MECH.4230

Effect of Surface Friction on the Behavior of a Centrifugal Pendulum Vibration Absorber

An Analytical and Computational Investigation

Alina Berkowitz | Stefanie Evans | Sean Freeman | Nicholas McLaughlin

University of Massachusetts Lowell

CPVA Background

CPVA

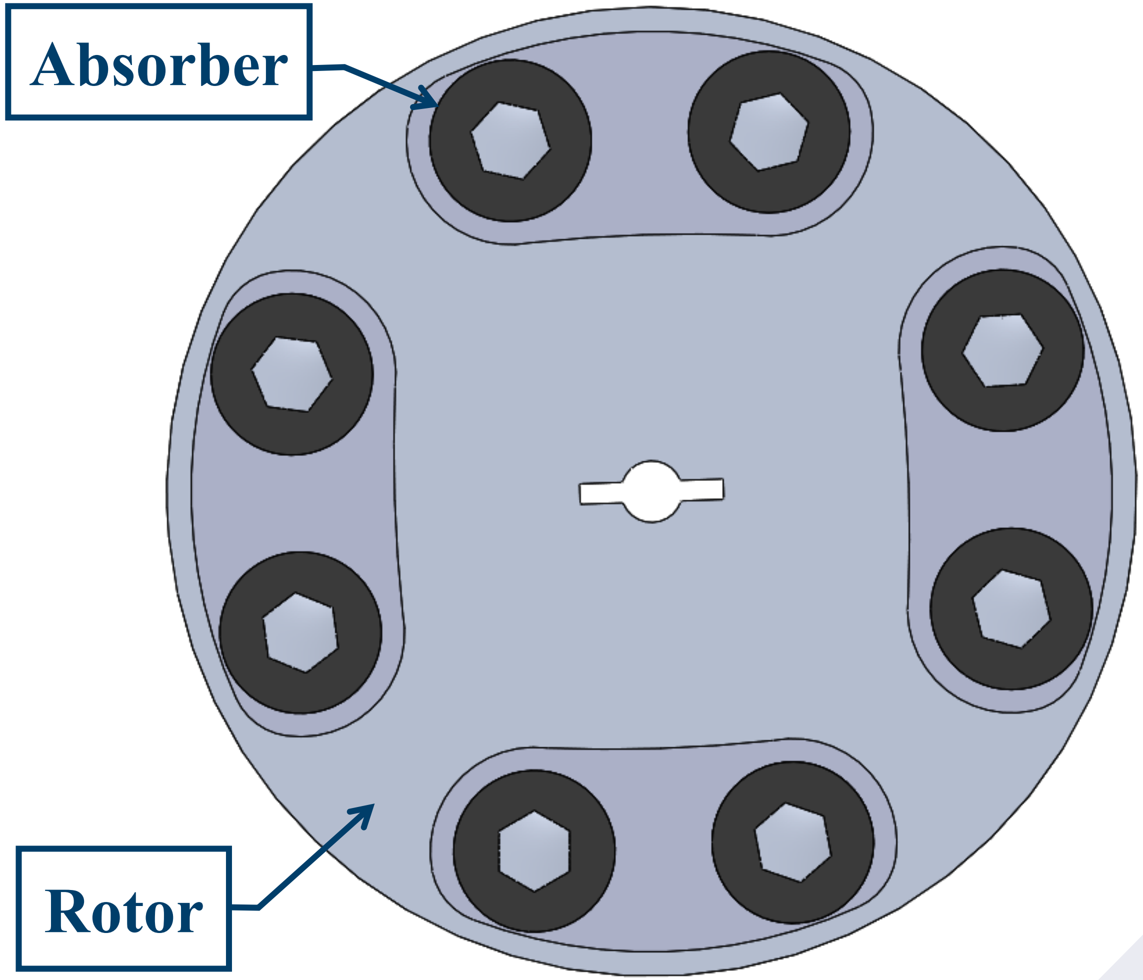
- Centrifugal Pendulum Vibration Absorber
- Used in automotive drive trains
  - Contributes to increased engine efficiency

Purpose

- To reduce vibrations in rotating machinery subject to periodic torque inputs

Mechanics

- Absorbers act as pendulums
  - However, restoring force comes form the centrifugal field
- Can reduce torsional vibrations at all rotor speeds
  - Complicated to tune properly



A. Jain, "Experimental Measurement of the Response of Centrifugal Pendulum Vibration Absorbers," University of Michigan, 2013.

Problem Statement

Design and manufacture a system to control friction that will be used to analyze the effects of friction on the CPVA's dynamics

The intention is to aid the development of understanding CPVAs and their mechanics

Primary Design Constraints

- Friction must be modifiable
- The absorber mass must stay the same
- Must fit within the existing assembly
- Produces consistent results across multiple trials
- Costs below $400

Current CPVA Configuration in the Structural Dynamics and Acoustics Systems Laboratory in Kitson Hall

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Post Project Gantt Chart

Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	***Phase***
	19-Jan	26-Jan	2-Feb	9-Feb	16-Feb	23-Feb	1-Mar	8-Mar	15-Mar	22-Mar	29-Mar	5-Apr	12-Apr	19-Apr	26-Apr	3-May	
Establish Requirements and Deliverables								SPRING BREAK									Preplanning and Organization
Project Proposal																	
Background Literature Review																	
Determine Best Mode to Generate Artifical Friction																	Design and Progress in Friction Test
Source Friction Test																	
Design Friction Test																	
Order and Manufacture Coupons																	
Sandblast																	
Sandblast Aluminum Coupons																	
Generate Probabalistic Surfaces in MATLAB																	Numerical Simulation of Coefficient of Friction
Simulate Contact Between Rough Surfaces to Obtain a Coefficient Of Friction																	
Design Systems to Modify the Clamping Force																	Design of System
Construct Decision Matrix and Decide on Best Design																	
Simulate Best Design																	
Write Capstone Report/ Prepare Presentation																	Final Report and Presentation
Final Capstone Report and Presentation Due																	
Present Project																	

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Problem Solving Approach

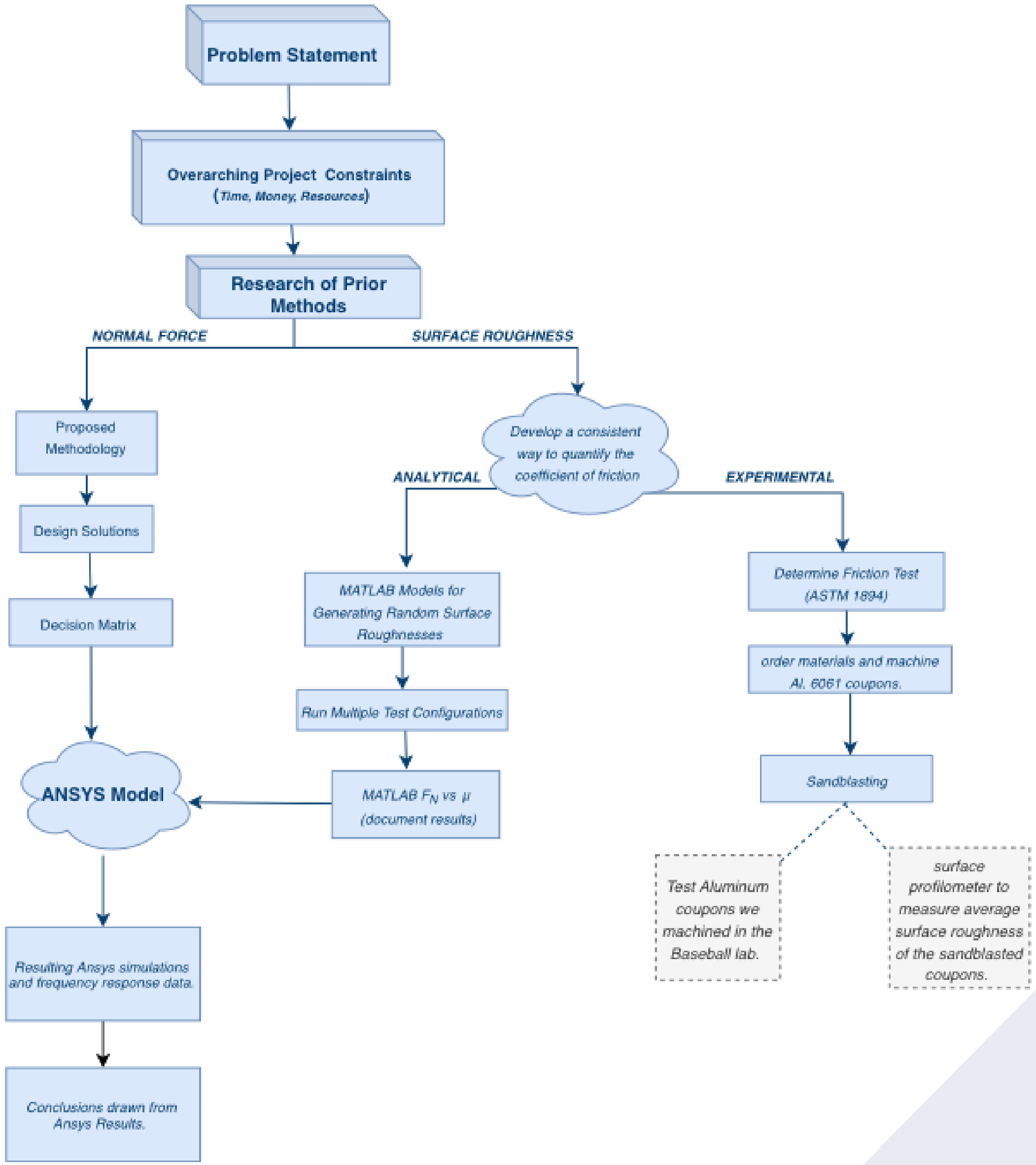
Problem Deconstruction

1. Design and manufacture an auxiliary subsystem to the CPVA that can modulate the normal force applied between the absorbers and rotor
2. Design and implement a method to control and modify the coefficient of friction in the absorber-rotor interface

Coefficient of Friction

Can be investigated for implementation through the following:

- Experimental Testing
- Computational Methods (Finite Element Analysis)
- Analytical Methods (Theory)



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Physical Approach

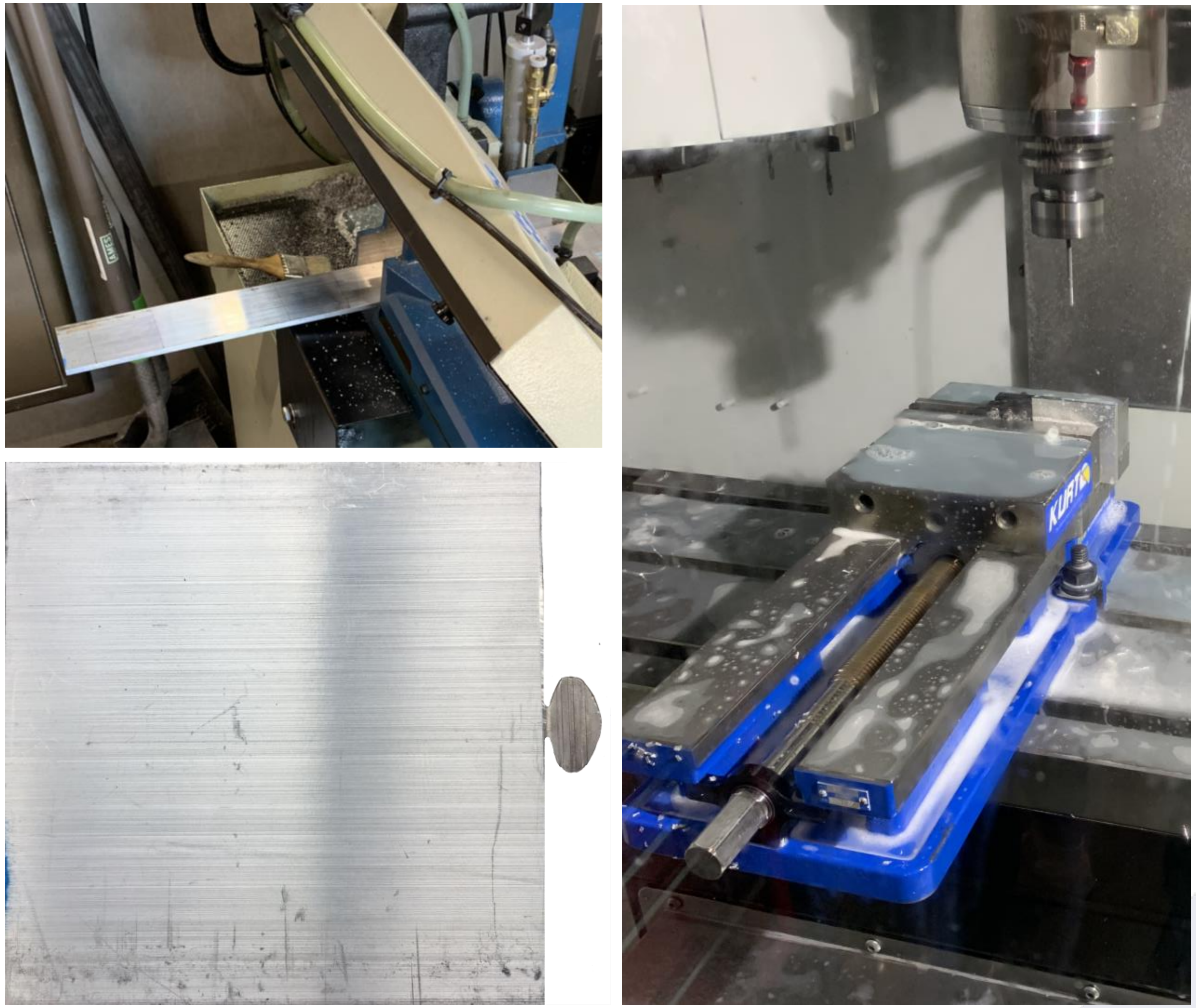
Experimental Testing

Friction Test

- Developed a procedure to determine the coefficient of friction
- Utilized ASTM D1894
- Simple pull test
    - Apply known load to the interface
    - Measure force required to move the coupon

Makerspace Manufacturing

- 12 2.5” square aluminum coupons were cut
- CNC Mill was used to drill precisely in the center of a side
- Hole tapped and thumb screw inserted for a pull string to be attached to



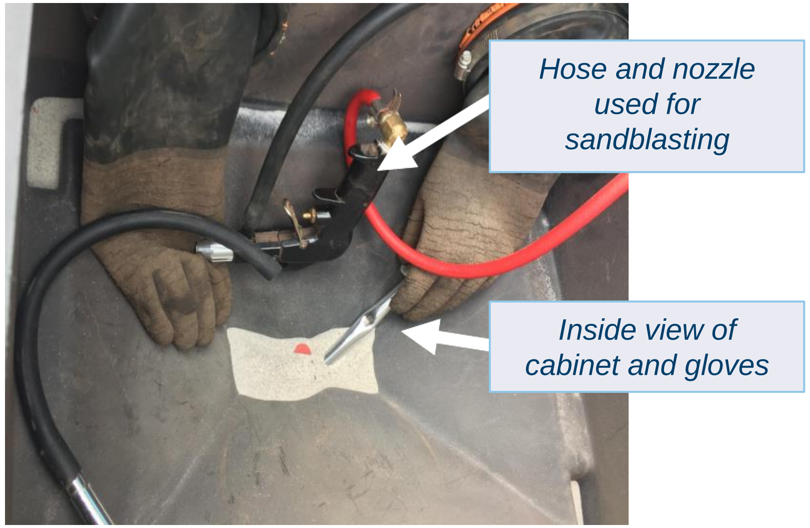
Top Left: Cutting of aluminum coupons; Lower Left: Aluminum coupons manufactured for testing; Right: CNC milling of coupons

Experimental Testing

Sandblasting

- Sandblasting was determined to be the most consistent and cost-efficient method to reliably introduce a surface roughness
- A sandblaster was acquired, and 6 coupons were roughened
- This was structured to fill a Design of Experiments full factorial array

Prepped for sandblasting



Factor	A	B
Trial No.	**Pressure**	**Grit Size**
1	*60*	*Fine*
2	*70*	*Fine*
3	*80*	*Fine*
4	*60*	*Large*
5	*70*	*Large*
6	*80*	*Large*

Video of sandblasting procedure

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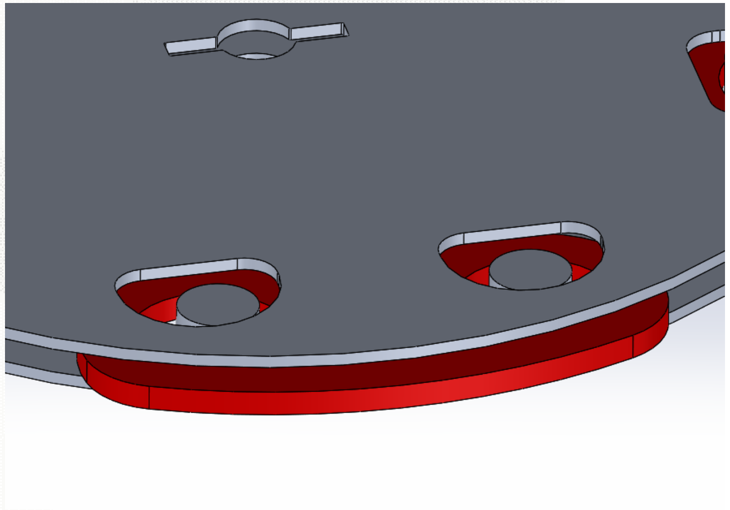
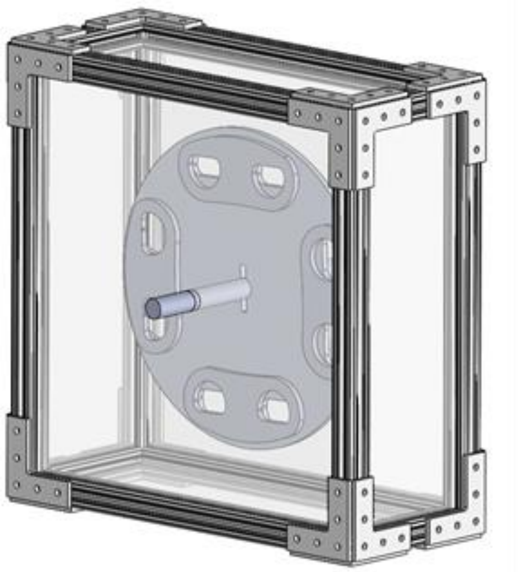
Normal Force Application Designs



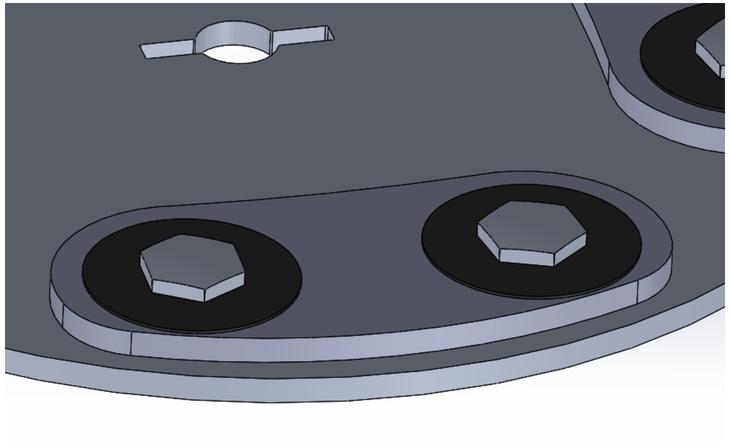
Design 1. Absorber-Compressing

- Split the rotor into two halves
- Place absorbers in between
- Control normal force with screws



Design 2. Pressure Vessel

- Introduce a sealed vessel around the CPVA
- Control normal force by filling vessel with pressurized fluid



Design 3. Loading Existing Bolts

- Use the existing CPVA design
- Manage normal force with the tightness of the connecting bolts

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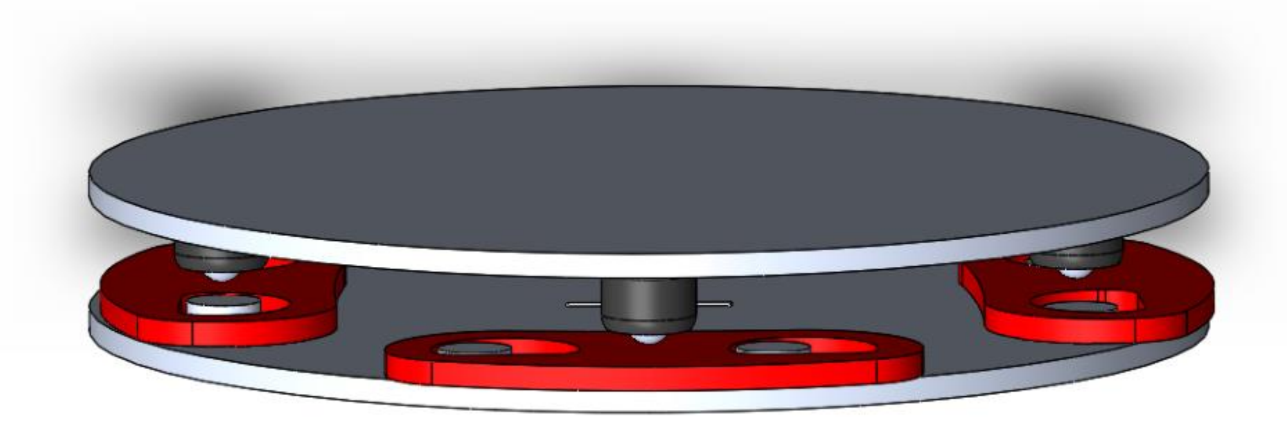
Normal Force Application Designs

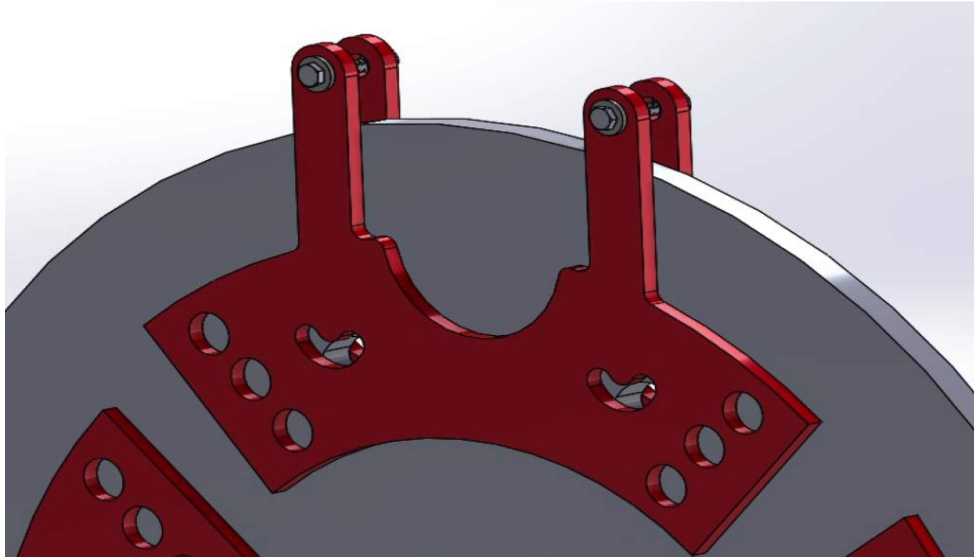
Design 4. Ball Bearing Rollers

- Introduce a plate with ball bearings on each absorber
- Control normal force by adding pressure with the plate



Design 5. Rotor-Compressing

- Split absorber into two halves
- Control normal force by tightening the absorbers with screws



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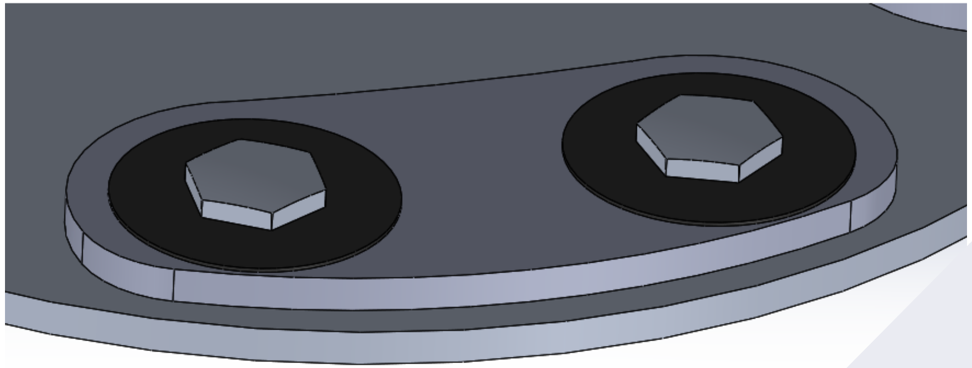
Decision Matrix

Design Method	Price	Complexity	Resource Intensity	Safety	Feasibility	Reliability	Maintenance	Durability	Total
1. Rotor-Compressing	3	8	7	9	8	9	10	8	**62**
2. Pressure Vessel	6	7	5	2	2	4	3	2	**31**
3. Loading Existing Bolts	9	9	10	10	8	7	8	7	**68**
4. Ball Bearing Pressure	6	7	8	8	8	9	9	9	**64**
5. Absorber-Compressing	2	8	7	9	8	9	9	8	**60**

- This decision matrix was generated after careful analysis and evaluation of each design
- The best design was the "Loading Existing Bolts" method
  - Favored in matrix due to simplicity, low cost, and safety
  - Purple Loctite should be used to prevent vibration loosening



Existing absorber mounting design

Decision Matrix Criteria

Criteria	Description	"0" Rating	"10" Rating
Price	Upfront cost of the assembly (Bill of Materials)	~$1,000	~$0
Complexity	Number of pieces in the assembly/resources, skills required to put together assembly	20 or greater additional components	no additional resources required
Manufacturing Intensity	Unique pieces in assembly, tools required for assembly (e.g. torque wrench)	10 hours of processing time required for the most complicated component	No processing time required
Safety	Probability/danger if pieces malfunction and potential hazards	Unsuitable to be operated in the presence of people	No additional safety hazards are imposed
Feasibility	Estimated likelihood of success informed by engineering analysis	Highly unlikely to work	Highly likely to operate as intended
Reliability	Will this design consistently deliver the results expected for this configuration	Several anticipated inconsistencies	No anticipated inconsistencies
Maintenance	Ease of access to components for modifications/replacements during lifetime	Requires more than 2 steps for disassembly	Easy to access and modify
Durability	Withstanding long term use, considering yielding, structural integrity, wear	Anticipated failure within 6 months	Useful life expected beyond 5 years

Analytical Approach

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Motivation for an Analytical Model

COVID-19 School Closure

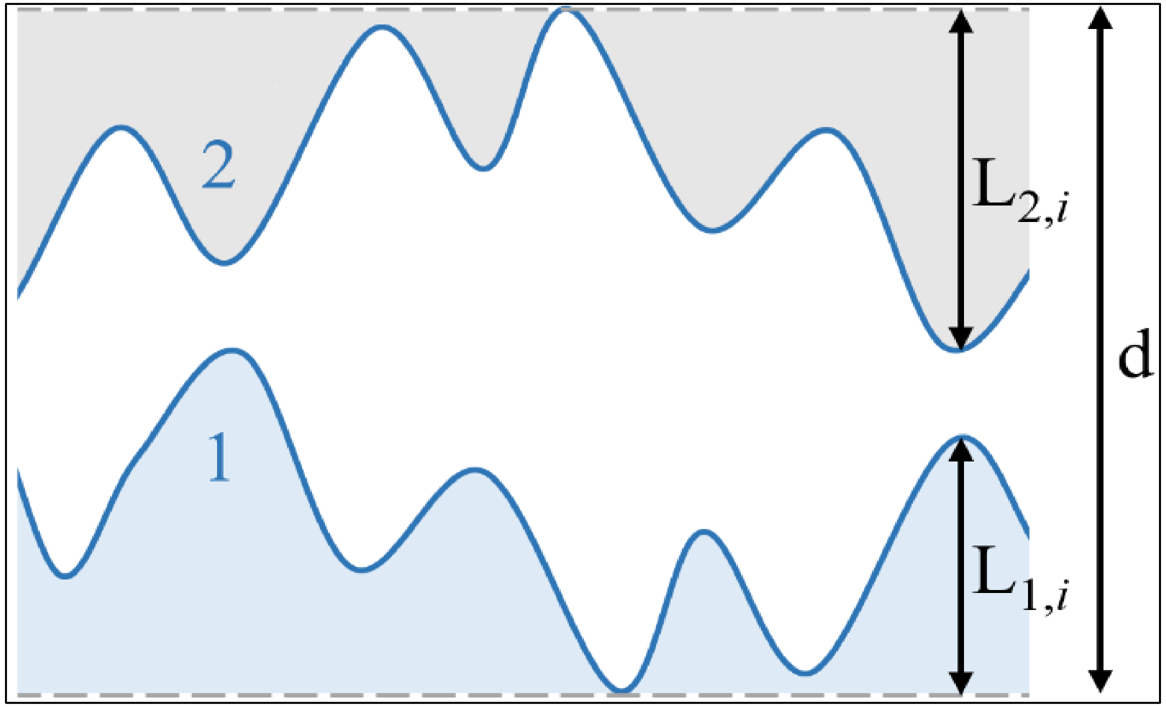
- Had to abandon experimental approach

Computational Approach

- Rough surfaces were generated in MATLAB and exported to ANSYS for analysis
- ANSYS was unable to simulate the surfaces deforming as required

Analytical Approach

- Last option was to develop a contact model in MATLAB
- This would generate two rough surfaces to calculate the coefficient of friction when they are contacting



Inflated schematic diagram of two rough surface profiles coming in contact with each other

Definition of the Coefficient of Friction:

$$\mu = \frac{F_S}{F_N}$$

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MATLAB Generated Surfaces

Gaussian Distribution

- MATLAB's normrnd function was used to generate an array of randomly distributed heights
  - This command requires a standard deviation (sigma) and an average (mu)

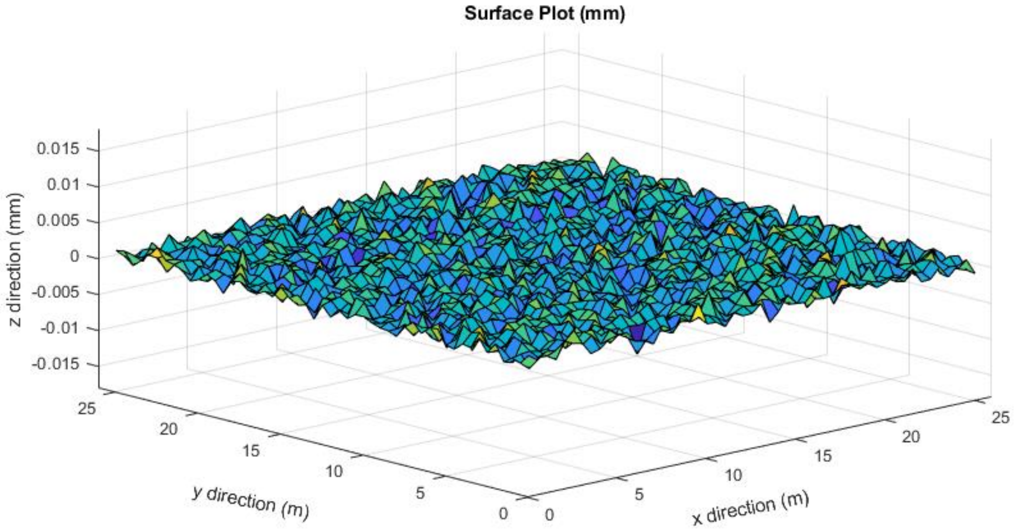
MATLAB Code

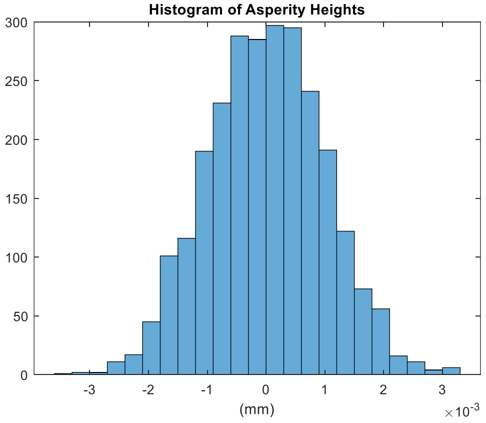
- An array is generated for a specific width, resolution, and input sigma
  - Each surface is assumed to have an average height of 0 (mu = 0)

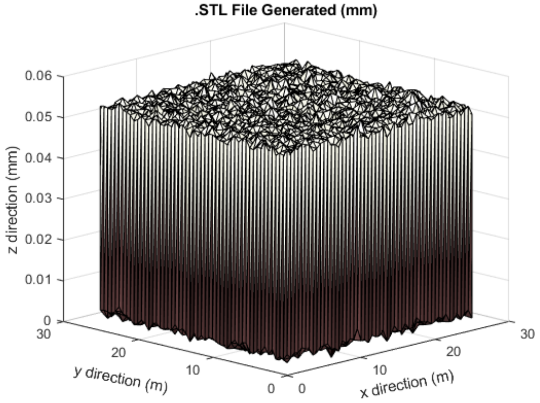
Measurement Parameters

- Surfaces are most often characterized by their Ra and Rms values

$$Ra = \frac{1}{n}\sum |z_i - \bar{z}| \qquad Rms = \sqrt{\frac{\sum {y_i}^2}{n}}$$



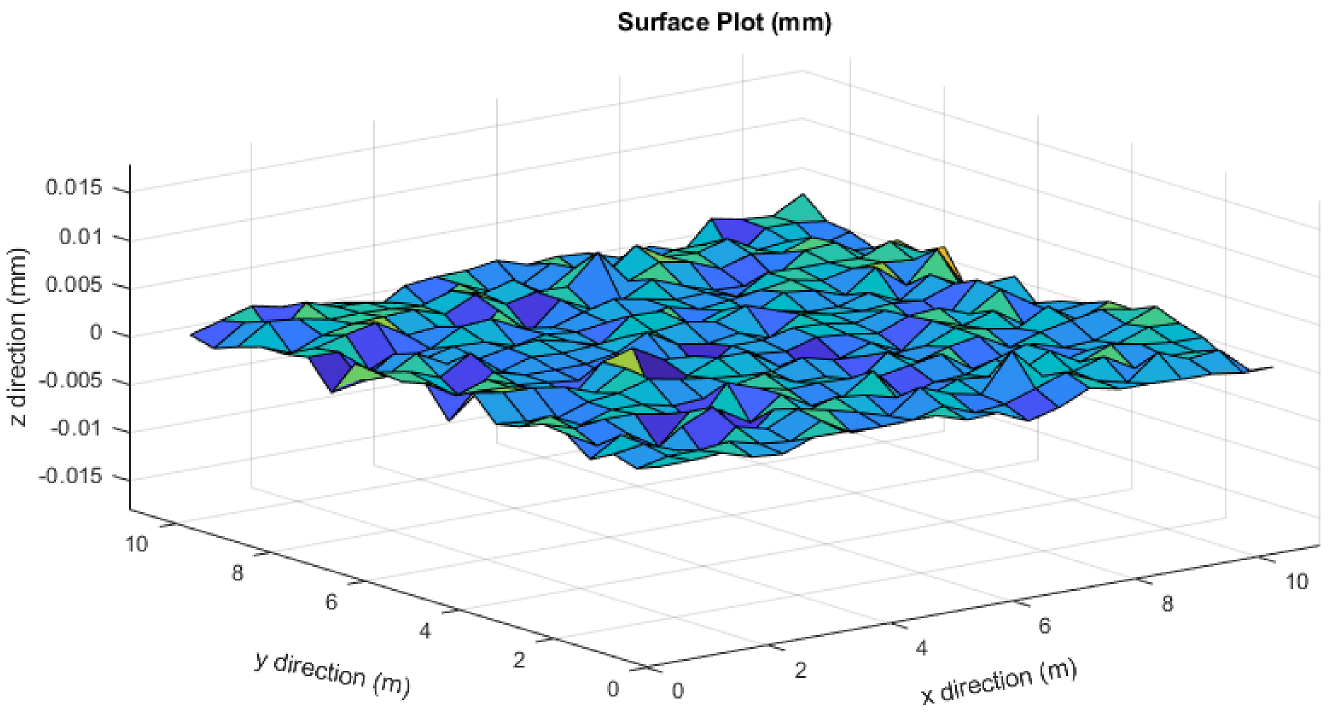


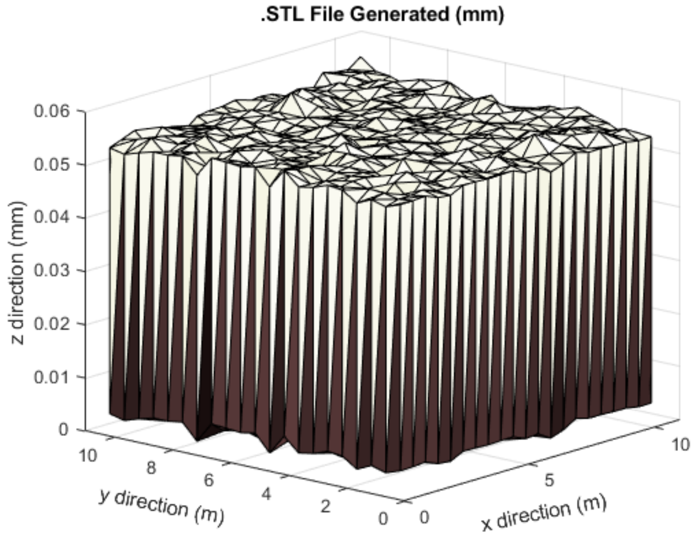


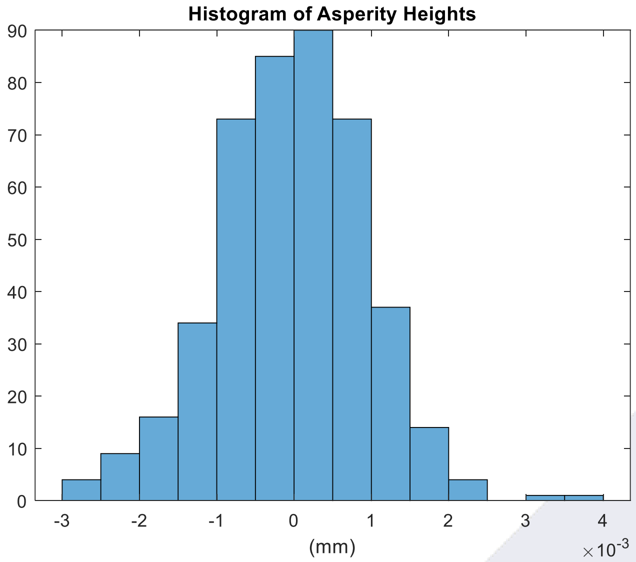
2 asperities per mm, 5 interpolation points; Ra = 3.3 μm, Rms = 0.988 μm, Equivalent Grit = 110 Grit Sandpaper

MATLAB Generated Surfaces

Asperity Only Model







2 asperities per mm, 1 interpolation point; Ra = 3.6 µm, Rms = 0.968 µm, Equivalent Grit = 101 Grit Sandpaper

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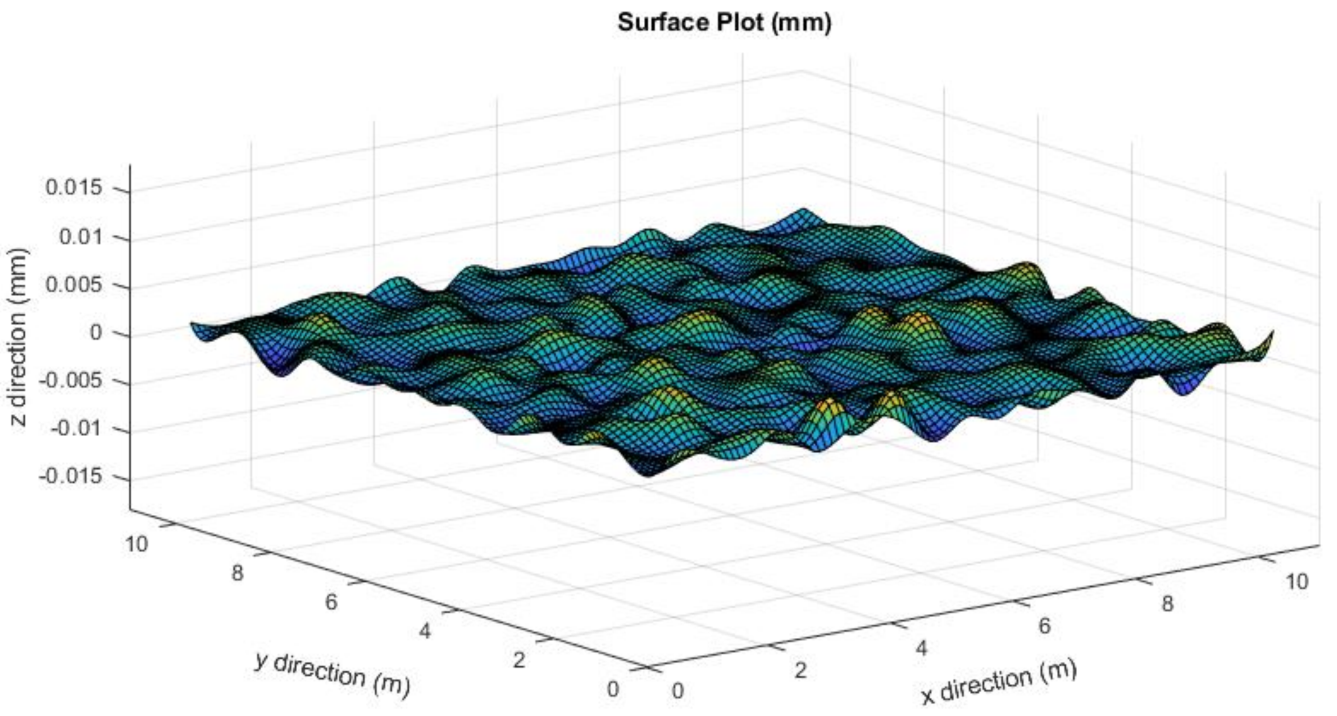
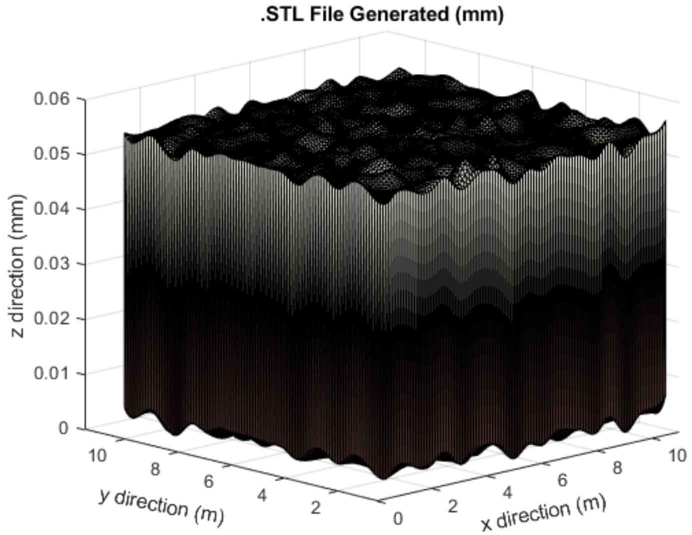
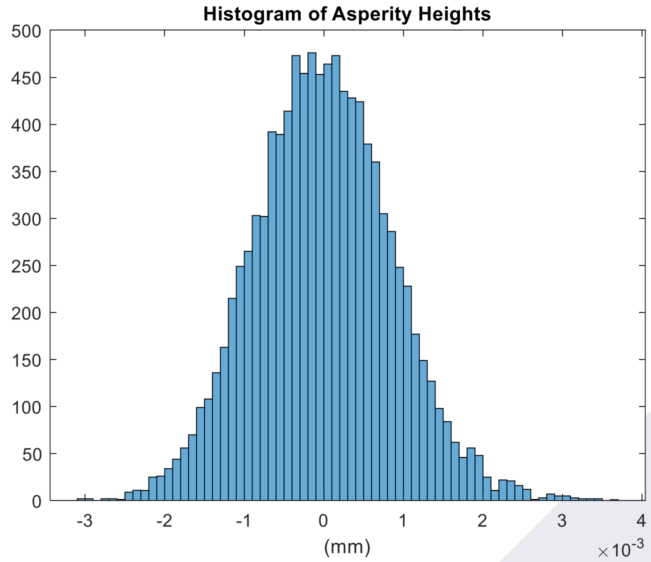
MATLAB Generated Surfaces

Interpolated Model







2 asperities per mm, 5 interpolation points; Ra = 3.7 μm, Rms = 0.204 μm, Equivalent Grit = 100 Grit Sandpaper

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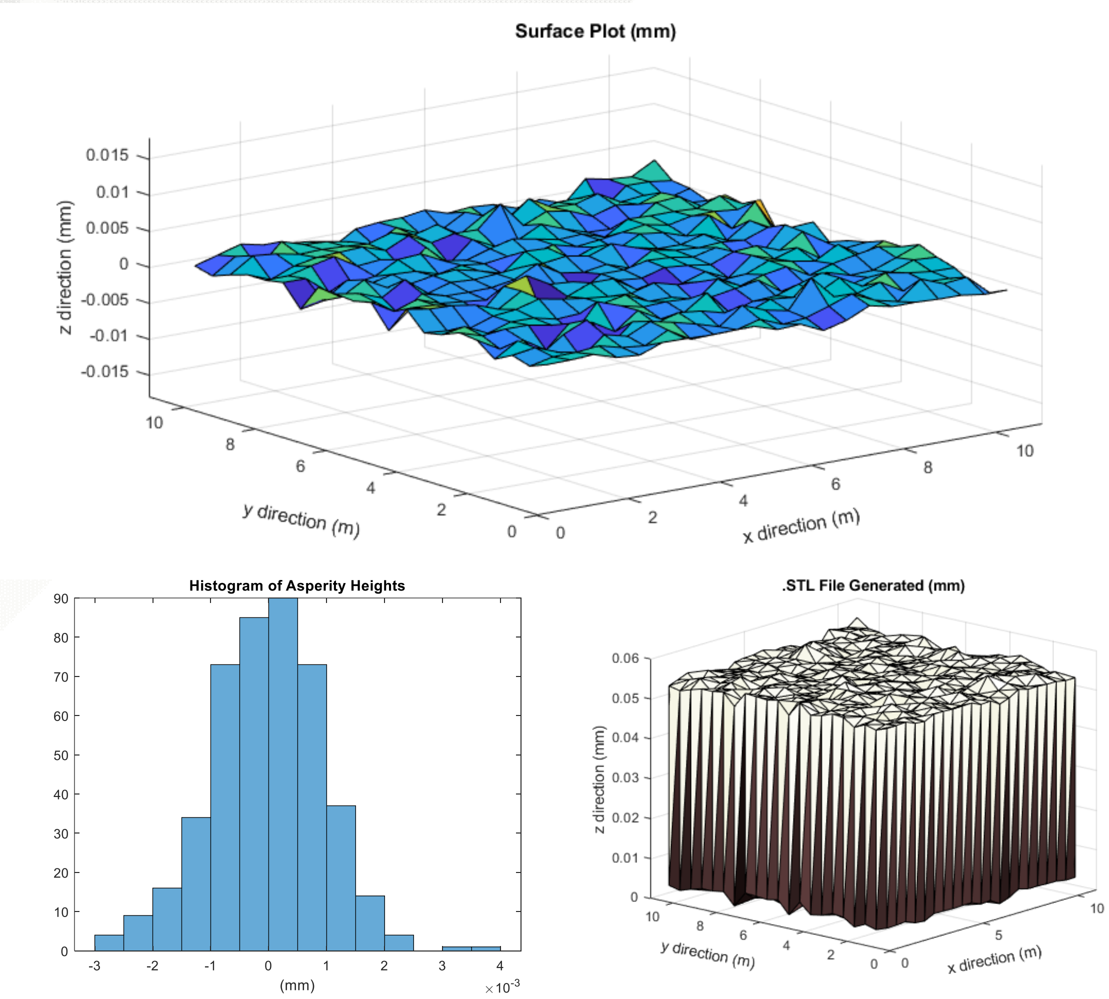
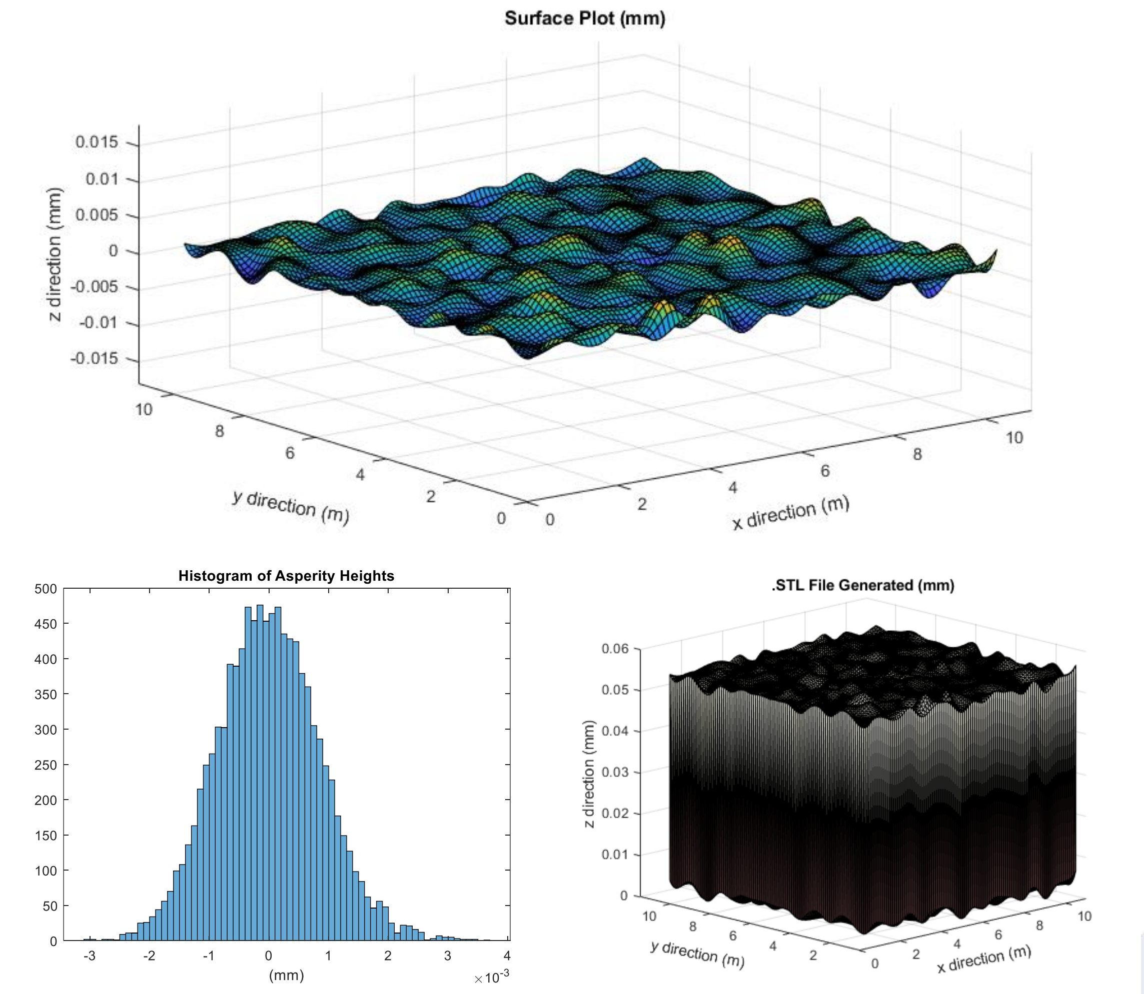
MATLAB Generated Surfaces

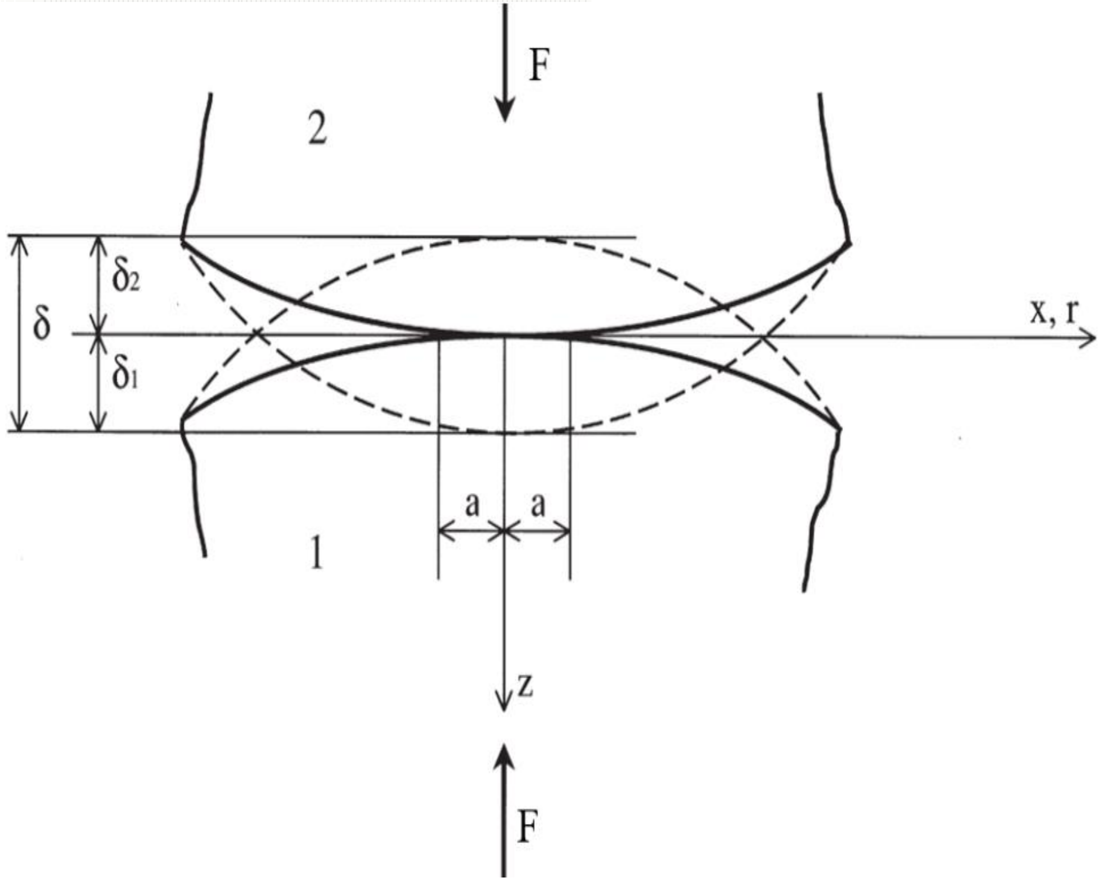


2 asperities per mm, 1 interpolation point; Ra = 3.6 μm, Rms = 0.968 μm, Equivalent Grit = 101 Grit Sandpaper



2 asperities per mm, 5 interpolation points; Ra = 3.7 μm, Rms = 0.204 μm, Equivalent Grit = 100 Grit Sandpaper

Fundamental Contact Equations



Hertzian Contact Model Schematic Diagram [1]

Hertz Contact

- The seminal work by Heinrich Hertz is considered here
  - This is an old model, but is relatively simple
- The force as a function of interference (δ_i) is given by the following equation.[2]

$$F_i = \frac{4E^*}{3}\left(\delta_i{}^3 R\right)^{1/2}$$

- The radius and modulus are given by[2]

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}, \qquad \frac{1}{E^*} = \frac{1-\nu_1{}^2}{E_1} + \frac{1-\nu_2{}^2}{E_2}$$

- In a contact matrix, the interference is conditional, as shown.[3]

$$\delta_i = \begin{cases} \left[\left(L_{1,i} + L_{2,i}\right) - d\right] & if\ \left[\left(L_{1,i} + L_{2,i}\right) - d\right] > 0 \\ 0 & else \end{cases}$$

1. G. Adams and M. Nosonovsky, "Contact modeling - forces," Tribology International, vol. 33, pp. 431-442, 2000.
2. B. Bushan, "Contact mechanics of rough surfaces in tribology: multiple asperity contact," Tribology Letters, no. 4, pp. 1-35, 1998.
3. S. Hulikal, N. Lapusta and K. Bhattacharya, "Static and sliding contact of rough surfaces: effect of aspertiy-scale properties and long-range elastic interaction," Department of Mechanical and Civil Engineering, California Institute of Technology, Pasadena, CA

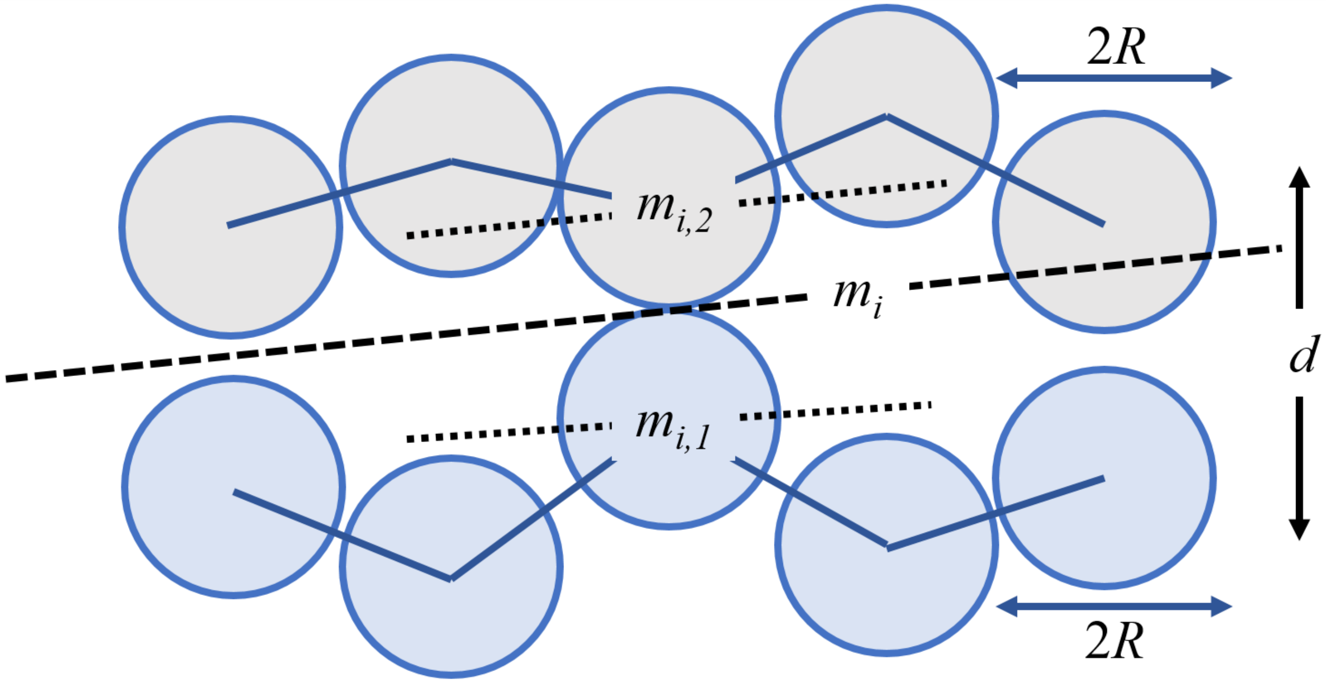
MATLAB Contact Model

Existing Contact Models

- Either exceptionally complicated or unacceptably simplified

Derivation Steps

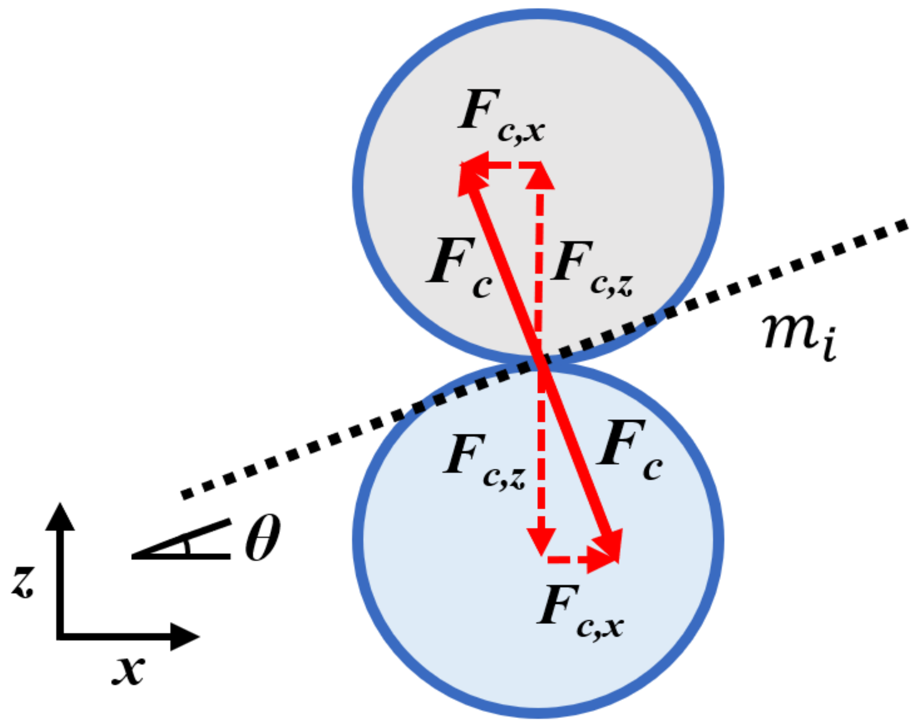
- Existing contact models and procedures were taken into consideration
  - Especially Hulikal, Lapusta, and Bhattacharya's model as well as the work by Bushan
- A modified version of Hertzian Contact was determined to be the most viable
  - The original Hertz model considers two sphere tipped asperities contacting on an orthogonal plane
  - This newly derived considers the contact coplanar with the average instantaneous slope of the rough surfaces in contact



Two interfacing rough surfaces with sphere-tipped asperities considering the instantaneous slope for each surface at the point of contact

B. Bushan, "Contact mechanics of rough surfaces in tribology: multiple asperity contact," Tribology Letters, no. 4, pp. 1-35, 1998.
S. Hulikal, N. Lapusta and K. Bhattacharya, "Static and sliding contact of rough surfaces: effect of aspertiy-scale properties and long-range elastic interaction," Department of Mechanical and Civil Engineering, California Institute of Technology, Pasadena, CA

MATLAB Contact Model



Two sphere-tipped asperity elements in contact at some angle θ

Derived Equations

- Using the premise set forth and the Hertz contact equations, 4 new equations are derived to consider an individual asperity.

$$\theta_i = \arctan(f_i')$$

$$\Delta_i = \delta_i(\cos\theta)$$

- Normal Force

$$F_{c,z} = \frac{4}{3}\sqrt{{\Delta_i}^3 R {E^*}^2}\left|\sin(\frac{\pi}{2} - \theta)\right|$$

- Shear Force

$$F_{c,x} = \frac{4}{3}\sqrt{{\Delta_i}^3 R {E^*}^2}\cos(\frac{\pi}{2} - \theta)$$

- The macroscopic forces can be considered by summing the forces for each element across the entire surface

MATLAB Contact Model

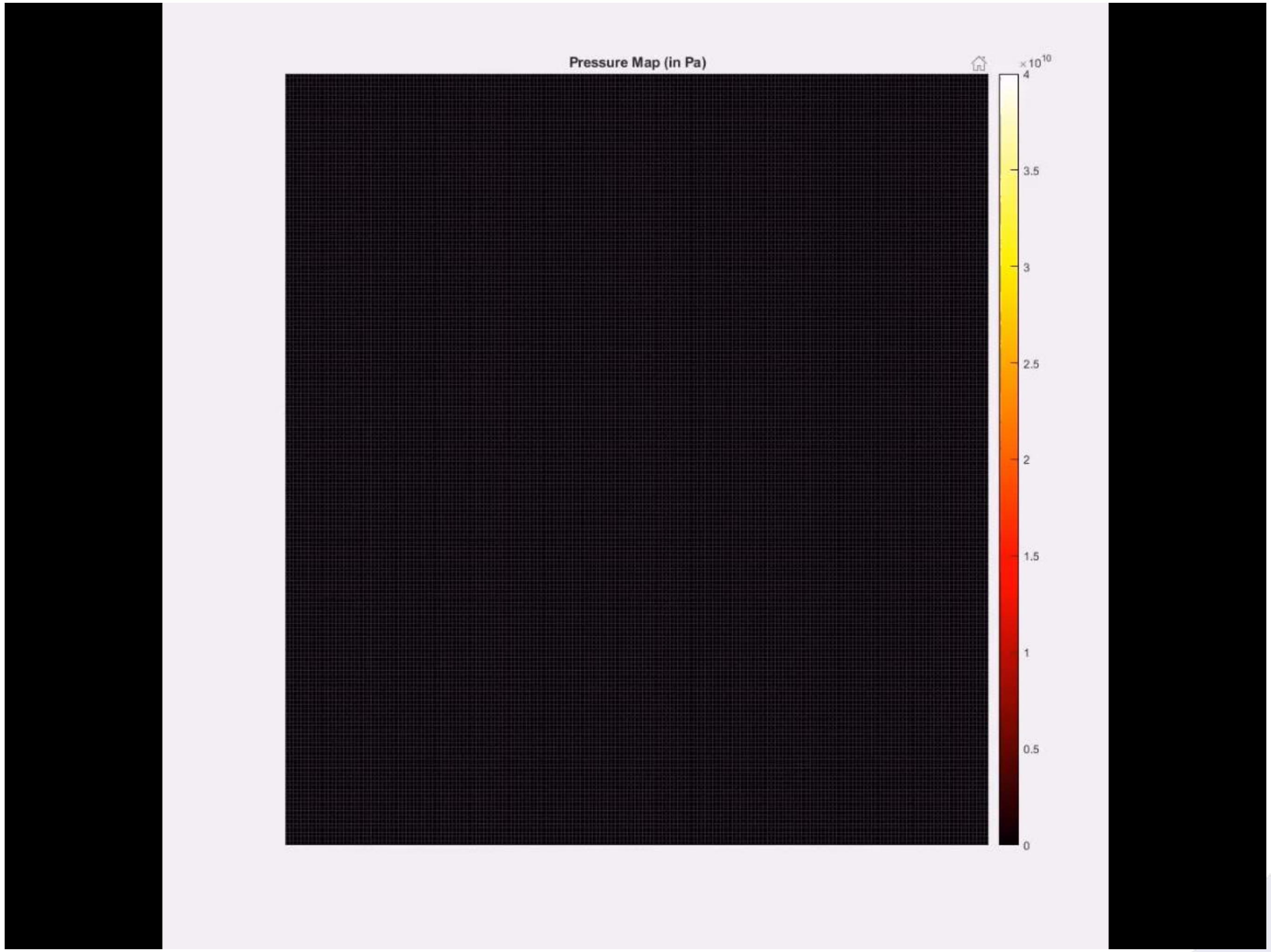
Efficacy

- Unfortunately, cannot verify with experimental results
- Output μ is within expectations

Further Improvements

Due to time constraints, the following were not able to be integrated:

- Evolution of system through time
- Effect of surface relative motion
- Dynamic plasticity
- Rudimentary contact model
- Computational inefficiencies



Pressure animation of two rough surfaces being loaded to 1000 N and unloaded (2 asperities per mm, 10 interpolation points; Ra = 3.1 μm, Rms = 0.082 μm, Equivalent Grit = 117 Grit Sandpaper)

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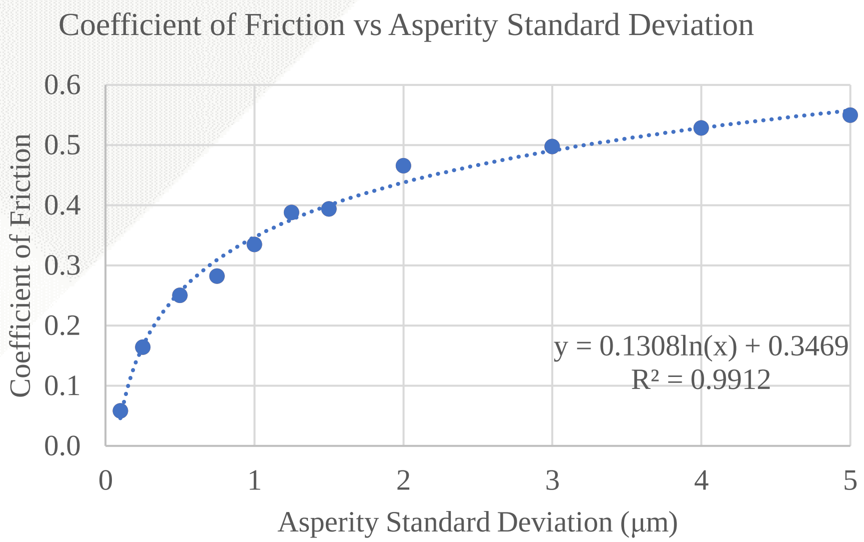
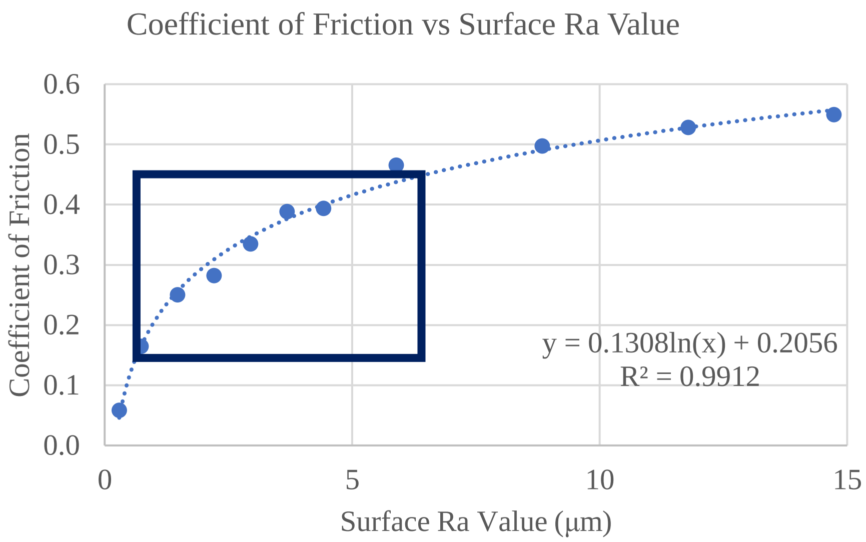
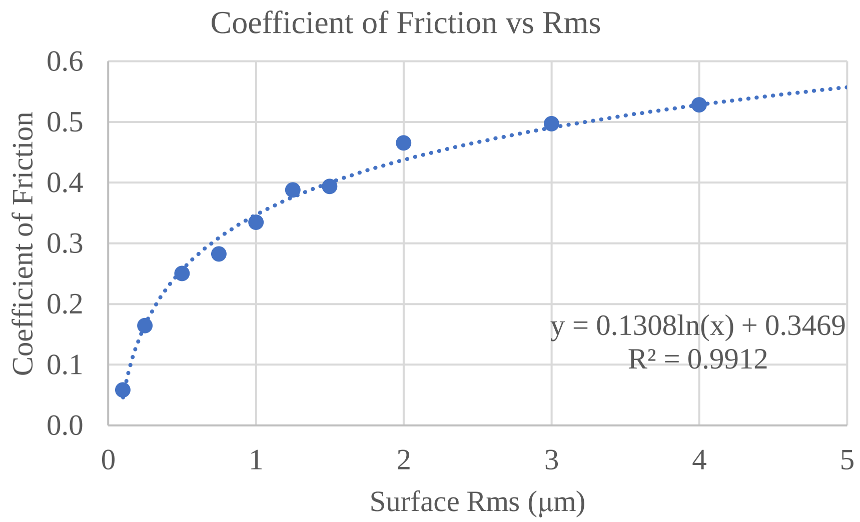
MATLAB Contact Model Results







Resulting Equations

$$\sigma = 0.0721e^{7.5803\mu} \quad [\mu m]$$

$$Ra = 0.2127e^{7.5803\mu} \quad [\mu m]$$

$$Rms = 0.0721e^{7.5803\mu} \quad [\mu m]$$

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Computational Approach

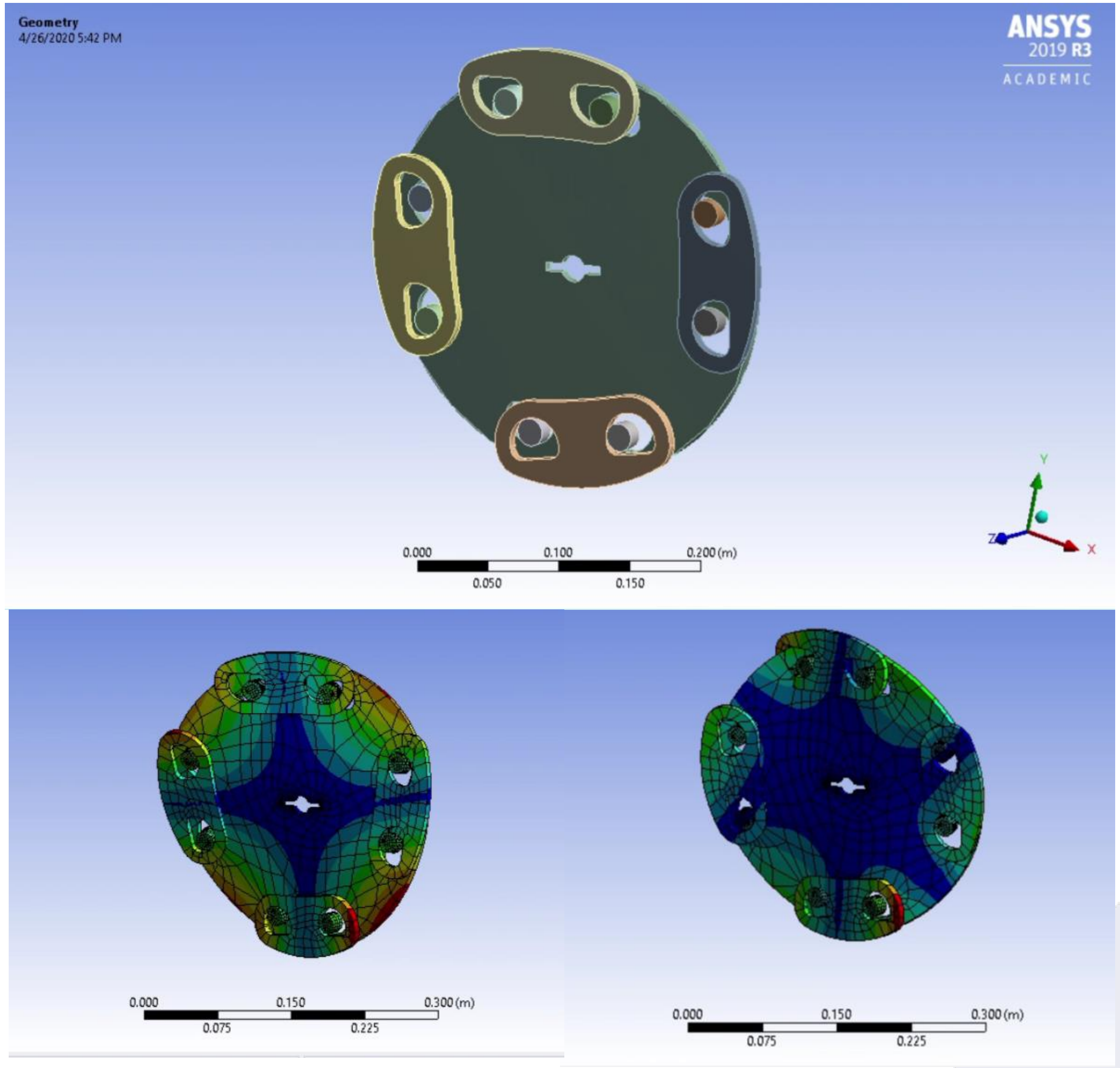
ANSYS Simulations

Analytical to Computational

- From MATLAB, it was determined to use the frictional coefficient from 0.15 - 0.45
  - This, as shown by the coefficient of variation plot, is the most consistent range

ANSYS Model

- Team decided next step was a simulation approach
- Tools considered: Abaqus, ANSYS, and COMSOL
- ANSYS was the chosen tool based on the team's familiarity with the software
- Modal analysis and harmonic response analysis were performed based on ANSYS workshop followed in class

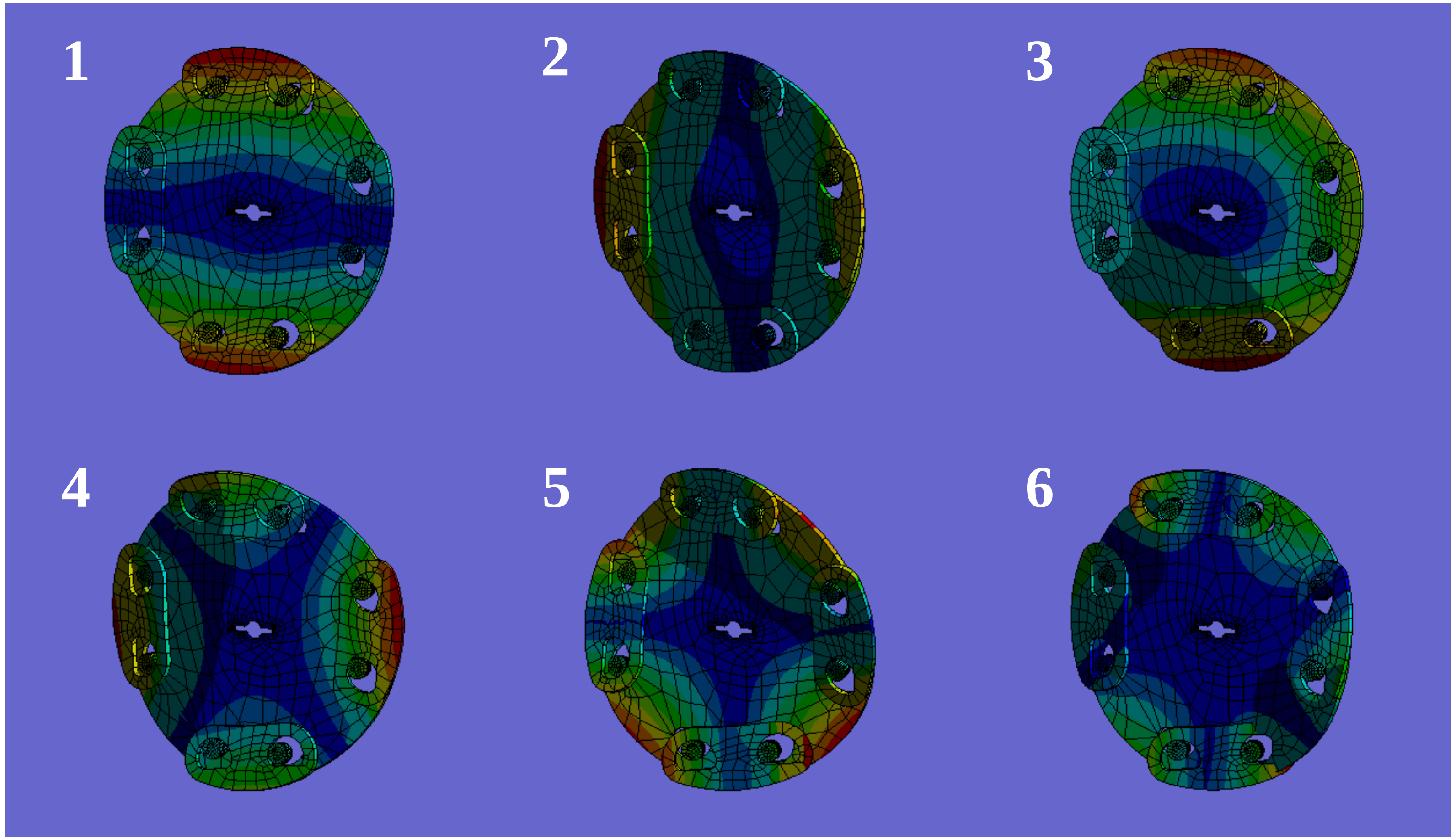


Screenshots of CPVA assembly in ANSYS

ANSYS Simulations

Mode	Frequency [Hz]
1	*166.28*
2	*197.25*
3	*222.94*
4	*267.15*
5	*304.63*
6	*586.18*

- Modal Analysis was performed for first 6 modes, for all coefficients.
- Example of modal analysis and results presented for coefficient of 0.35



Top left to right: Deformation of modes 1, 2, and 3. Bottom left to right: Deformation of modes 4, 5, and 6

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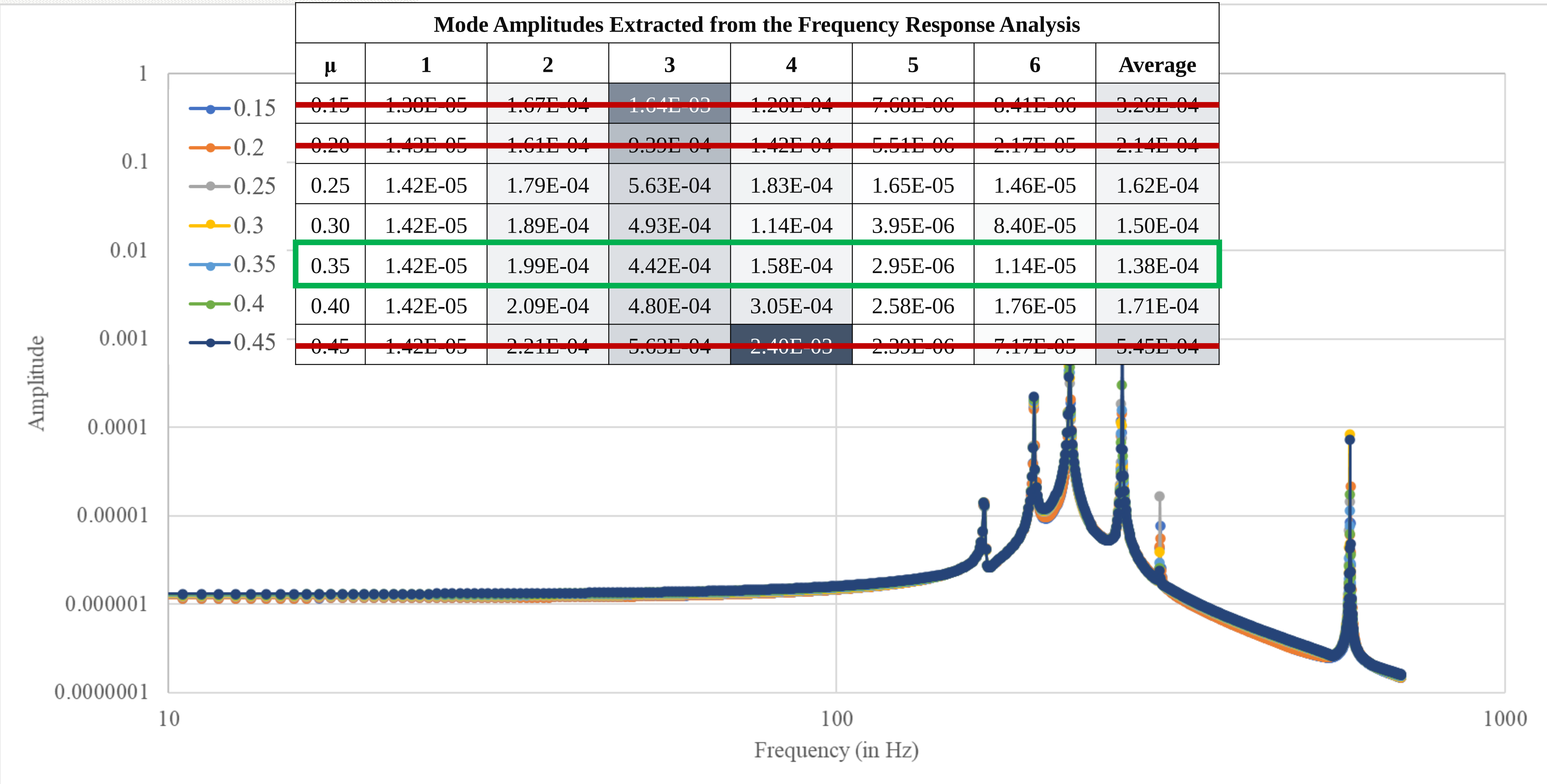
Frequency Response Plots



Mode Amplitudes Extracted from the Frequency Response Analysis							
μ	1	2	3	4	5	6	Average
~~0.15~~	~~1.38E-05~~	~~1.67E-04~~	~~1.64E-03~~	~~1.20E-04~~	~~7.68E-06~~	~~8.41E-06~~	~~3.26E-04~~
~~0.20~~	~~1.43E-05~~	~~1.61E-04~~	~~9.39E-04~~	~~1.42E-04~~	~~5.51E-06~~	~~2.17E-05~~	~~2.14E-04~~
0.25	1.42E-05	1.79E-04	5.63E-04	1.83E-04	1.65E-05	1.46E-05	1.62E-04
0.30	1.42E-05	1.89E-04	4.93E-04	1.14E-04	3.95E-06	8.40E-05	1.50E-04
0.35	1.42E-05	1.99E-04	4.42E-04	1.58E-04	2.95E-06	1.14E-05	1.38E-04
0.40	1.42E-05	2.09E-04	4.80E-04	3.05E-04	2.58E-06	1.76E-05	1.71E-04
~~0.45~~	~~1.42E-05~~	~~2.21E-04~~	~~5.63E-04~~	~~2.40E-03~~	~~2.39E-06~~	~~7.17E-05~~	~~5.45E-04~~

Frequency response deformation plot for the varying coefficients of friction with corresponding table of values

Final Design

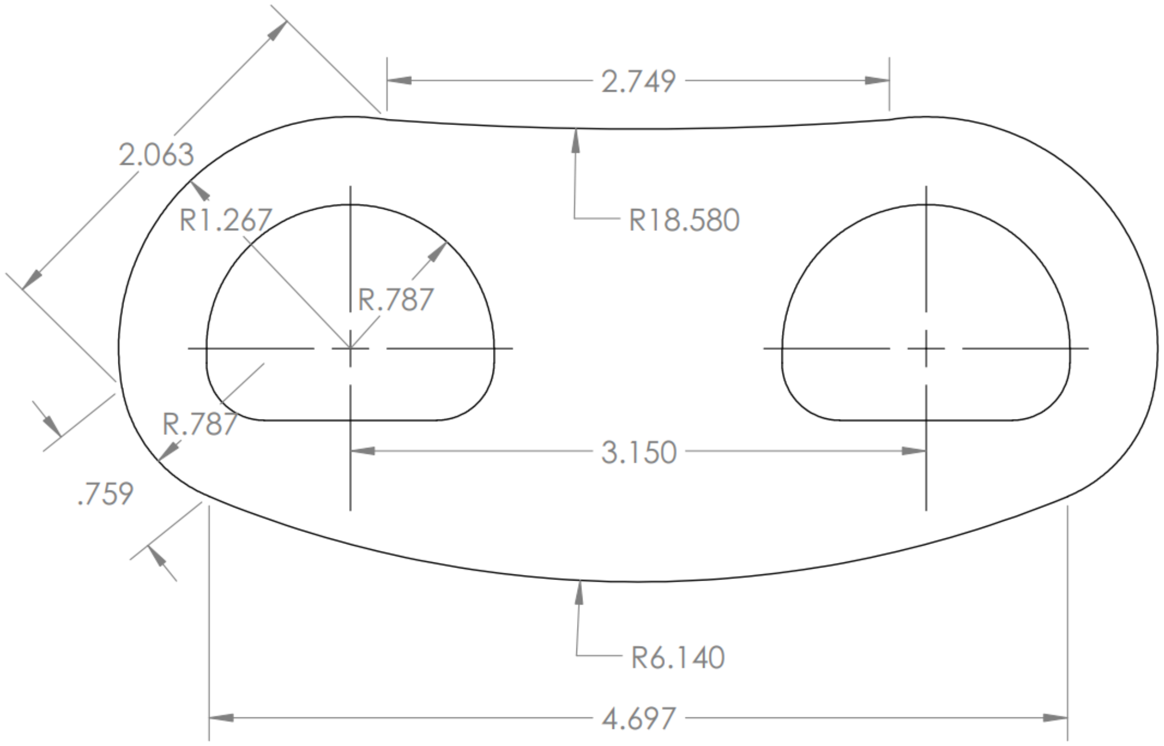
Conclusions

- Maintain the current CPVA configuration
- To use the "tightening bolts" method
- Utilize sandblasting for artificial surface roughening
- Aim for a coefficient of friction of 0.35

Implementation

To do this, a surface Ra = 3.020 μm is required on the absorber and rotor

- This is approximately the roughness of 120 grit sandpaper



CPVA absorber engineering drawing to be manufactured with a surface roughness of Ra = 3.020 μm

Thank You

Appendix – Cost Analysis

Purchased Items Ledger						
Part Name	Part Number	Vendor	Description	Quantity	Unit Cost	Cost
Aluminum Bar	*89015K236*	*McMaster-Carr*	*Multipurpose 6061 Aluminum Sheet 1/8" Thick, 6" x 12"*	*2*	*$ 16.63*	*$ 33.26*
Aluminum Plate	*8975K68*	*McMaster-Carr*	*Multipurpose 6061 Aluminum 1/4" Thick x 2-1/2" Wide, 3 Feet Long*	*2*	*$ 16.44*	*$ 32.88*
Thumb Screws	*91745A192*	*McMaster-Carr*	*Stainless Steel Spade-Head Thumb Screw 8-32 Thread Size, 3/8" Long*	*1*	*$ 9.38*	*$ 9.38*
Screw Tap (8-32)	*26955A33*	*McMaster-Carr*	*General Purpose Tap Plug Chamfer, Uncoated High-Speed Steel, 8-32 Thread Size*	*1*	*$ 4.61*	*$ 4.61*
Drill Bit (Gauge 29)	*2901A203*	*McMaster-Carr*	*Black-Oxide High-Speed Steel Drill Bit Wire Gauge 29, 2-7/8" Overall Length*	*1*	*$ 1.86*	*$ 1.86*
Glass Abrasive Media	*3398K15*	*McMaster-Carr*	*Abrasive Blasting Media Multipurpose, Glass Bead, 170-325 Mesh Size, 10 lbs.*	*2*	*$ 21.32*	*$ 42.64*
Sandblaster Kit	*N/A*	*Amazon*	*Sand Blaster, Sand Blaster Gun Kit, Sandblaster with 2 Replaceable Tips & ¼" Quick Connect, and Safety Goggles*	*1*	*$ 39.56*	*$ 39.56*
Sandblasting Gloves	*N/A*	*Amazon*	*Jewboer 23.6" Rubber Sandblasting Sandblaster Gloves for Sandblast Cabinets*	*1*	*$ 17.99*	*$ 17.99*
Sandpaper	*N/A*	*Amazon*	*120 To 3000 Assorted Grit Sandpaper for Wood Furniture Finishing, Metal Sanding and Automotive Polishing*	*1*	*$ 7.99*	*$ 7.99*
					Total	**$190.17**

Appendix – Cost Analysis

Final Design Proposed Ledger						
Part Name	**Part Number**	**Vendor**	**Description**	**Quantity**	**Unit Cost**	**Cost**
Aluminum Bar	*8975K87*	*McMaster-Carr*	*Multipurpose 6061 Aluminum 1/4" Thick x 3" Wide x 3' Long*	1	$ 19.68	$ 19.68
Threadlocker	*1810A27*	*McMaster-Carr*	*Adjustable Threadlocker, Loctite ® 222, 0.34 oz. Bottle*	1	$ 15.35	$ 15.35
					Total	**$ 35.03**

Estimated cost of Labor			
Task	**Hourly Cost**	**Estimated Hours**	**Total Cost**
Management	*$ 36.00*	*60*	*$ 2,160.00*
Design	*$ 30.00*	*270*	*$ 8,100.00*
Manufacturing	*$ 24.00*	*4*	*$ 96.00*
Assembly	*$ 15.00*	*2*	*$ 30.00*
Documentation	*$ 30.00*	*40*	*$ 1,200.00*
		Total	$ 11,586.00

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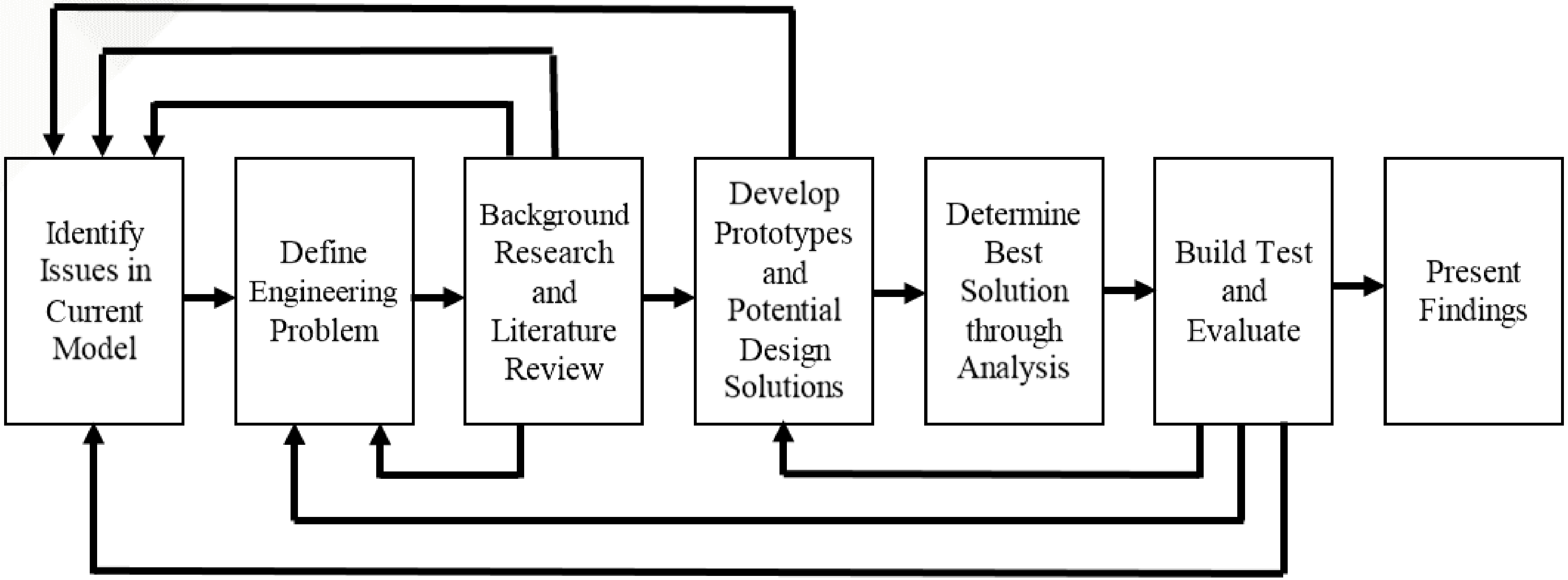
Appendix – Engineering Flow Chart



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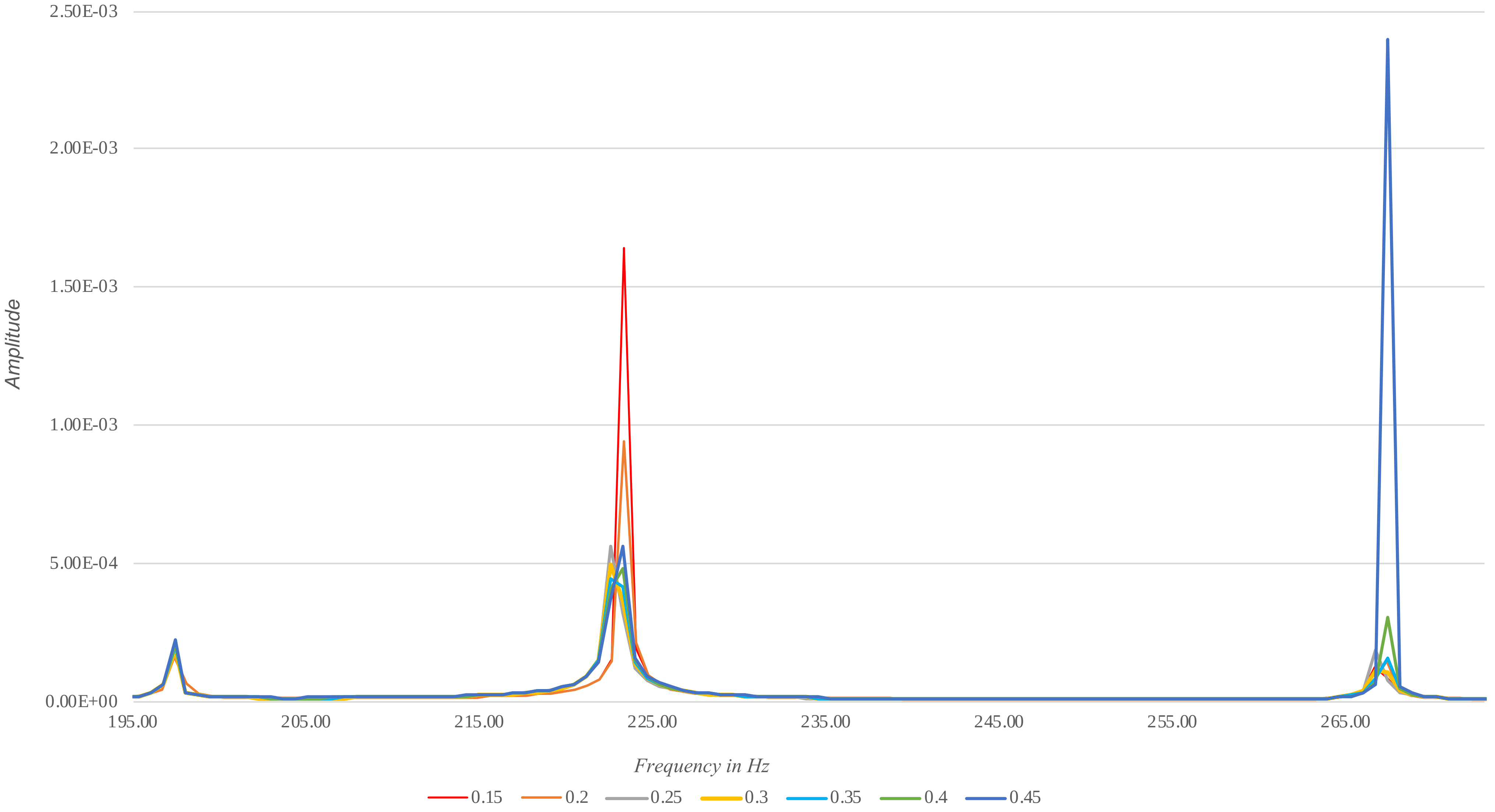
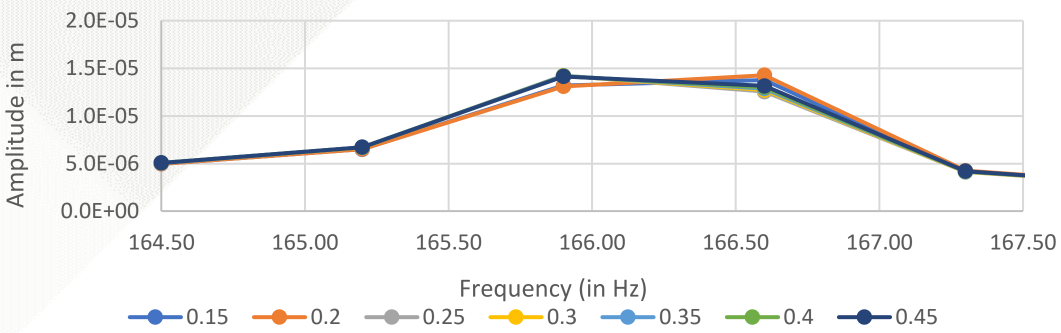
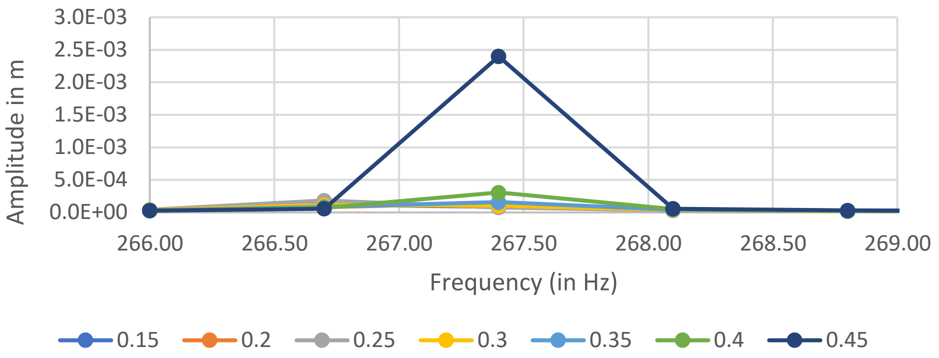
Appendix – ANSYS Results 195-265 Hz



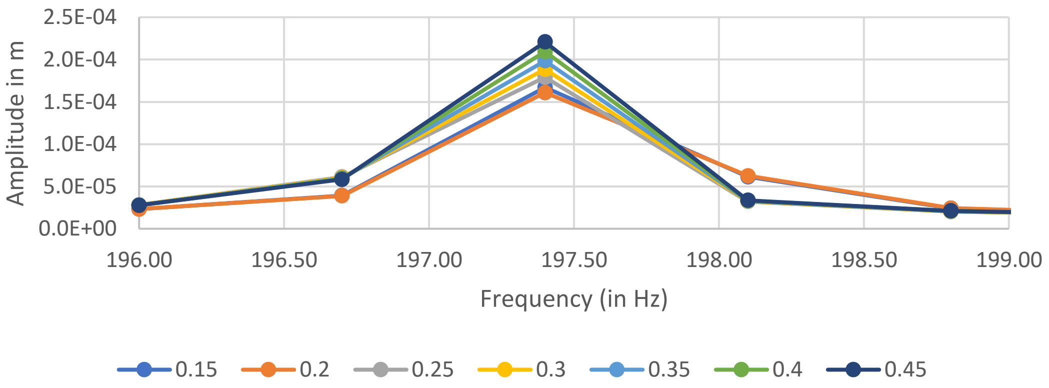
Appendix – ANSYS Results By Mode



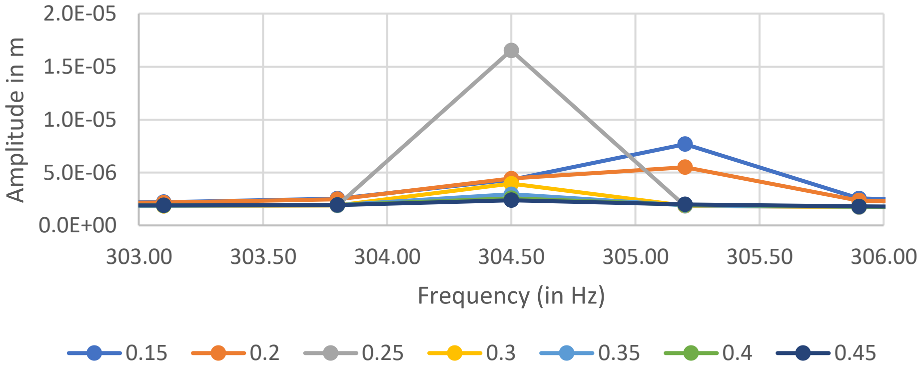
Mode 1 Frequency Response of CPVA (variable input friction)



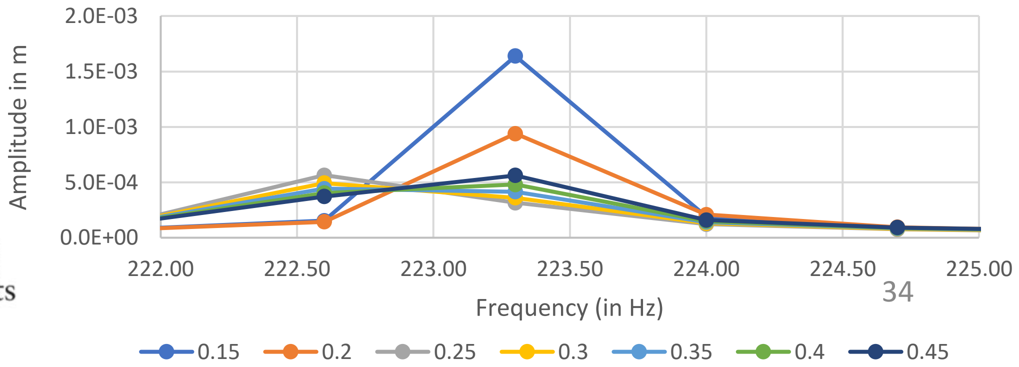
Mode 4 Frequency Response of CPVA (variable input friction)



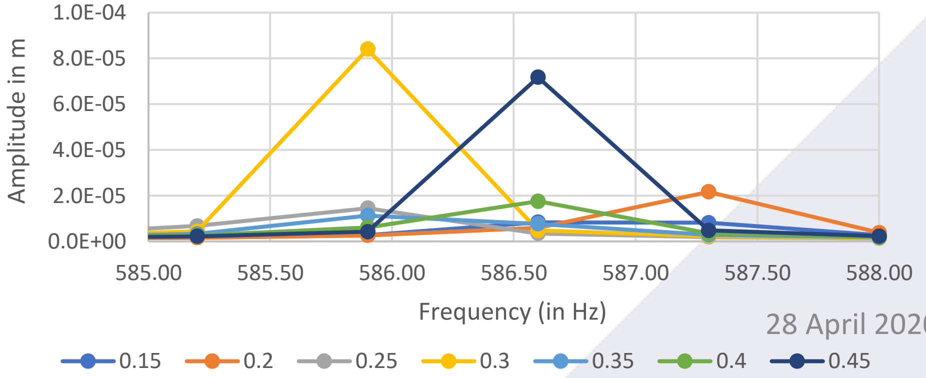
Mode 2 Frequency Response of CPVA (variable input friction)



Mode 5 Frequency Response of CPVA (variable input friction)



Mode 3 Frequency Response of CPVA (variable input friction)



Mode 6 Frequency Response of CPVA (variable input friction)

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