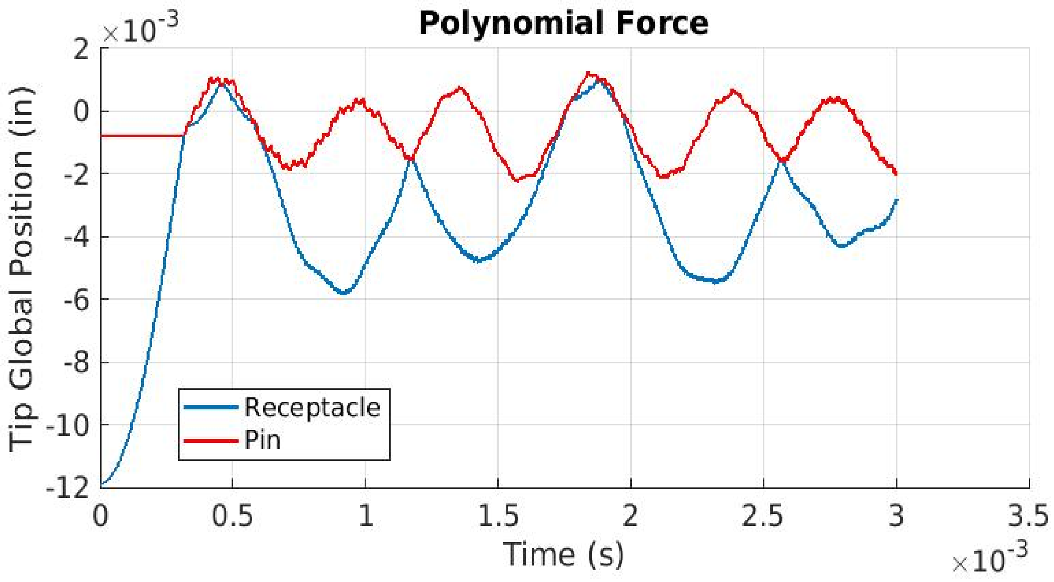


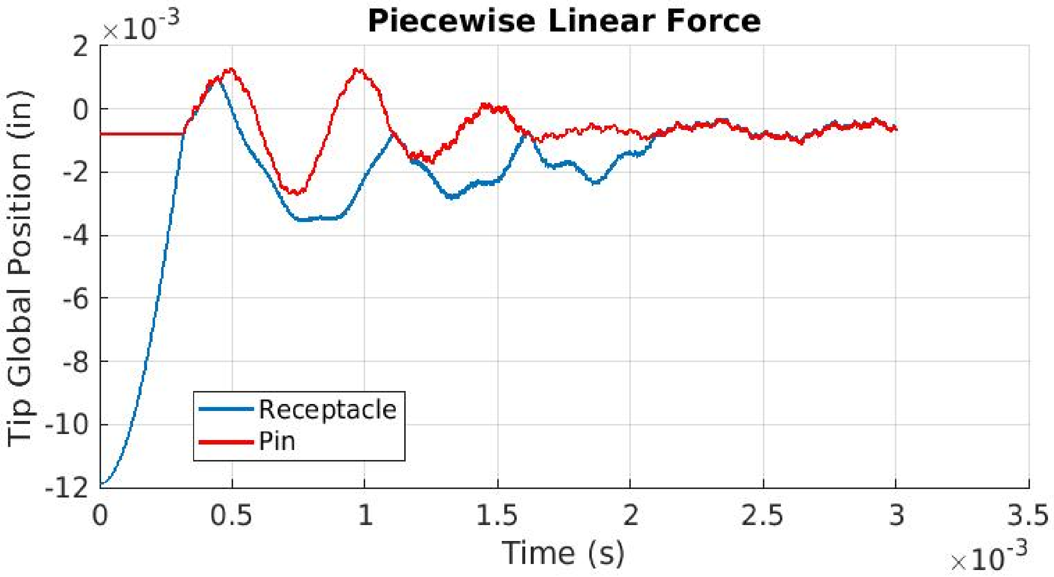


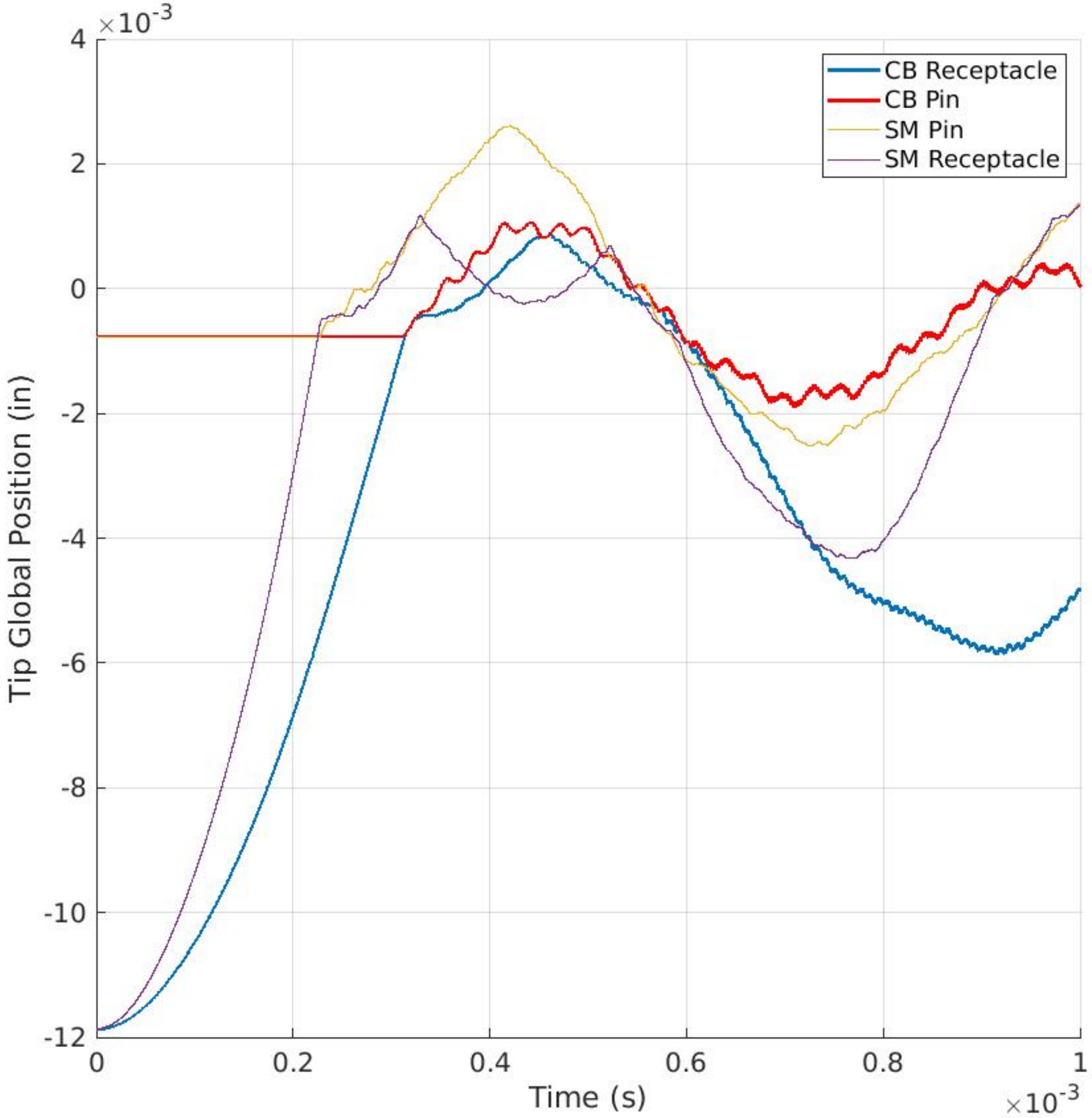


Validating the Reduced Order Model Against the High-Fidelity Model

Time Histories







Measuring an Empirical Relationship between Contact Force and Electrical Resistance

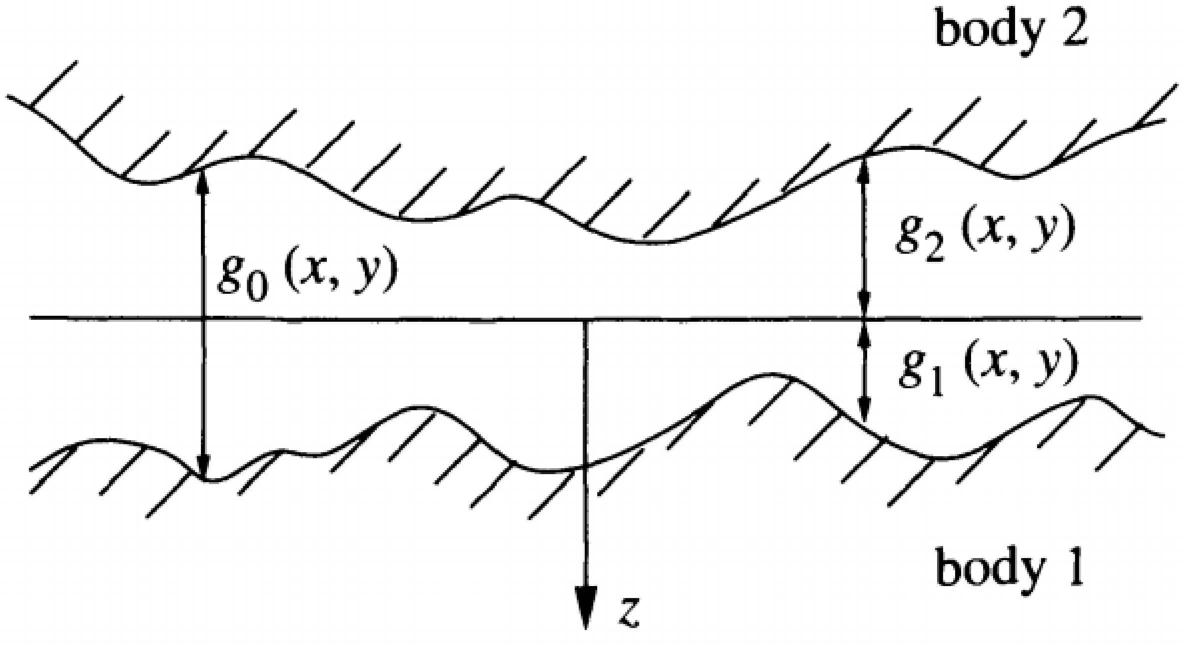
Atomic Force Microscope and Optical Profiler Measurements

Goal: To measure surface features of the pin and receptacle and develop an empirical relationship between contact force and electrical resistance.

$$R_e = \frac{(V_2 - V_1)}{I} = \frac{(\rho_1 + \rho_2)}{Q}$$

$$\frac{dF}{dw} = MQ$$

$$C \equiv \frac{1}{R_e} = \frac{1}{M(\rho_1 + \rho_2)} \frac{dF}{dw}$$



R_e = Resistance, V = Voltage, I = Current, Q = Total Flux, $\frac{dF}{dw}$ = Incremental Stiffness, M = Composite Modulus, C = Conductivity

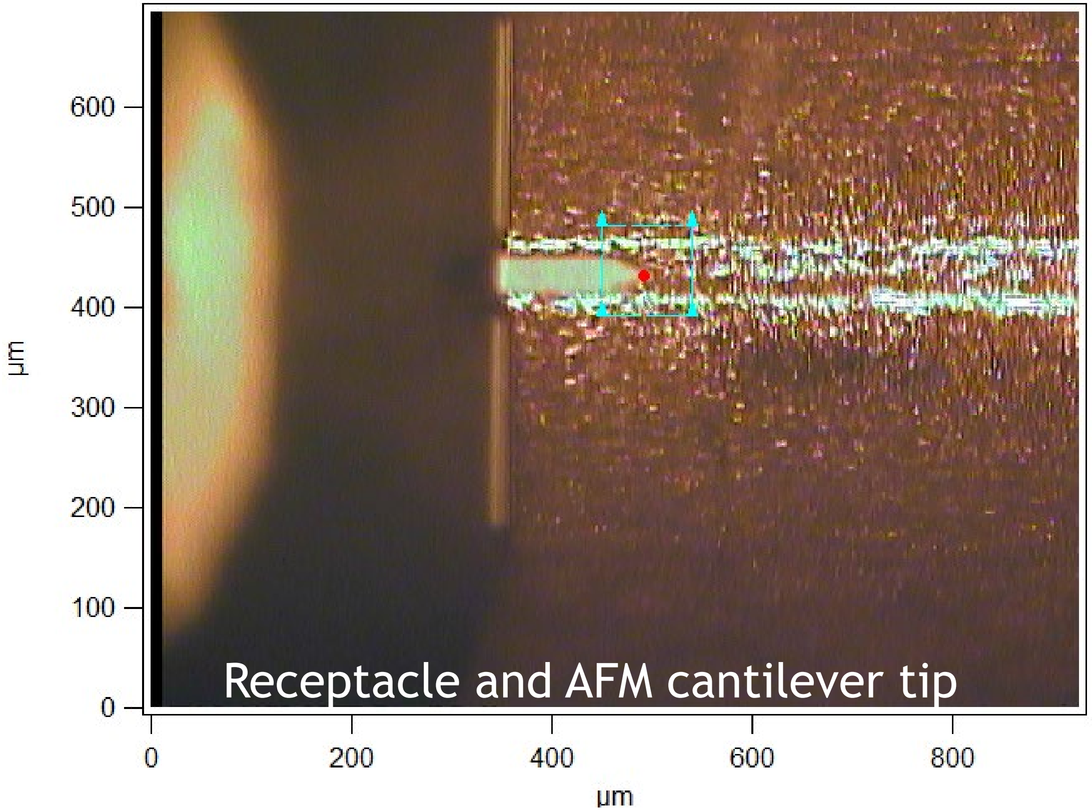
But these calculations require the knowledge of how many asperities share the applied load in a given contact occurrence. Therefore, the roughness of the surfaces need to be found.

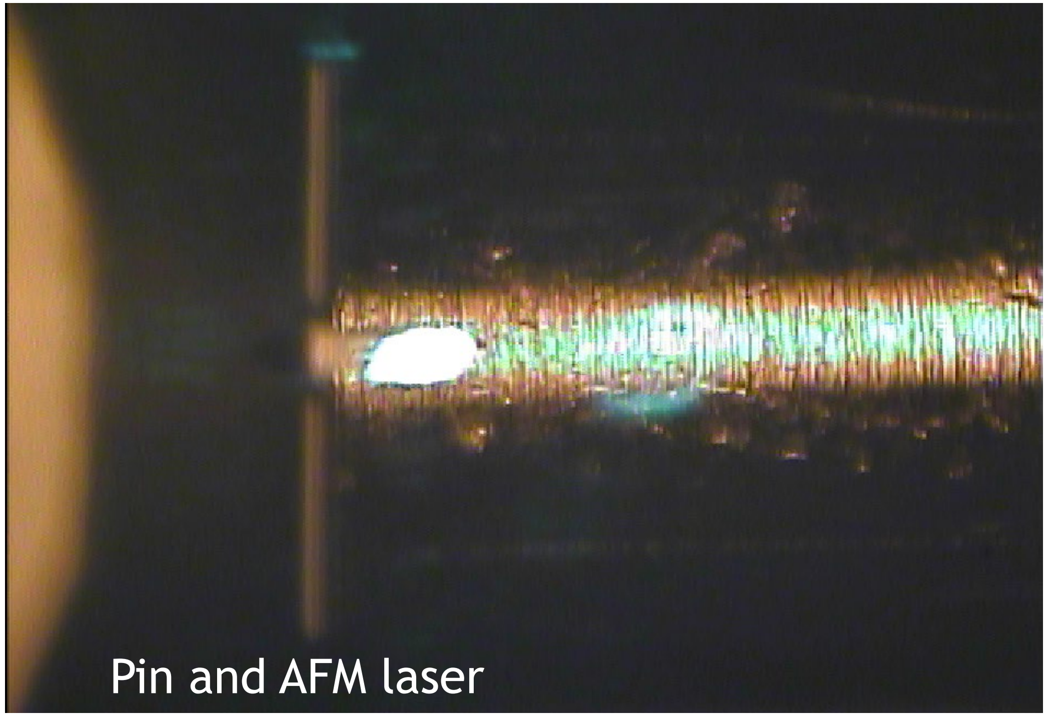
Barber, J. R. (2003). Bounds on the electrical resistance between contacting elastic rough bodies. Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 459(2029), 53–66. https://doi.org/10.1098/rspa.2002.1038

Atomic Force Microscope and Optical Profiler Measurements

Challenges:

Pin surface had rough machining marks from lathe, opted for profiler measurements instead





Additional Considerations: Oxidation, Temperature, Surface vs Bulk properties

Future Work

Additional tuning to get high fidelity and ROM to match better

- Time histories, frequency content

Use experimental data to validate both the high-fidelity and reduced-order models.

Incorporate AFM measurement data into a mutli-physics model which directly predicts electrical contact resistance.

Work to parallelize solvers for reduced-order model, enabling even faster computation time.

Perform the same analysis on different types of electrical connections.

Closing Remarks

Chatter is complicated!

- Extremely difficult to isolate all variables and unknowns in the process.

Successfully developed a versatile Craig-Bampton model for the pin-receptacle configuration

- Extremely short runtime relative to high-fidelity model.
- Same codes can be used to analyze different electrical component geometries and contact algorithms.

Questions remain on the best way to directly/indirectly compare various chatter simulation results.

Acknowledgements

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Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Additional Background Reading

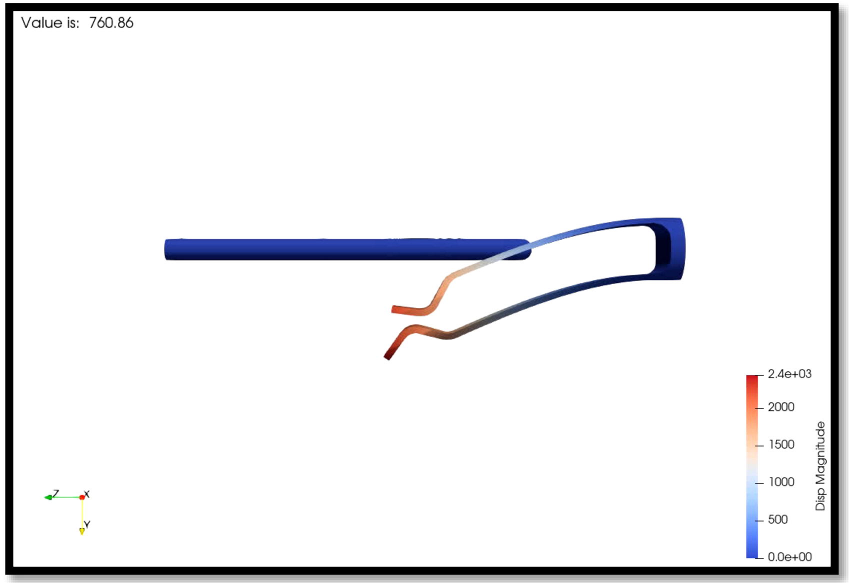
B. Johnson, C. Schumann, R. Fadi, R. Flicek, K. Johnson, K. Walczak, C. Medina, D. Quinn, B. Zastrow and R. Kuether, "Investigation of Electrical Contact Chatter in Pin-Receptacle Contacts," Sandia National Laboratories, Albuquerque, New Mexico, 2019.

E. Robbins, T. Schreiber, A.Malla, B. R. Pacini, R. J. Kuether, S. Manzato, D. R. Roettgen and F. Moreu, "Pre-test Predictions of Next-Level Assembly Using Calibrated Nonlinear Subcomponent Model," in *Proceedings of the International Modal Analysis Conference*, Virtual, 2021.

P. Logan and P.Avitabile, "Impact reconstruction Using Modal Filters," in *The 36th International Modal Analysis Conference*, Orlando, FL, 2018.

P. Avitabile, "Experimental modal analysis (A simple non-mathematical presentation)," [Online]. Available: http://faculty.uml.edu/pavitabile/downloads/S&V_Jan2001_modal_analysis_MACLpdf.pdf. [Accessed 31 March 2020].

No contact



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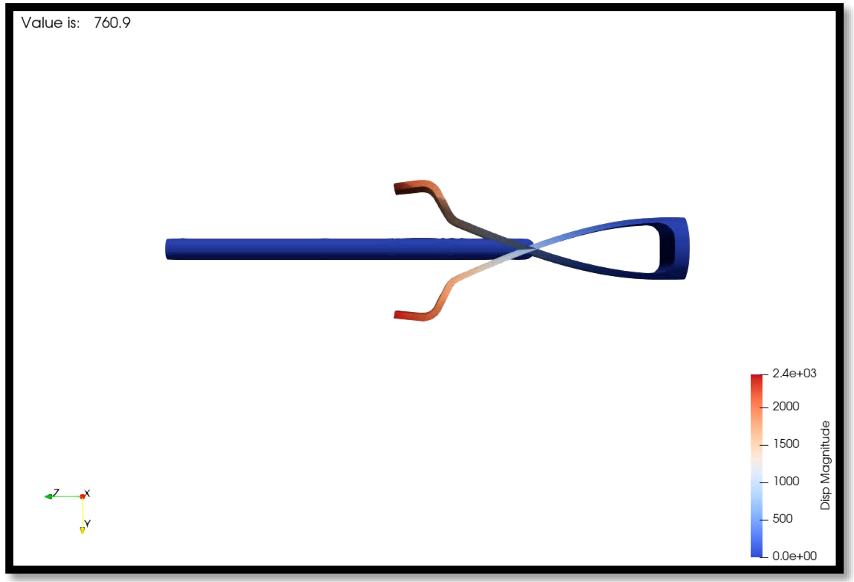

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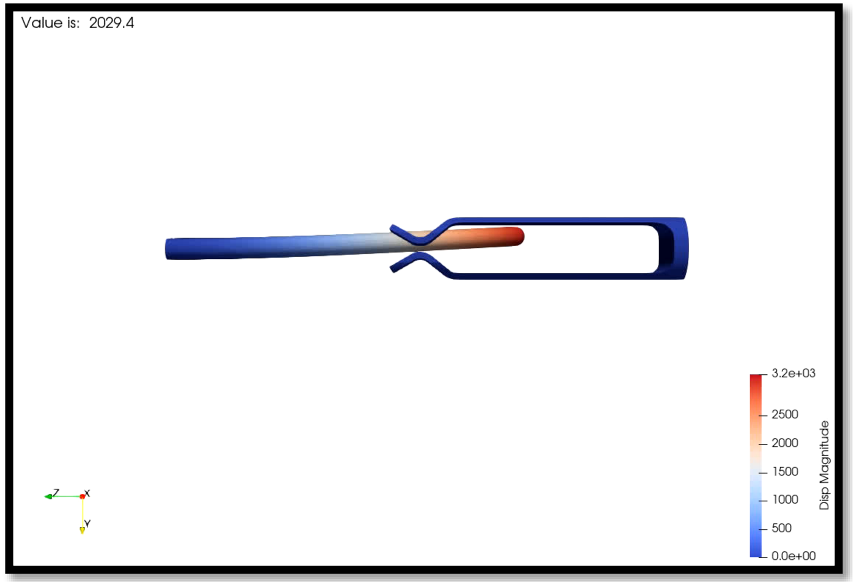

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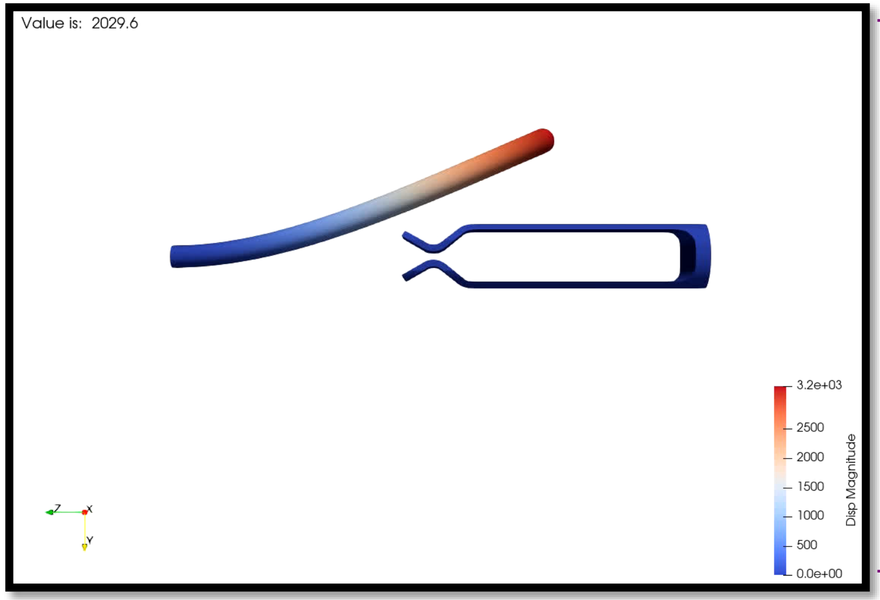
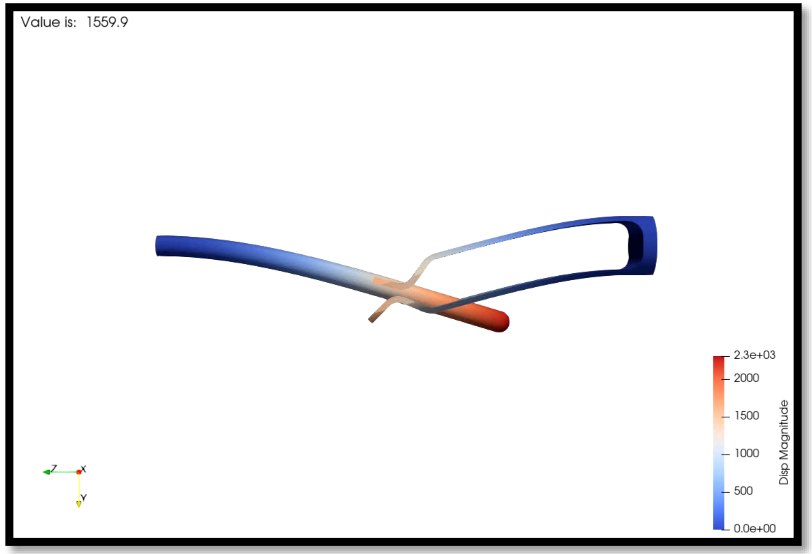


Mode 4

Full contact



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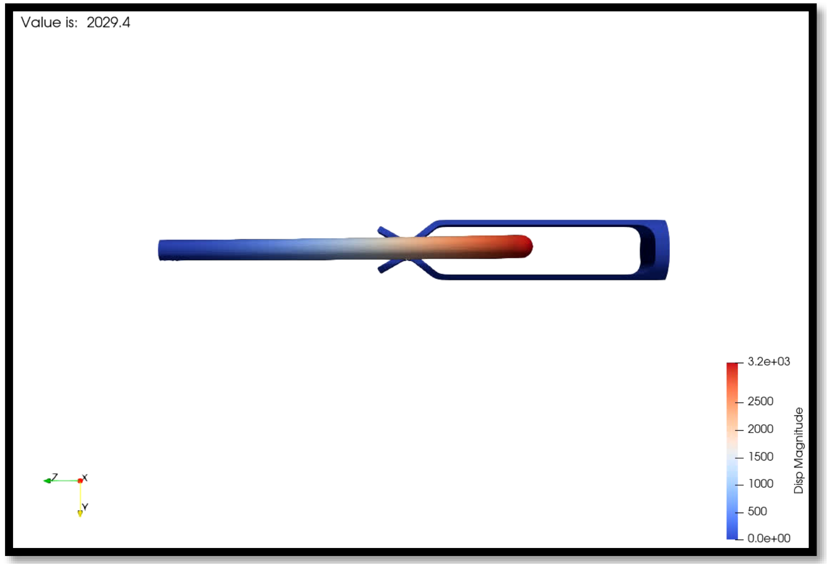

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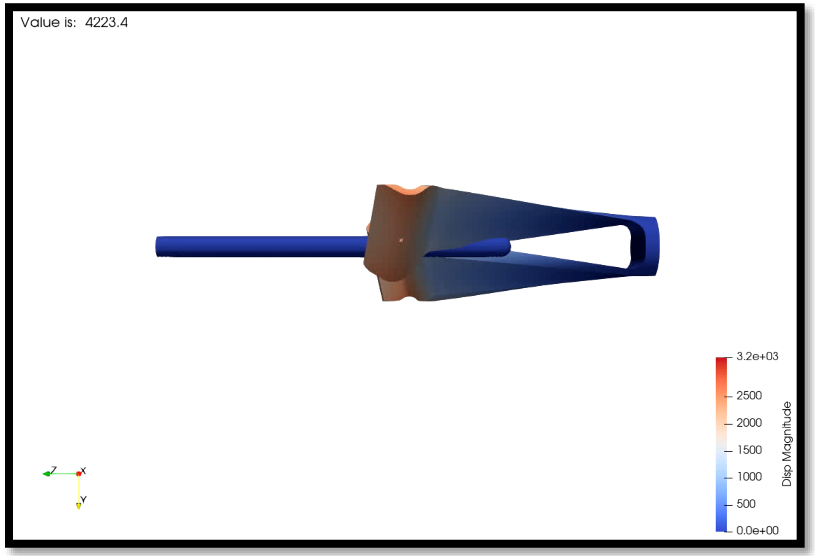

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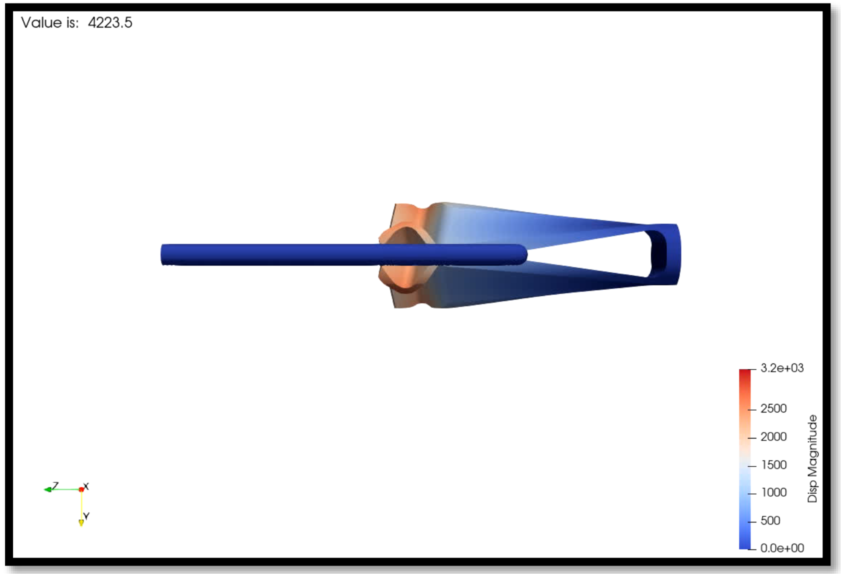
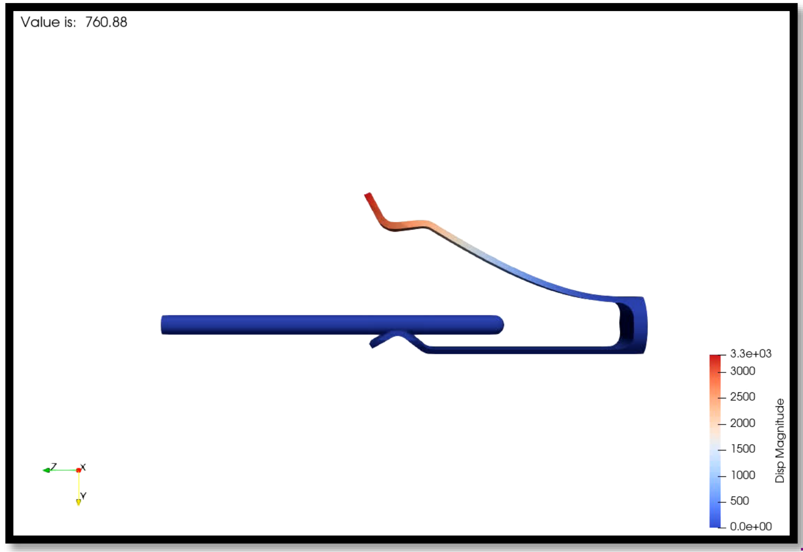
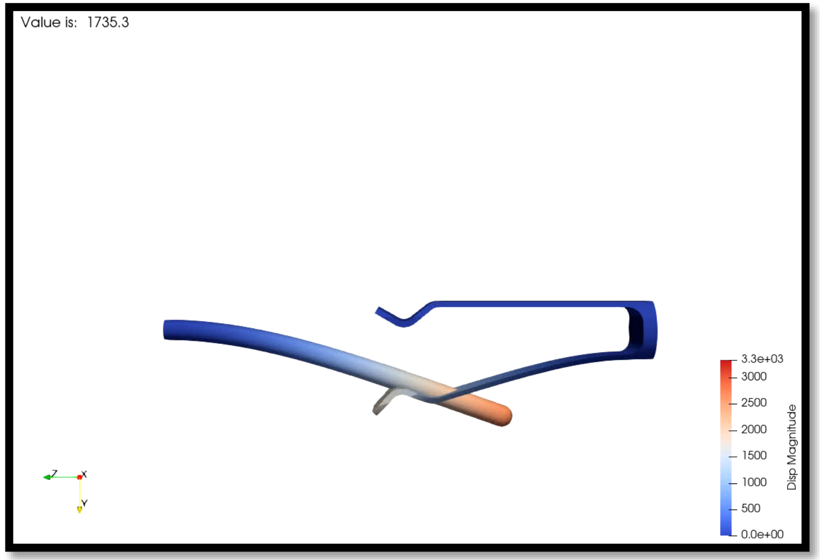


Mode 4

One arm contact



Mode 1



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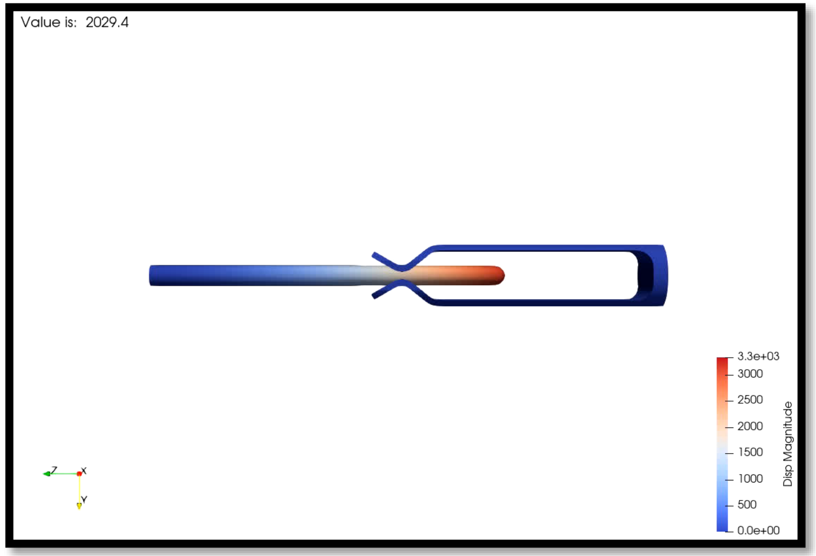

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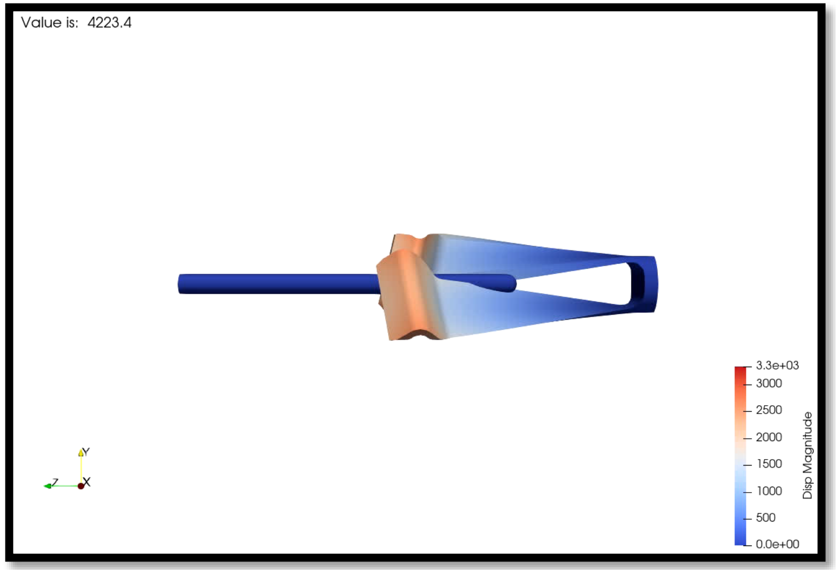
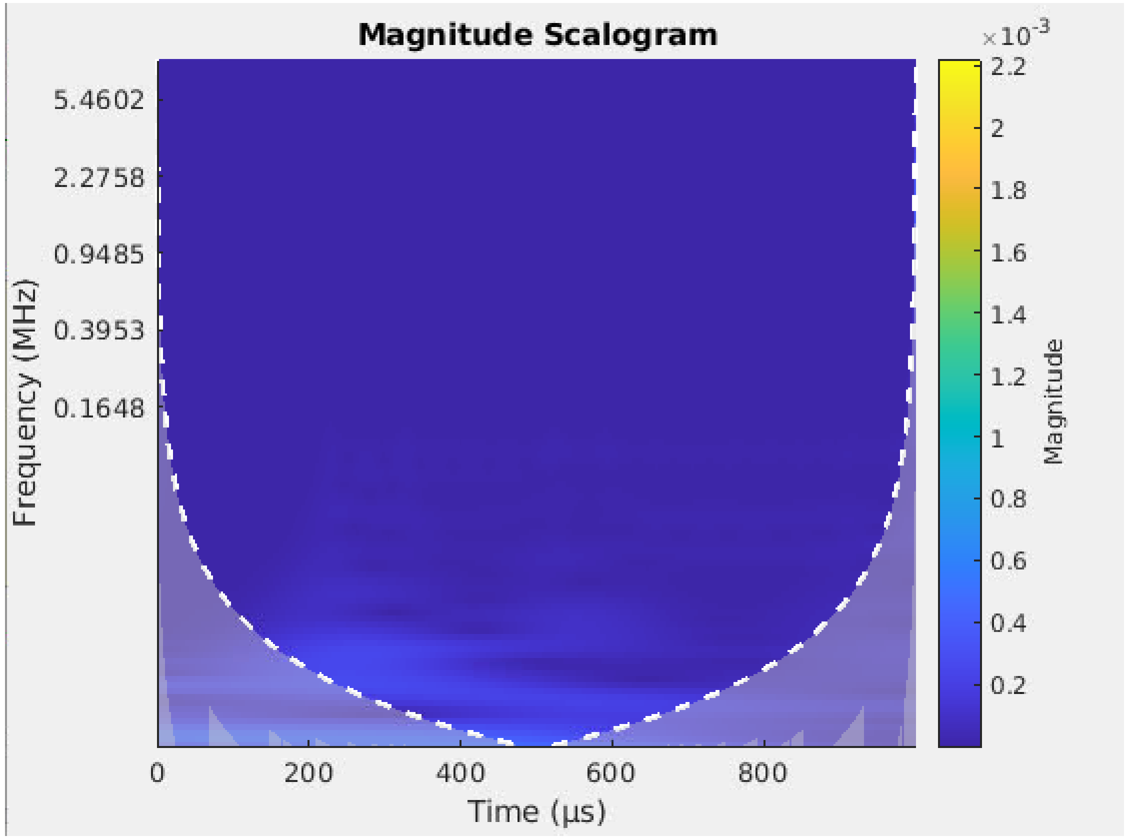


Mode 4

CB vs SM Wavelet transform

SM Model



CB Model