Europa Clipper Preliminary Design Review Propellant Slosh Analysis

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Europa Clipper

- Spacecraft to be sent to a Jupiter orbit and complete multiple flybys of the moon Europa
- Will map and study Europa, primarily focusing on investigating the existence of a subsurface ocean
- MMH fuel and NTO (MON-3) oxidizer [1]

Overview

- Slosh is the movement of a liquid within a container
- Spacecraft must deal with this phenomenon because liquid propellants will slosh throughout the course of the mission
- This study examined periodic slosh under constant settling acceleration
- Physical testing in an appropriate acceleration environment is preferred but prohibitively expensive
- Equivalent mechanical models to match CFD output were derived to simplify inputs to the attitude control system software

Categories

High-G Slosh

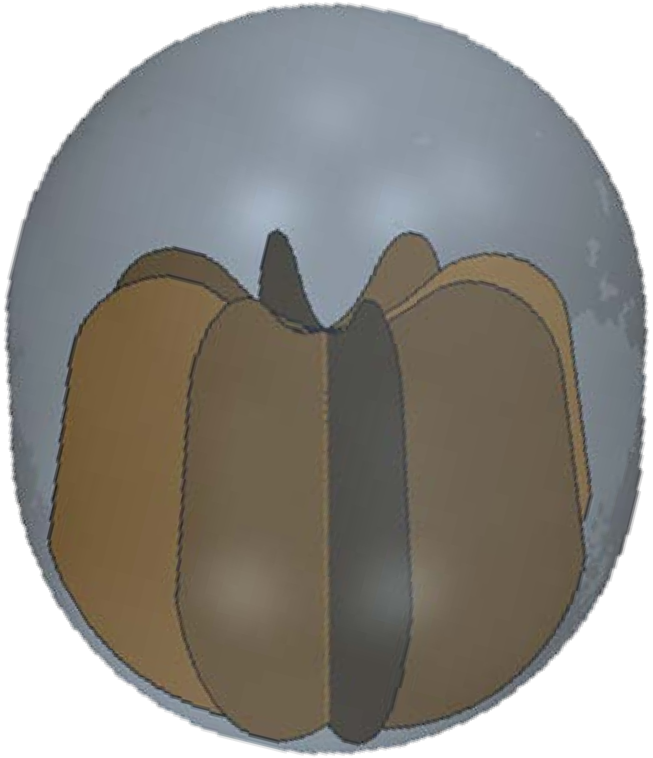
- Bond Number significantly greater than one
- Settling accelerations dominate
- Modeled with STAR-CCM+
- Mechanical model consists of two damped pendulums and a static mass [2]

Low-G Slosh

- Bond number significantly less than one
- Surface tension dominates
- Modeled in Surface Evolver
- Mechanical model consists of a single damped pendulum, a torsional spring, and a static mass [3]

Geometry

- Preliminary design for Europa Clipper tank and propellant management device (PMD)
- Mechanical design beyond scope of this presentation
- Design results in two slosh modes: full tank and sector slosh



High-G Cases

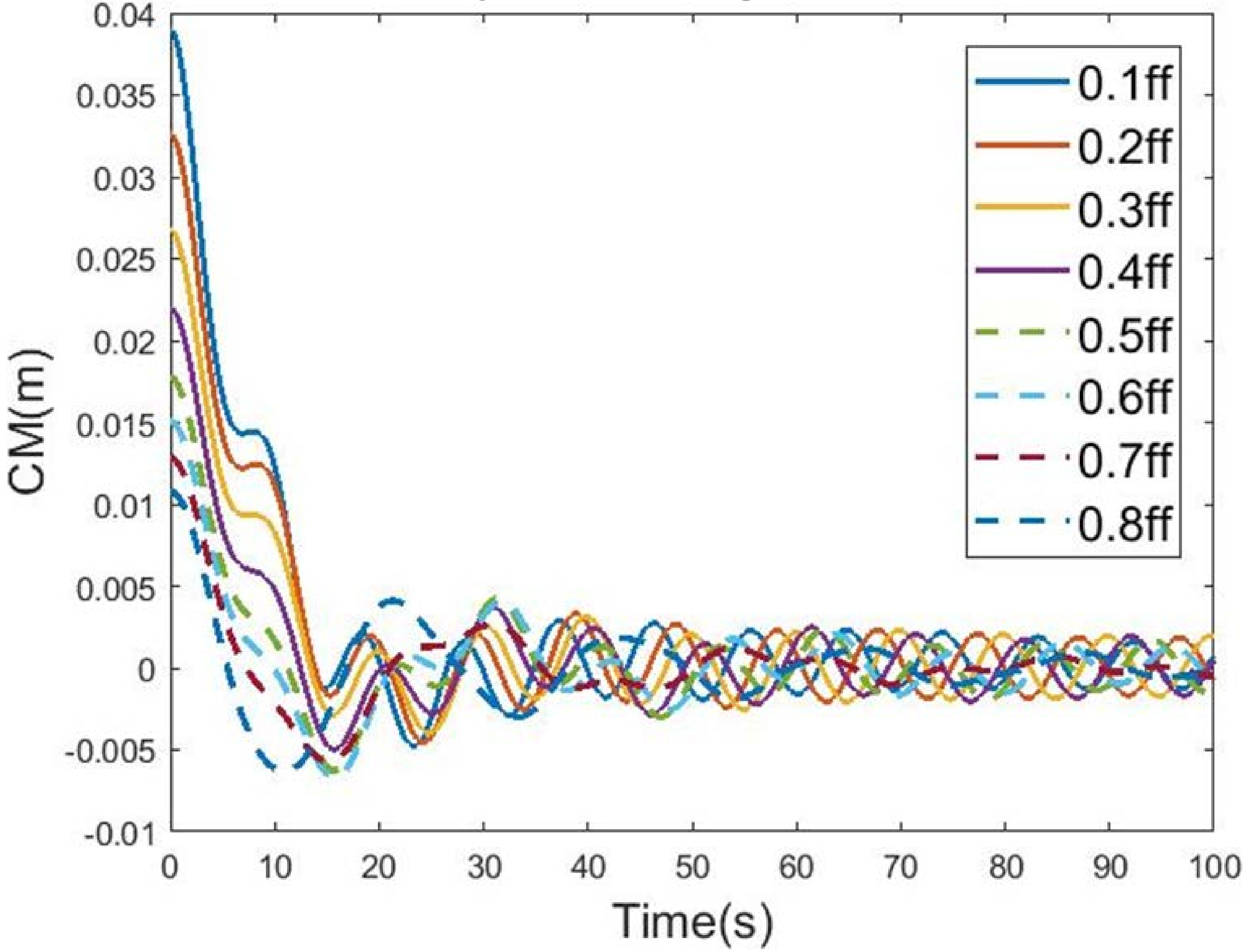
CFD Setup

- STAR-CCM+
- Program successfully used for previous NASA missions
  - ICESat-2, OSIRIS-Rex, GPM
- Provides center of mass, forces and moments on the tank and PMD, and moment of inertia of the settled propellant
- Propellant surface initialized at 5 degrees from horizontal
- Polyhedral mesh with prism cells at the walls
- 400,000-cell mesh chosen for modeling

Mesh Independence Analysis

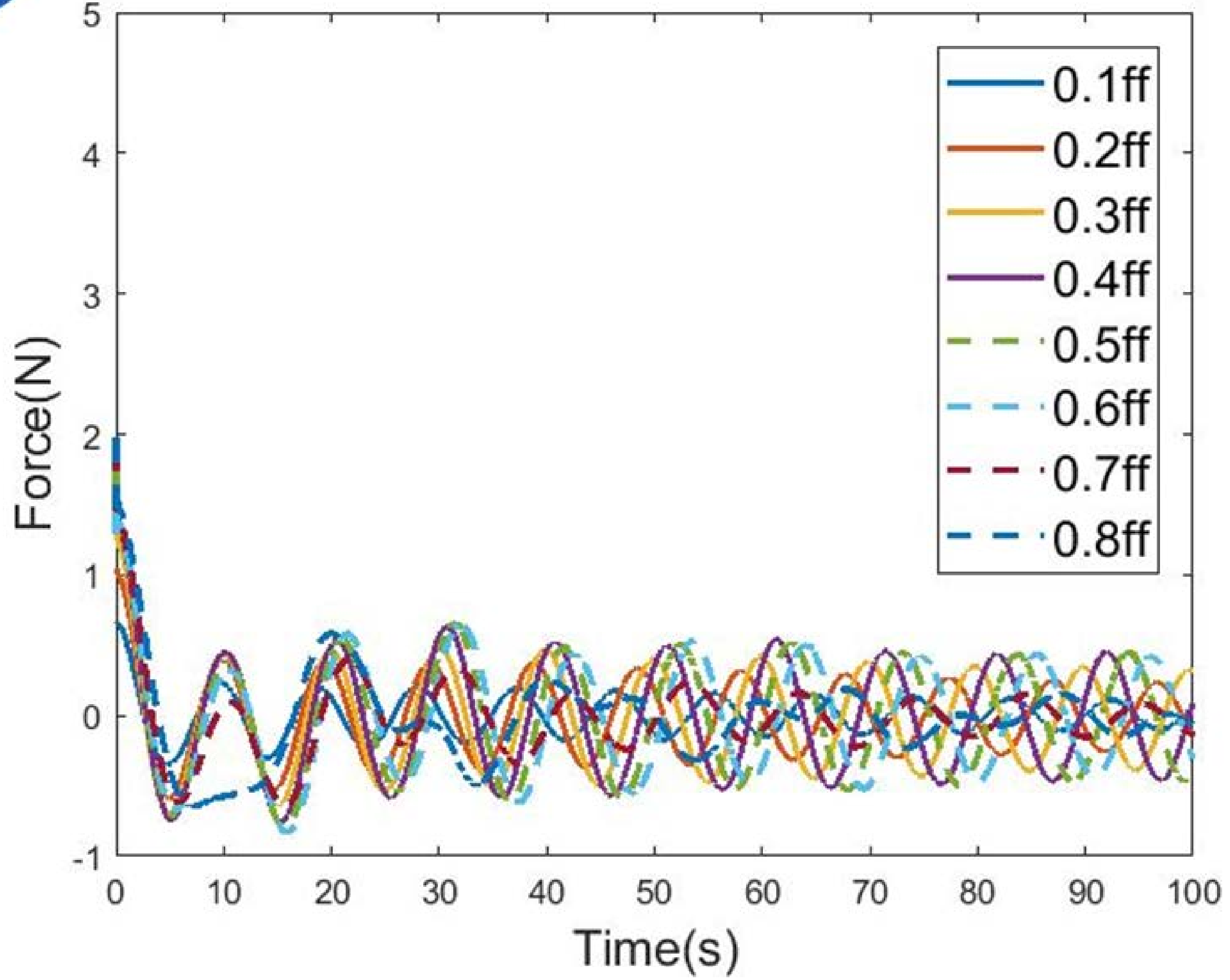
Cell Count	Acceleration (m/s^2)	Mesh Type	Avg % Diff from Finest Mesh CMy	Avg % Diff from Finest Mesh Fy	Avg % Diff from Finest Mesh Mx
116k	0.067	Polyhedral	31.57	140.31	233.61
250k	0.067	Polyhedral	11.32	6.44	8.86
400k	0.067	Polyhedral	4.32	4.23	3.36
500k	0.067	Polyhedral	2.66	2.29	1.88

MON-3 Center of Mass Movement in Principle Sloshing Direction



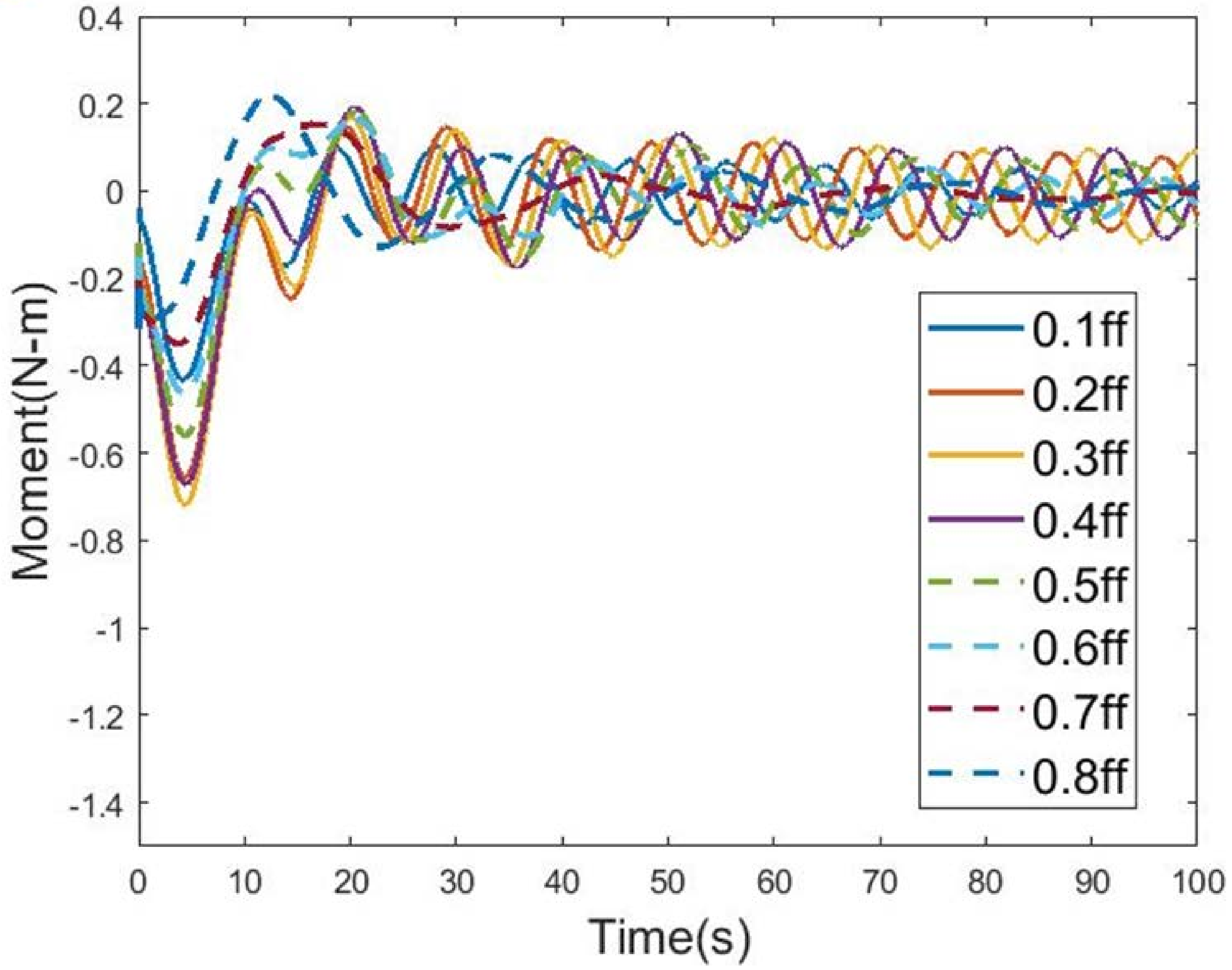
- Center of mass movement over time
- Smaller fill fractions have higher initial offsets due to larger percentage of mass displaced
- Higher fill fractions damp out more quickly

MON-3 Force Results



- Force on tank over time
- Higher fill fractions produce higher forces due to higher total mass

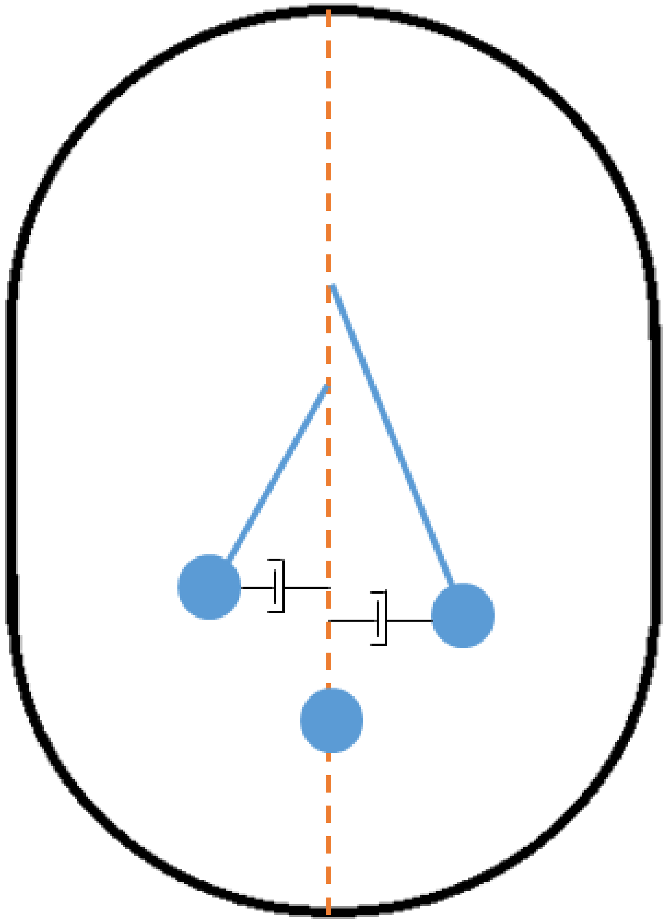
MON-3 Moment Results



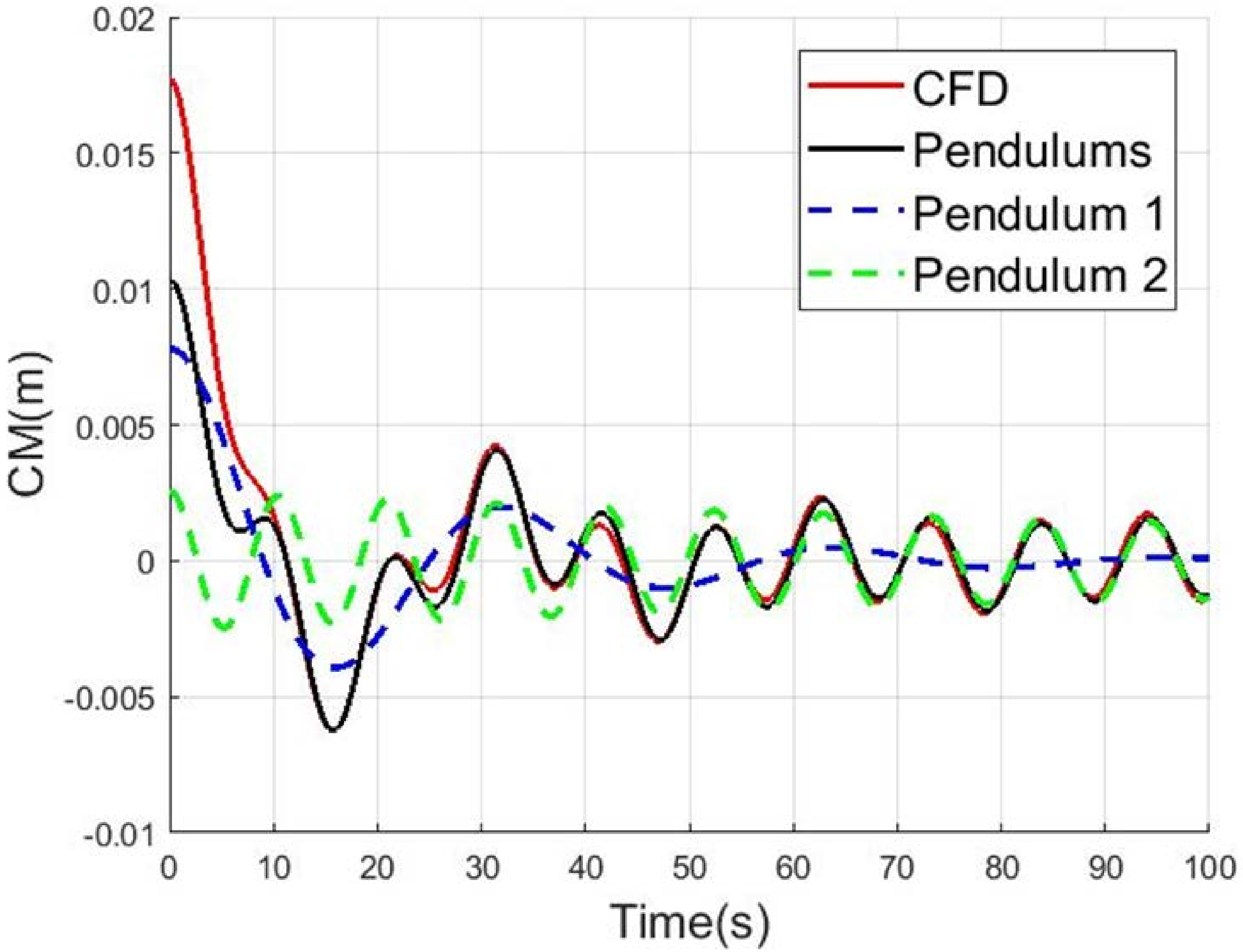
- Moment on the tank over time
- Moments calculated from forces so they have similar behavior

Pendulum Parameter Method

- Two damped pendulums and a static mass
- Pendulum parameters matched to CFD results using a MATLAB code written for this purpose [4]
  - Reduces error between CFD and pendulum model

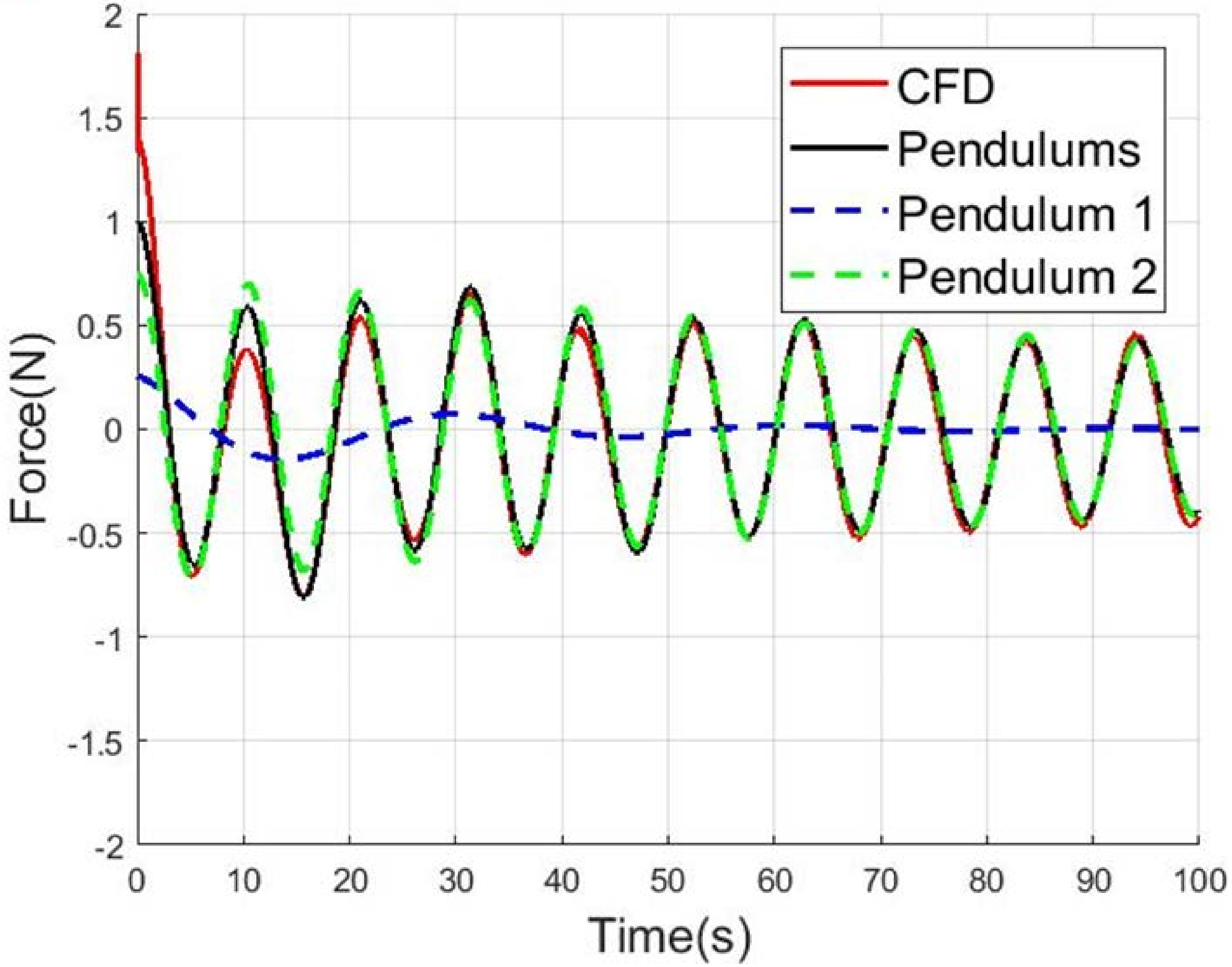


Pendulum Center of Mass Data for MON-3 at a Fill Fraction of 0.5



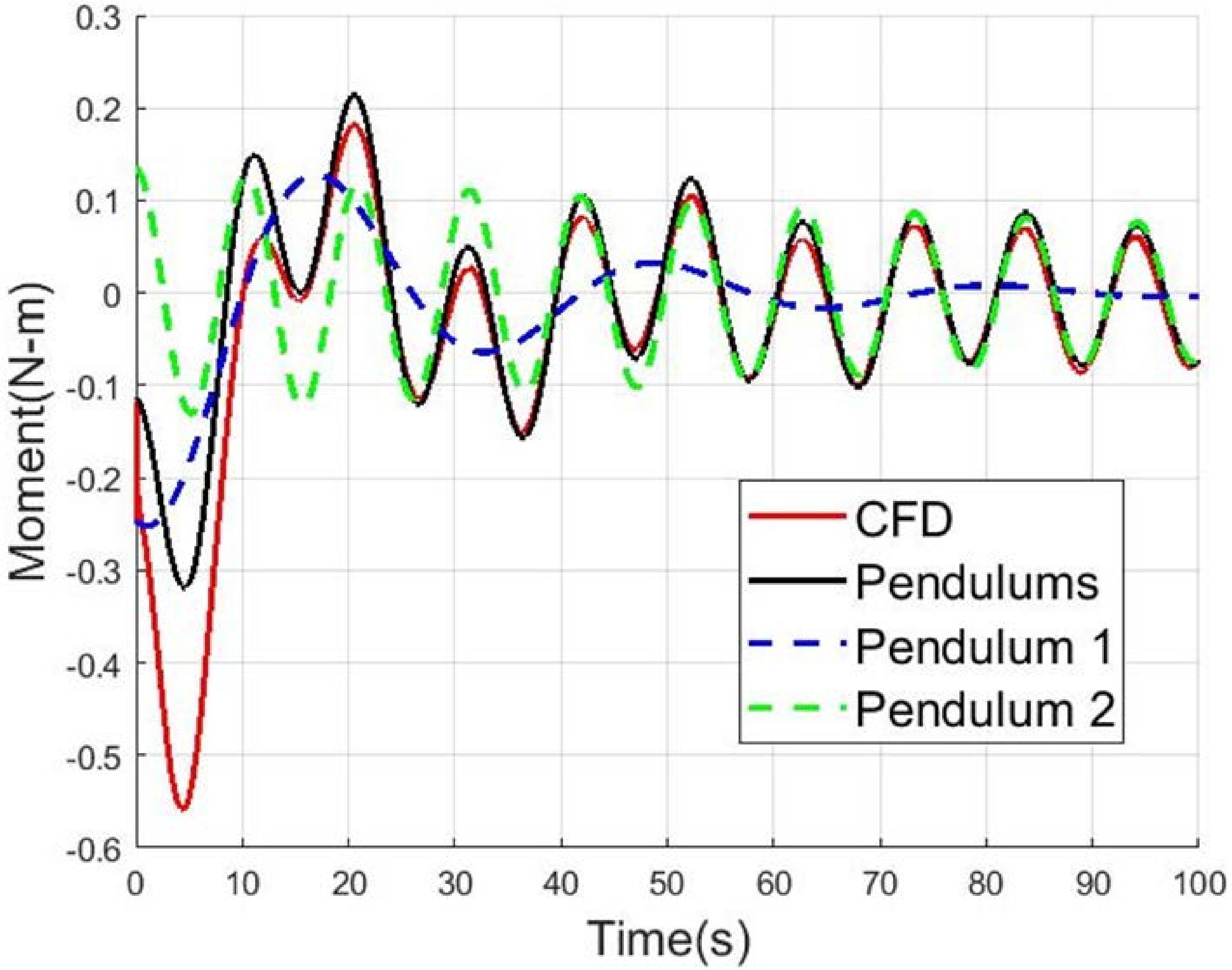
- Contribution from both the sector and full tank mode pendulums can be seen in the total behavior
- Full tank slosh has lower frequency, higher damping, and higher initial magnitude than sector slosh
- Matches CFD well except in beginning due to damping assumptions or surface initialization

Pendulum Force Data for NTO at a Fill Fraction of 0.5



- Force from pendulums matched CFD well if center of mass data matched well
- Full tank mode pendulum damps out very quickly

Pendulum Moment Data for NTO at a Fill Fraction of 0.5

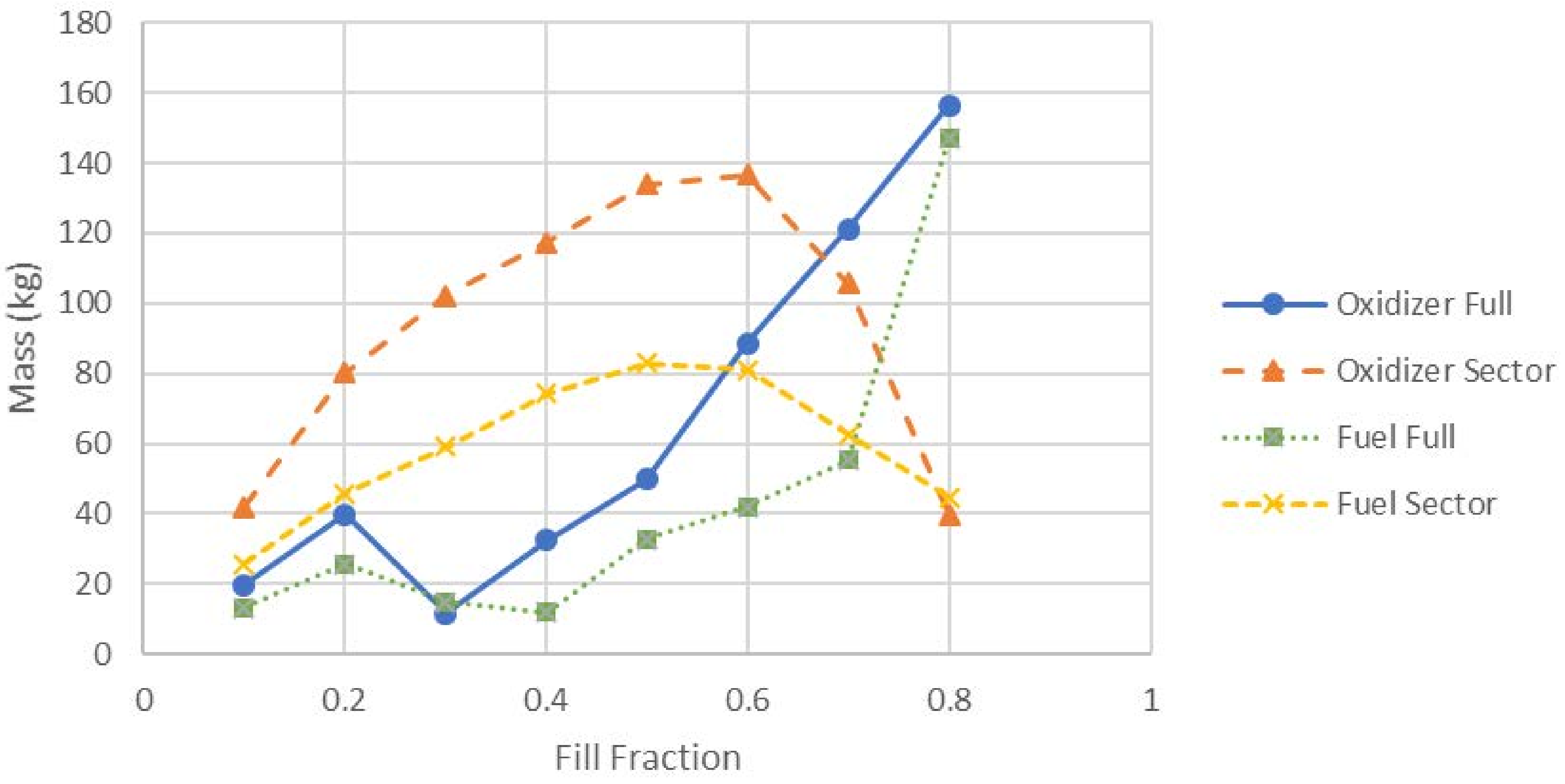


- Hinge point of the pendulums were adjusted to match data to CFD
- Full tank mode pendulum again damps out quickly

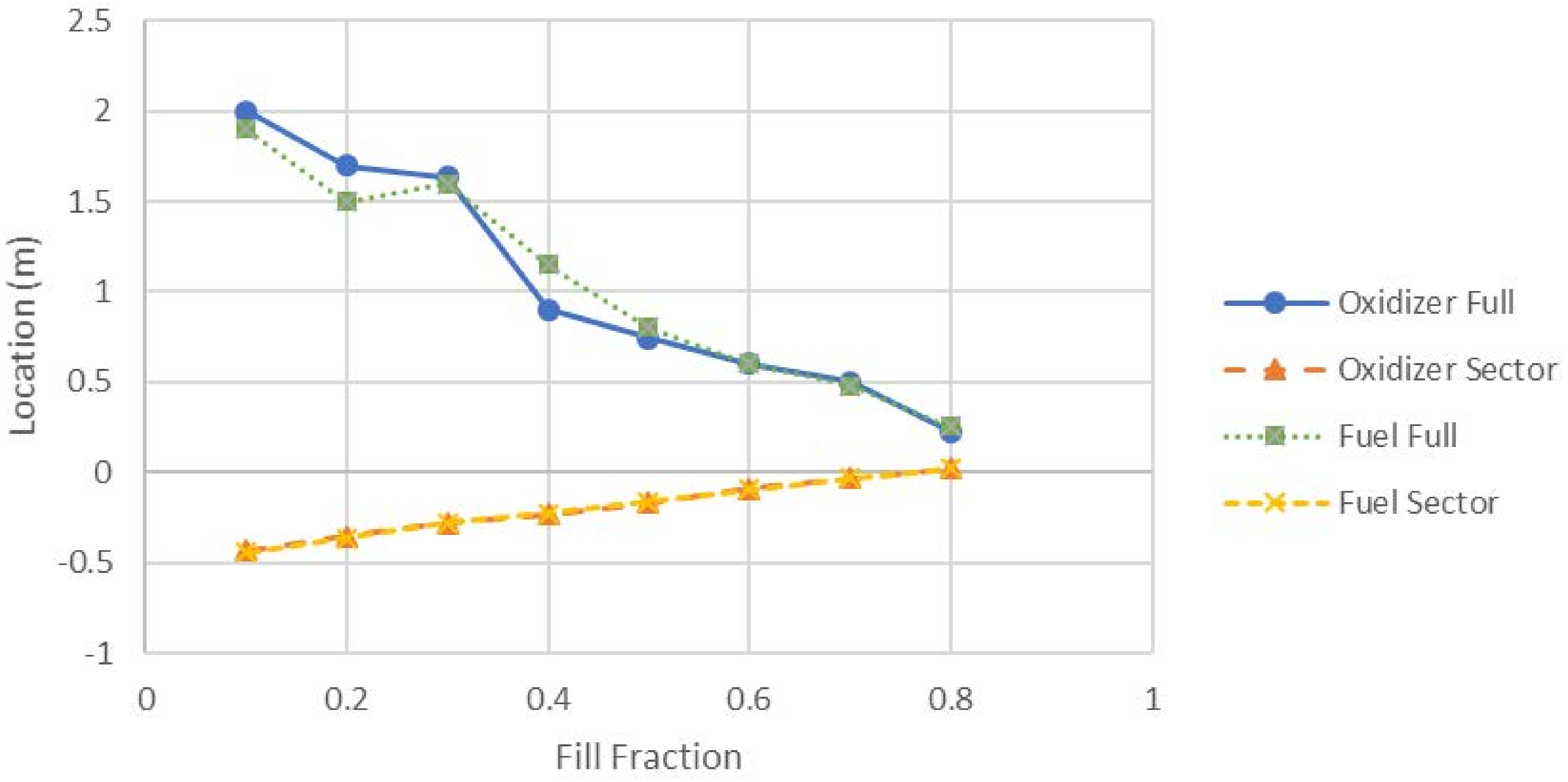
Pendulum Parameter Trends

- Trends allow interpolation between fill fractions not examined by CFD
- Two engineers completed the pendulum parameter matching process creating two sets of pendulum parameters at each fill fraction
  - Allowed analysis of impact of input variables on program output
- One set of parameters was chosen to represent each fill fraction in the trends to reduce error
  - To be used in other mission analyses

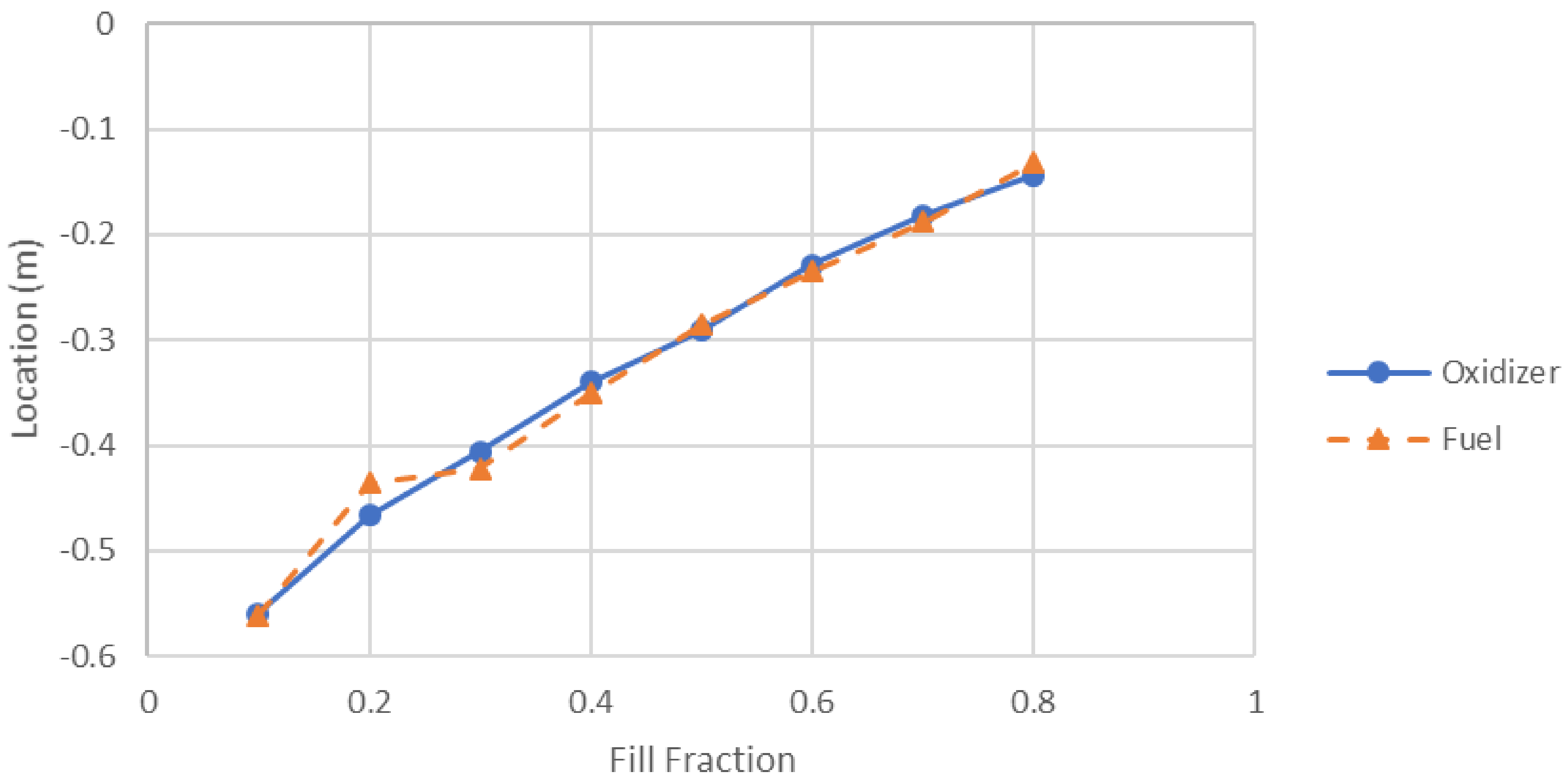
Pendulum Mass Trend for High Acceleration



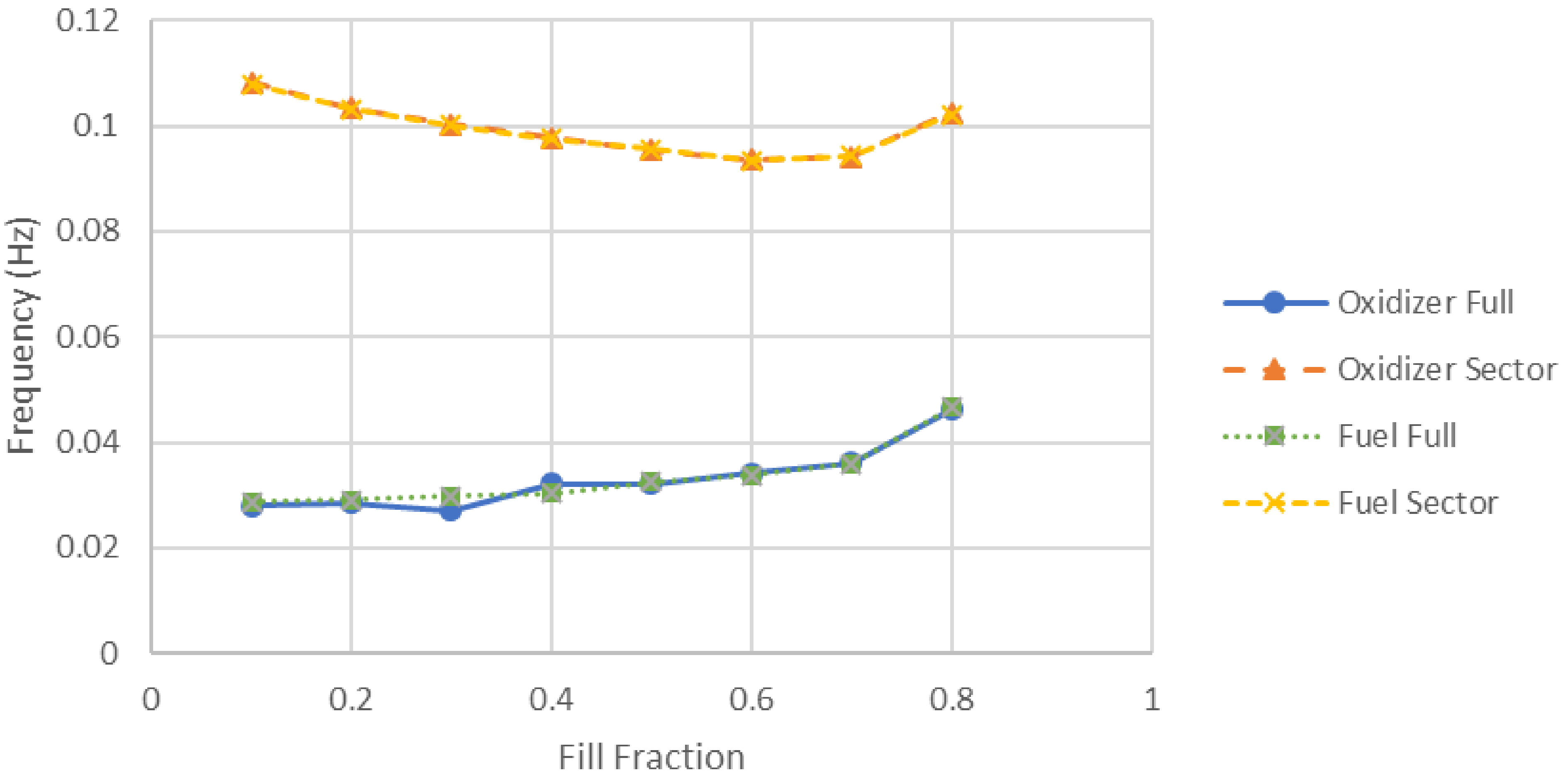
Pendulum Hinge Height Trend for High Acceleration



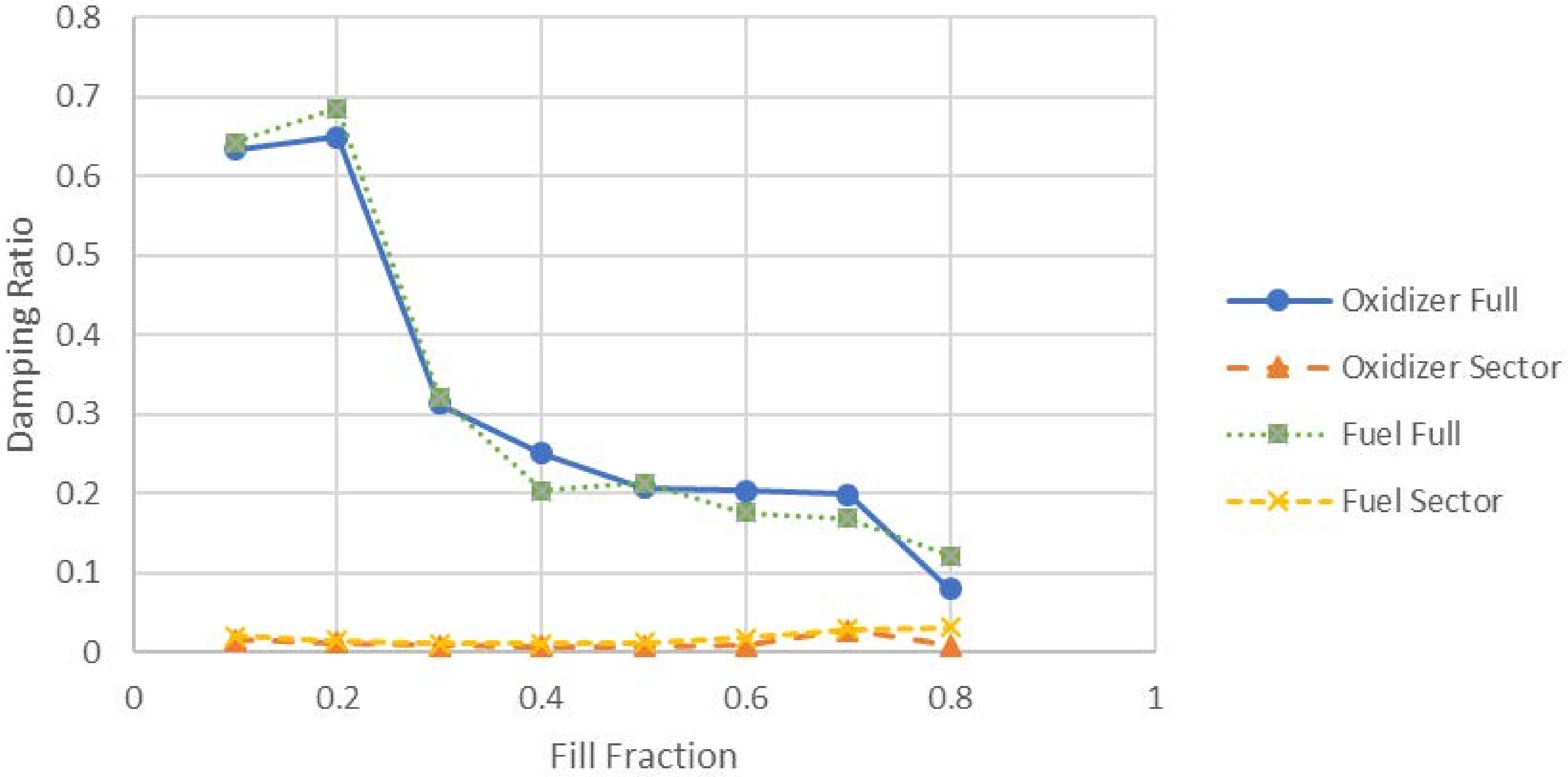
Static Mass Location Trend for High Acceleration



Pendulum Frequency Trend for High Acceleration



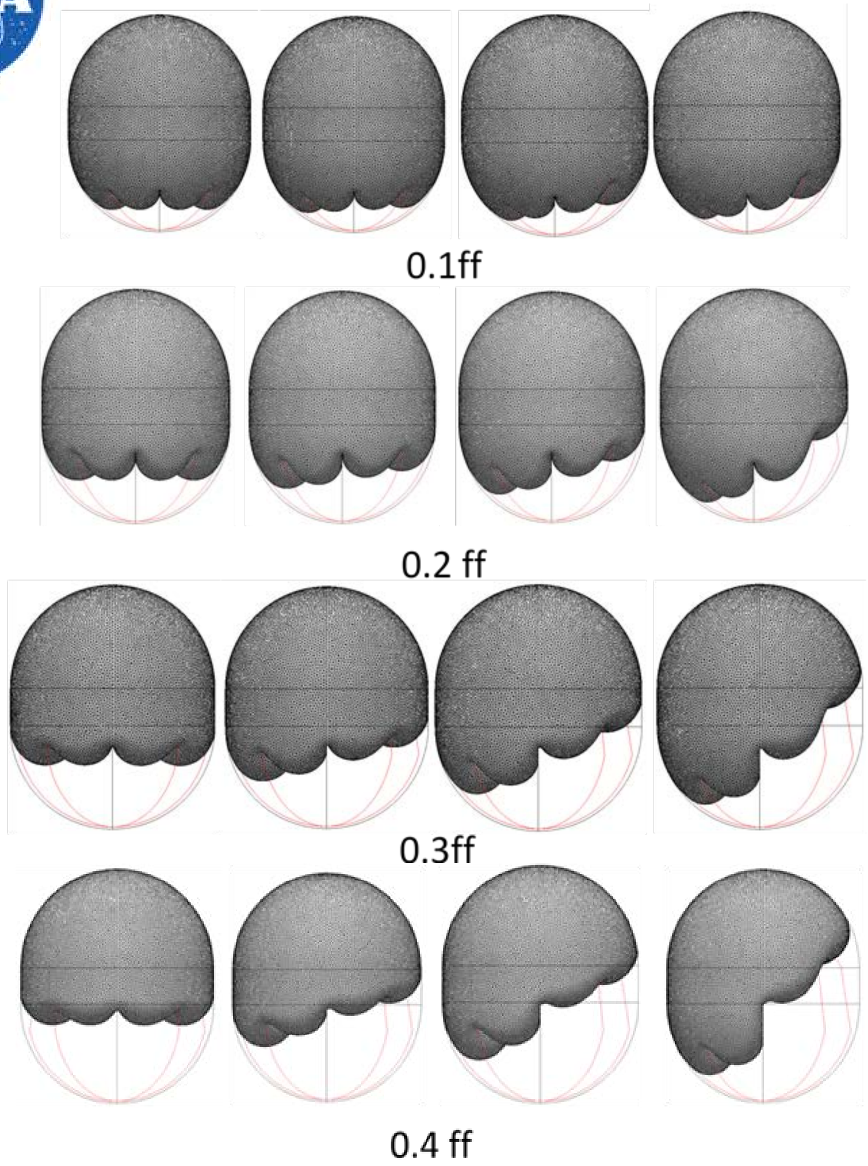
Pendulum Damping Ratio Trend for High Acceleration

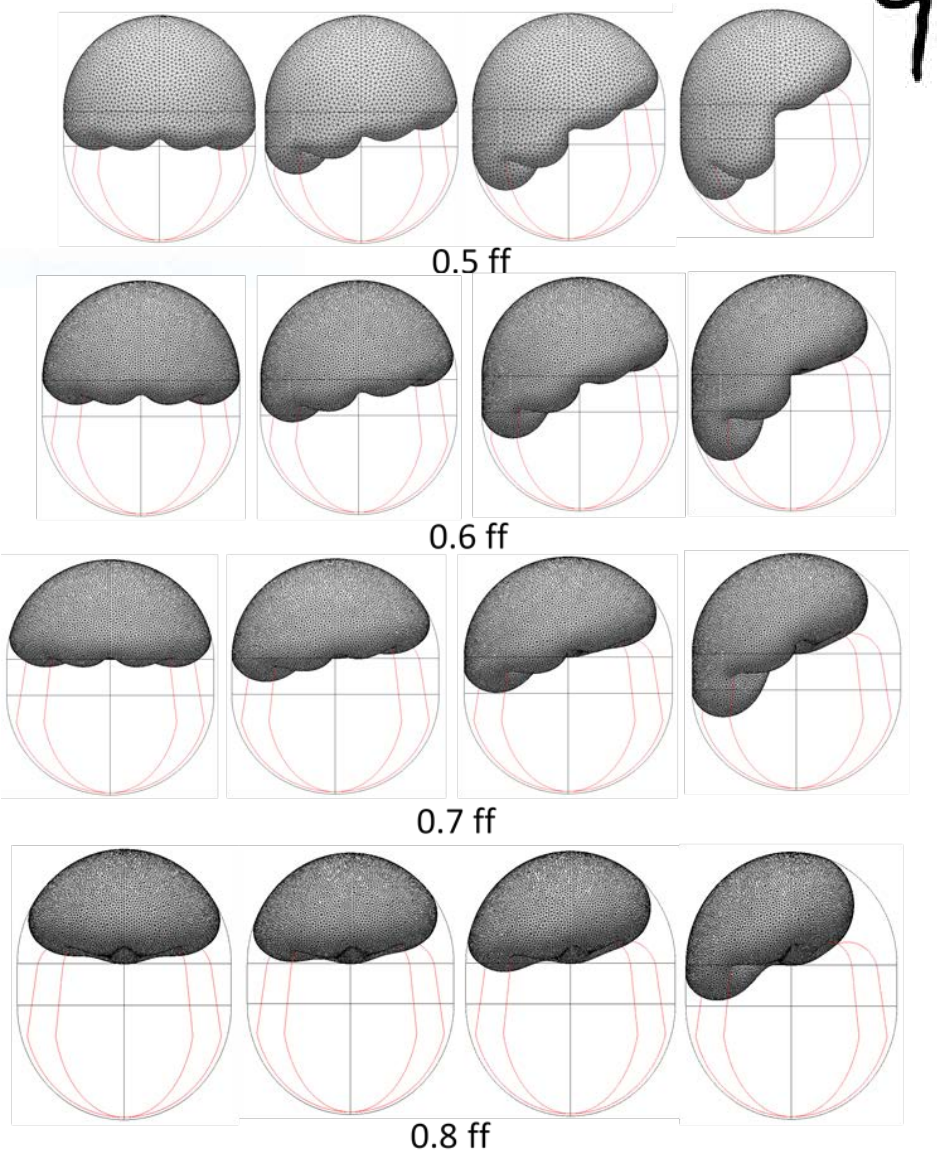


Low-G Cases

Method

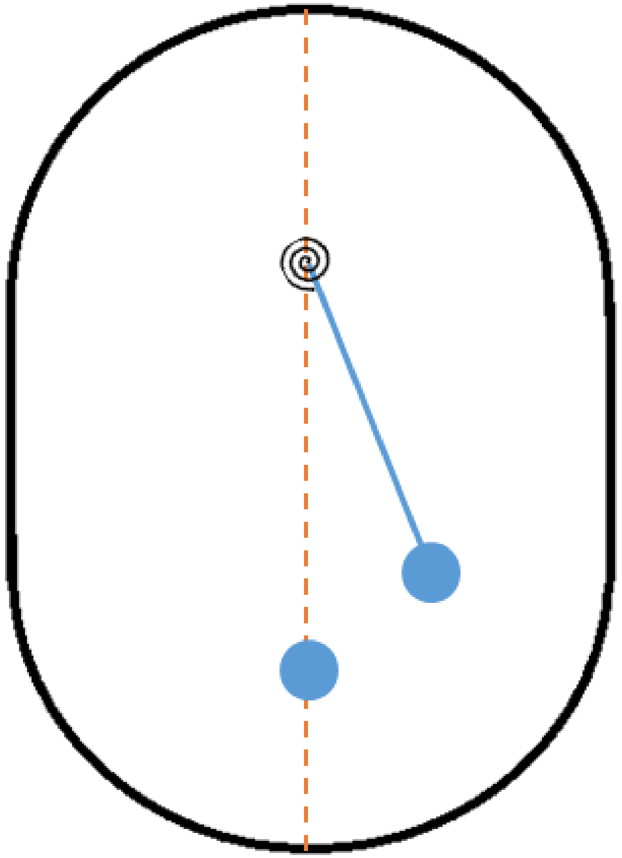
- Surface evolver used to model low-g cases
  - Program minimizes the energy of the system [5]
- Initialized with propellant symmetric about the centerline of the tank
- Iterated until no or insignificant movement in the center of mass was observed
- Run at multiple accelerations to allow pendulum model parameters to be found
  - Surface Evolver is a steady state code


0.1ff
0.2 ff
0.3ff
0.4 ff

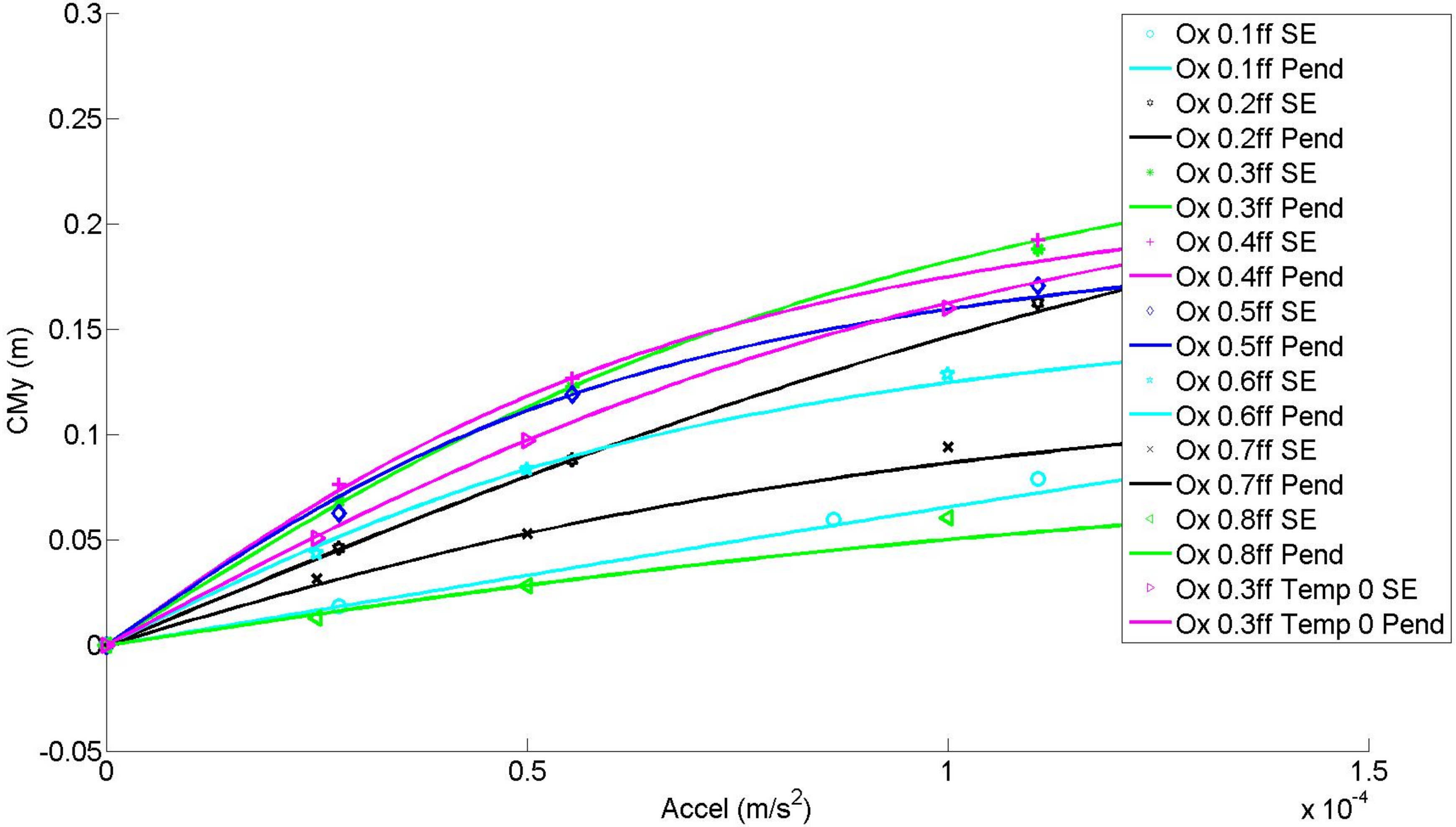

0.5 ff
0.6 ff
0.7 ff
0.8 ff

Pendulum Parameter Method

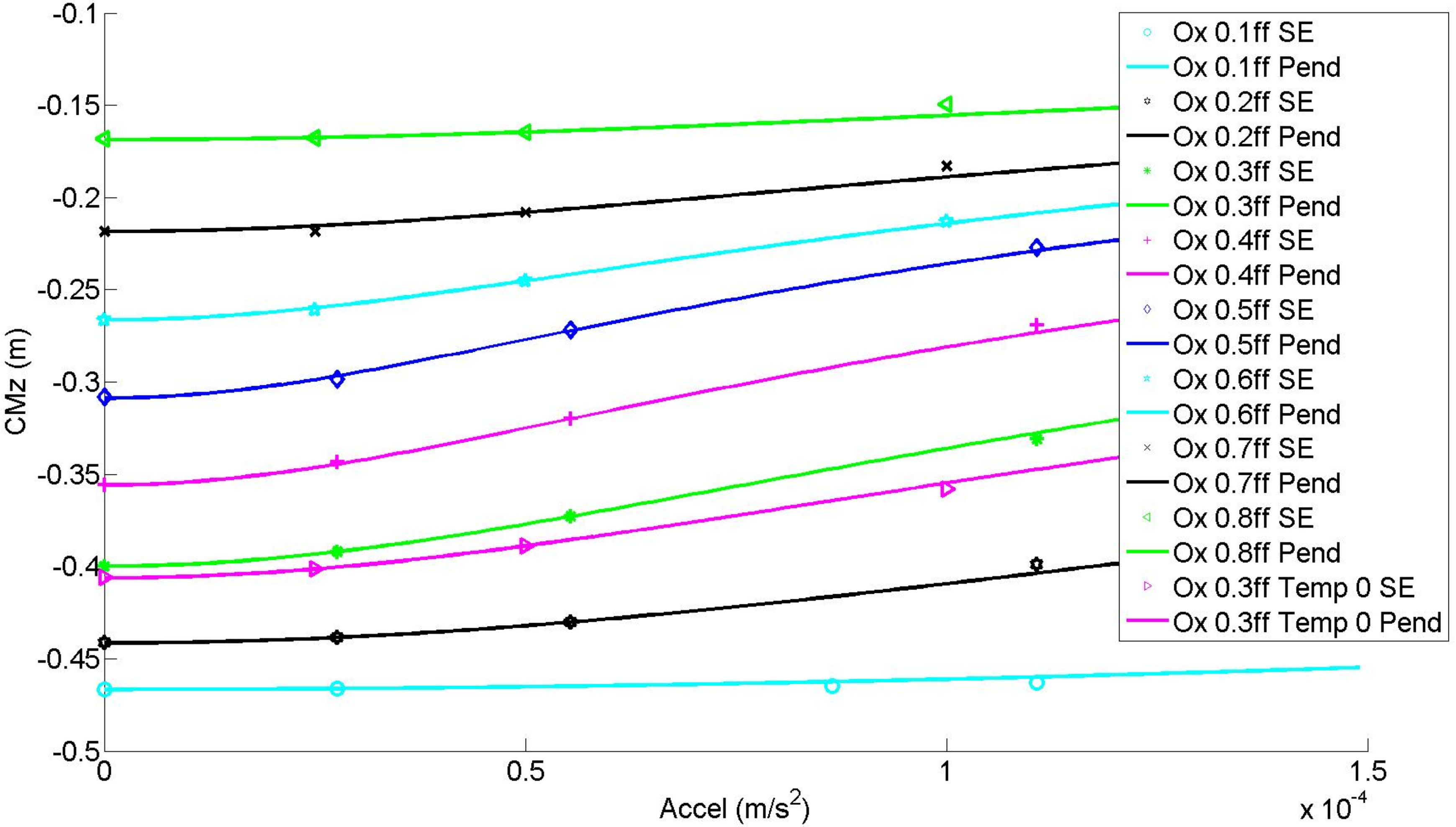
- Single damped pendulum with a torsional spring and a static mass
- Parameters derived through combination of graphical analysis of surface evolver results and a MATLAB code created for this purpose
- Damping ratio assumed to be 10% from heritage analyses [3]



Center of Mass Match Between Surface Evolver and Pendulum Model in the Horizontal Direction



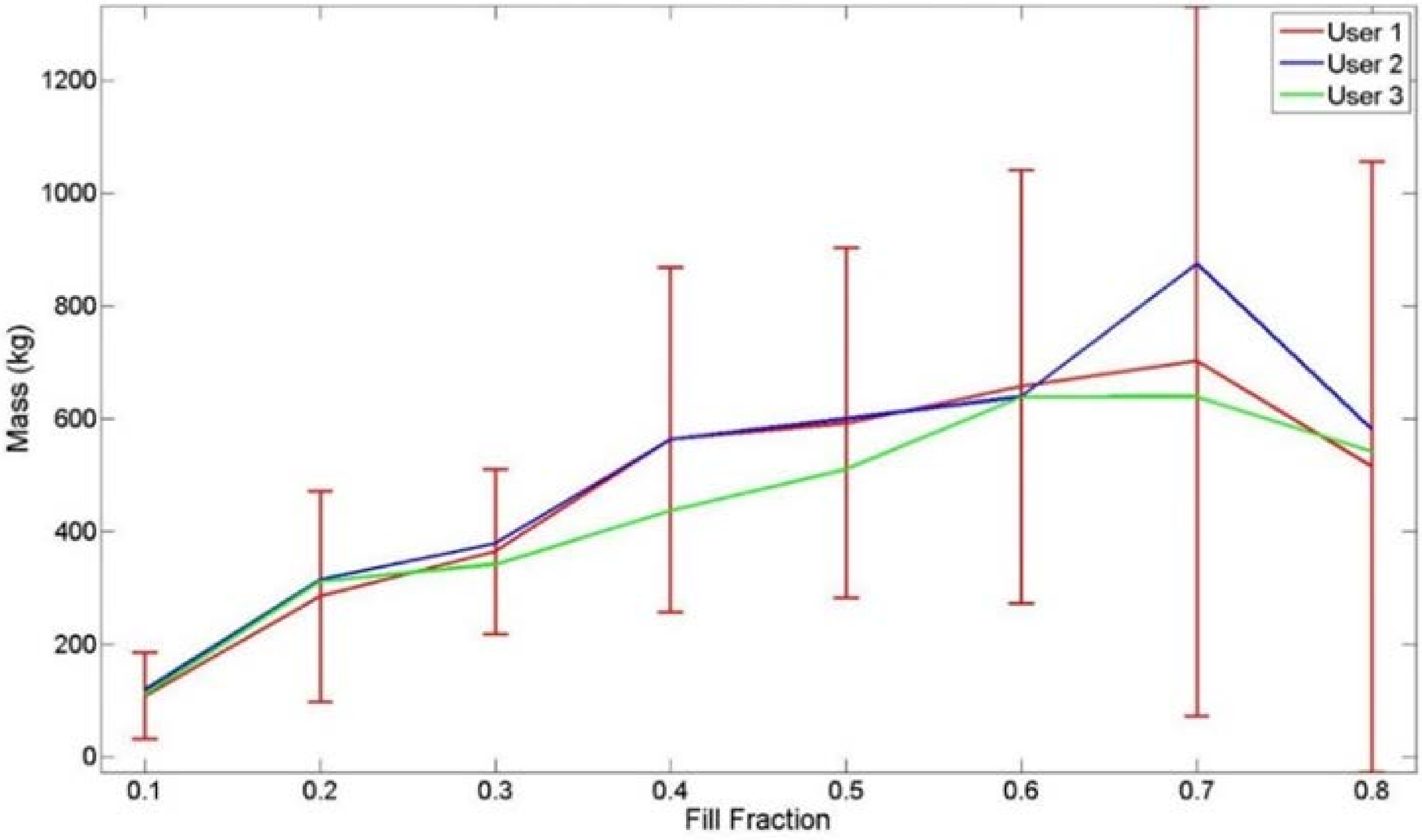
Center of Mass Match Between Surface Evolver and Pendulum Model in the Vertical Direction



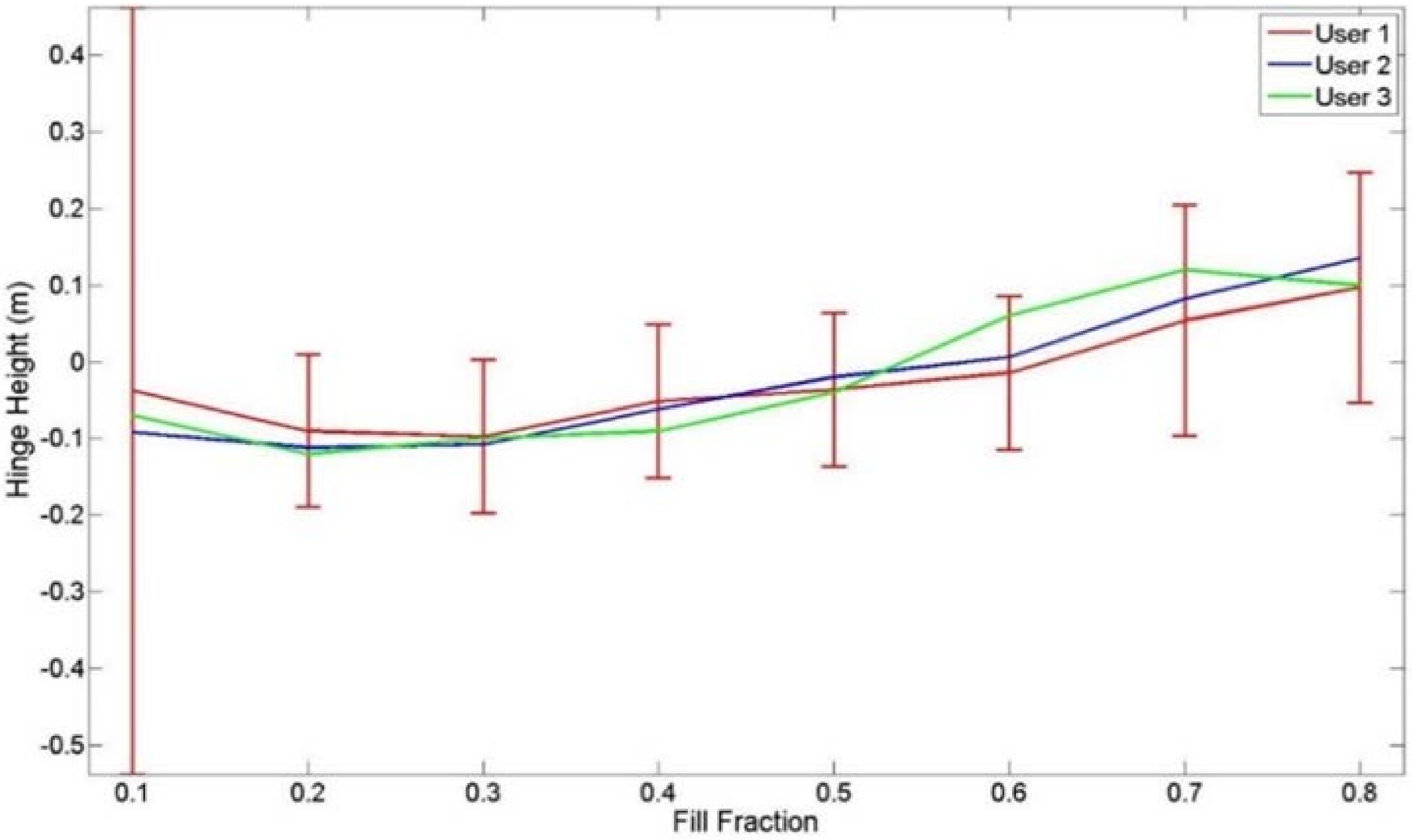
Parameter Uncertainty

- Uncertainty in the input values estimated from reasonable user decisions
- Partial derivatives of the equations used to derive the pendulum parameters were taken with respect to input variables
- Root squared sum method used to add errors from input variables
- Uncertainties checked using three engineers completing the same process for the same Surface Evolver results

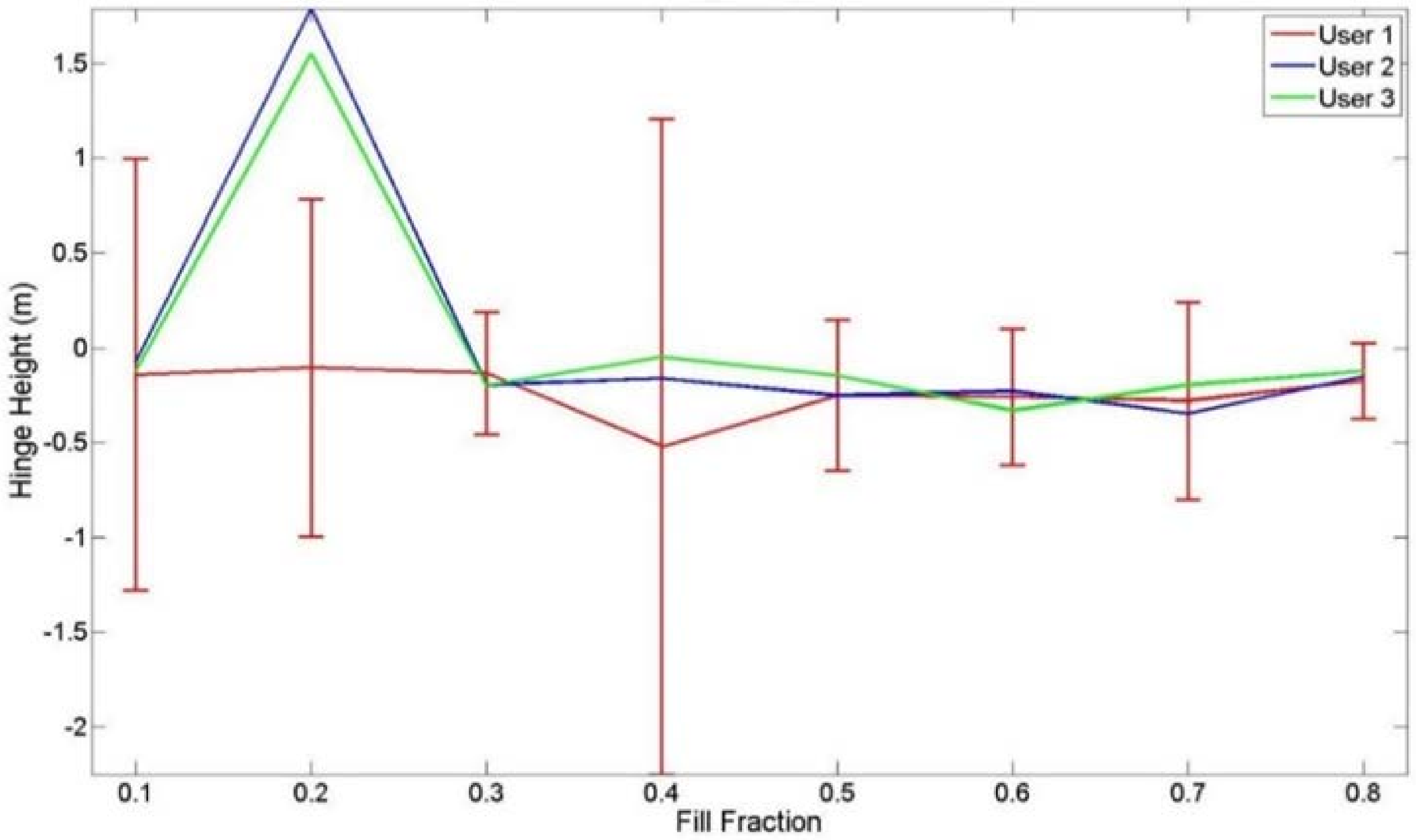
Pendulum Mass Versus Fill Fraction



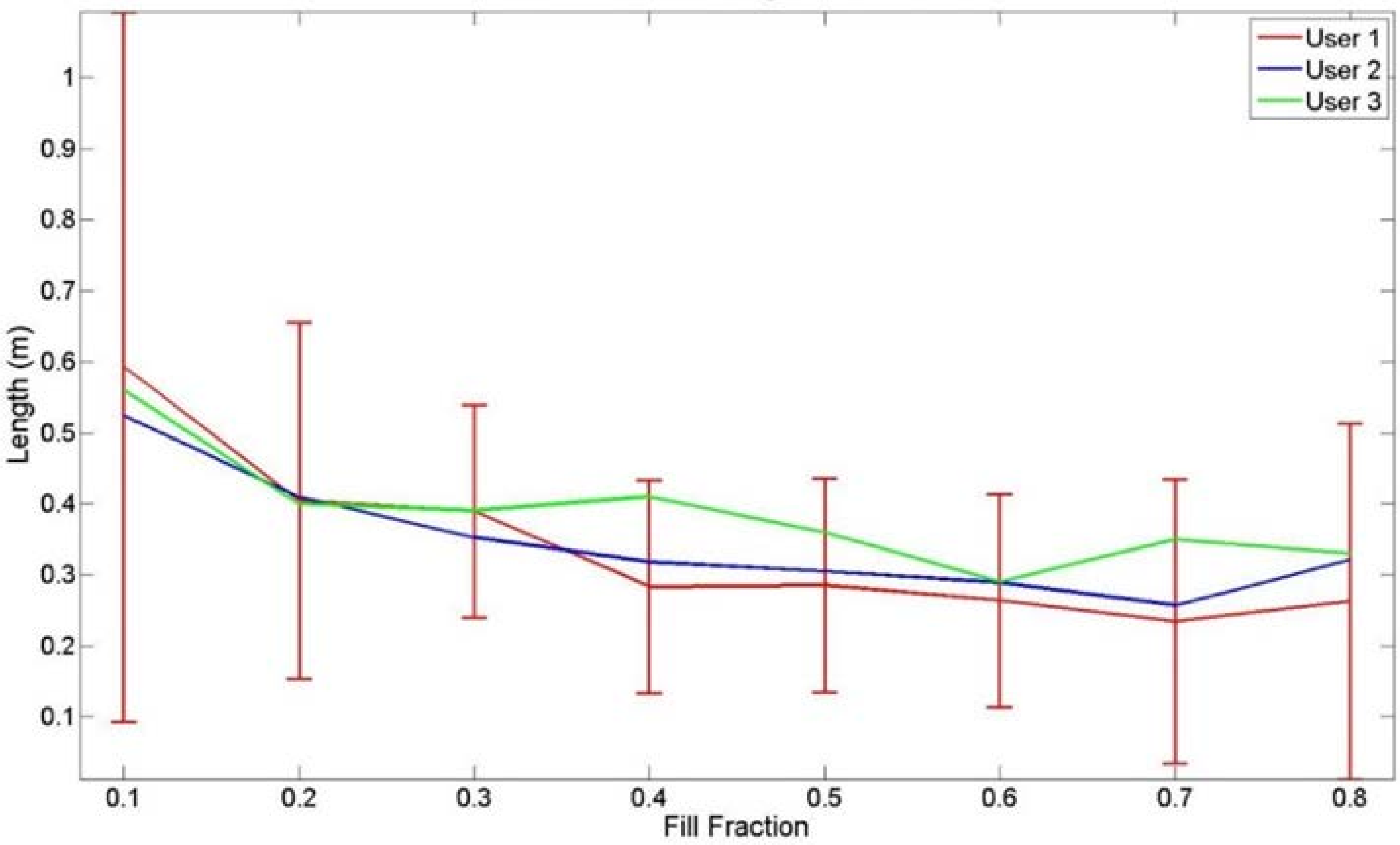
Pendulum Hinge Height Versus Fill Fraction



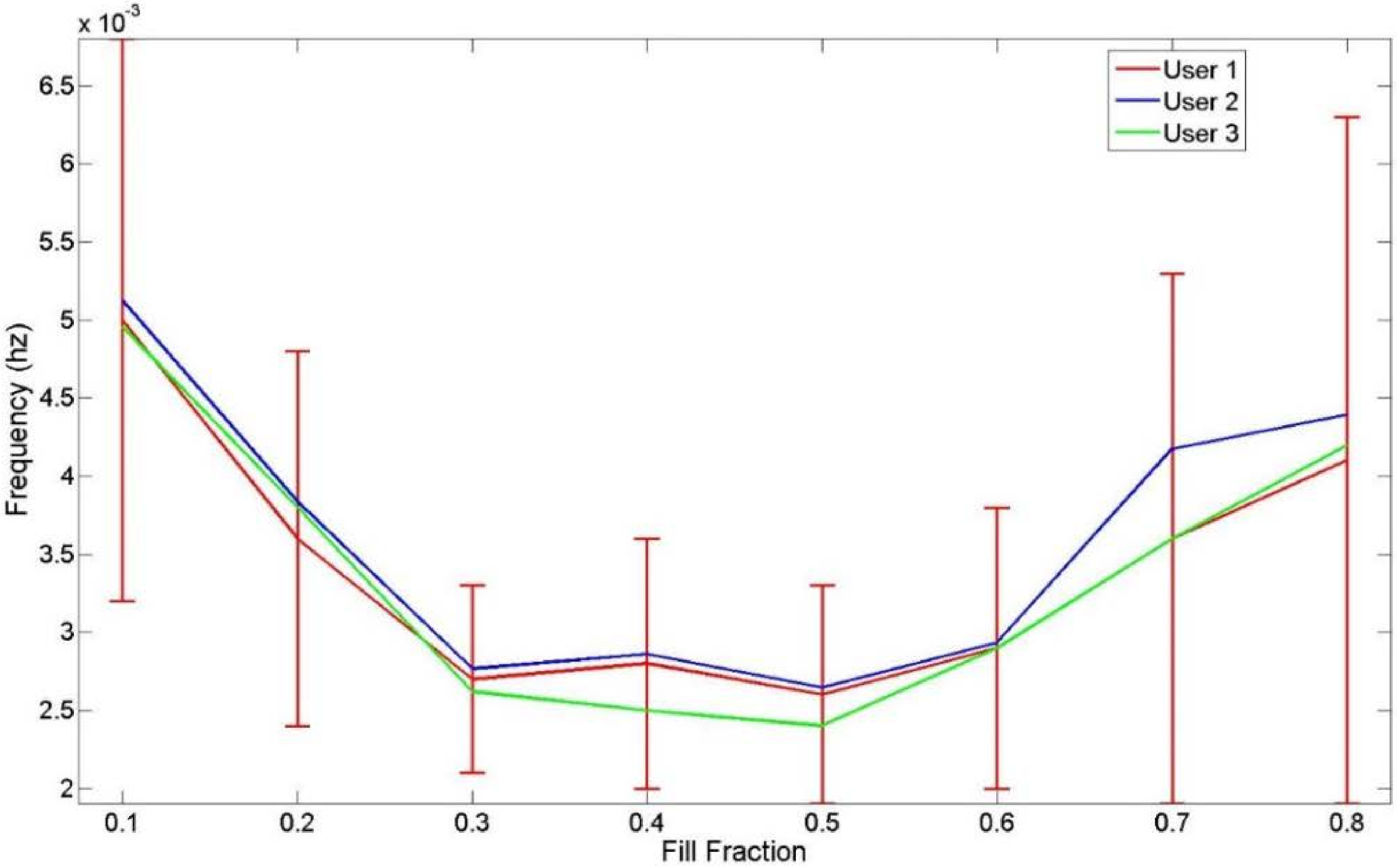
Pendulum Static Hinge Height Versus Fill Fraction



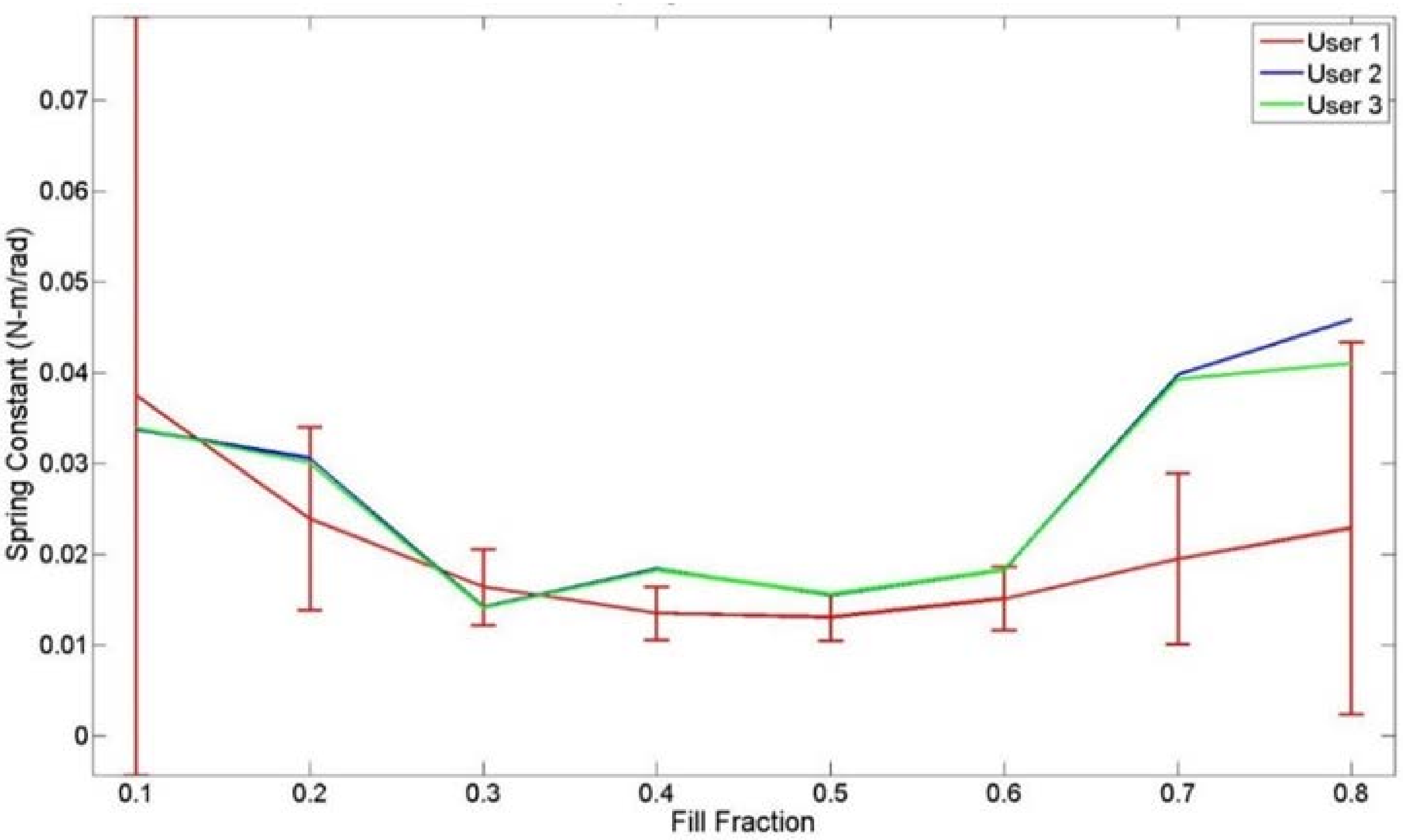
Pendulum Length Versus Fill Fraction



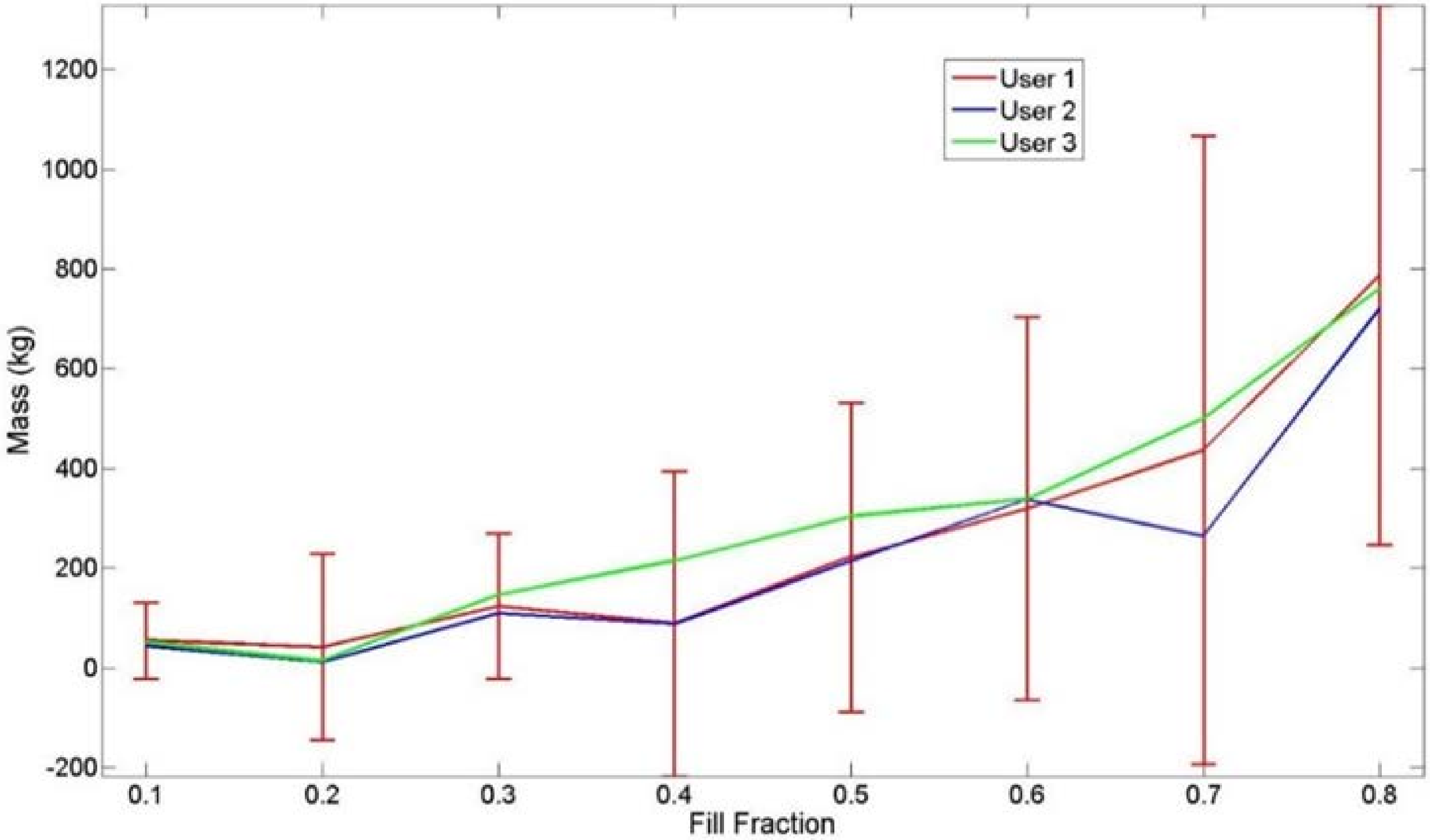
Pendulum Frequency Versus Fill Fraction



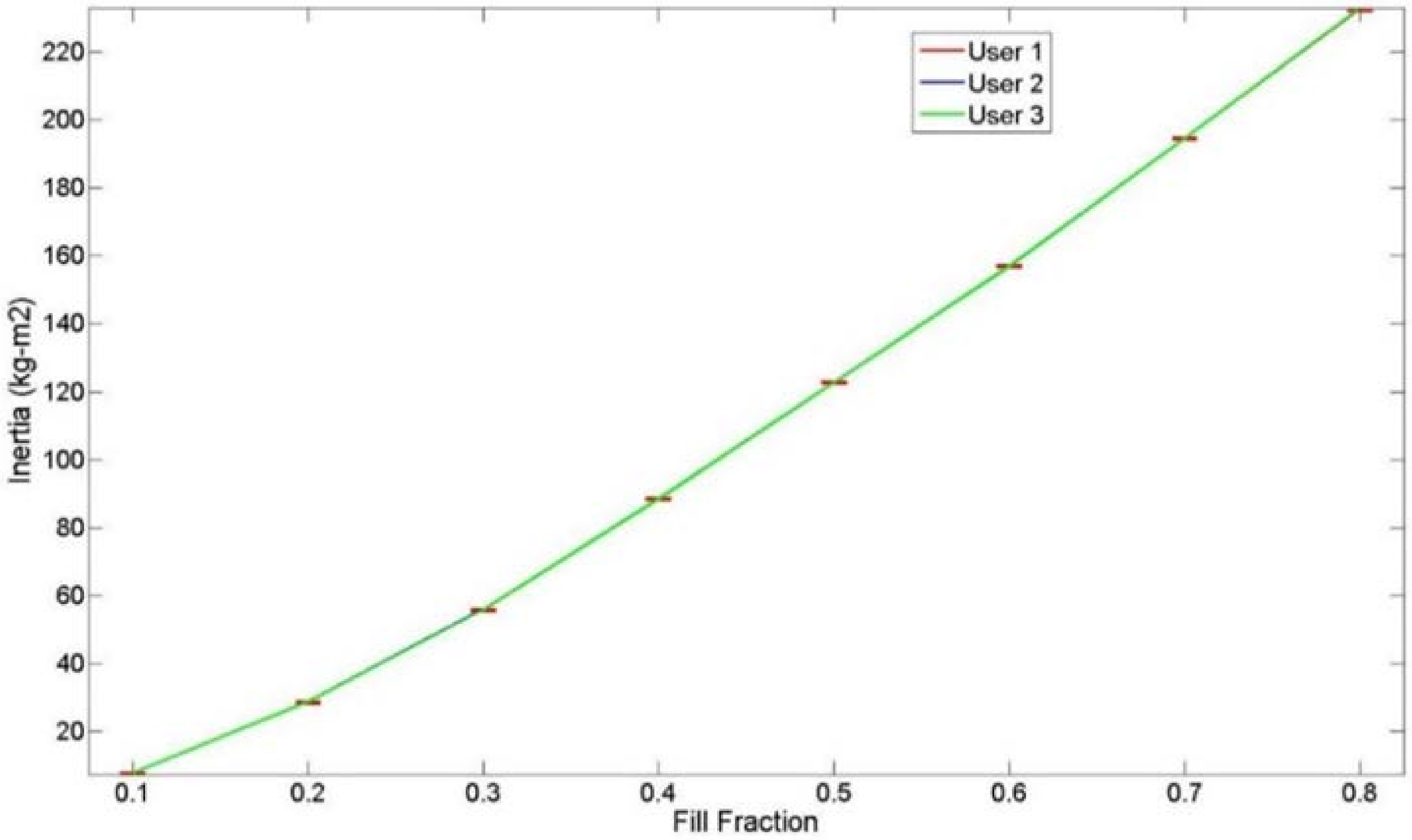
Pendulum Spring Constant Versus Fill Fraction



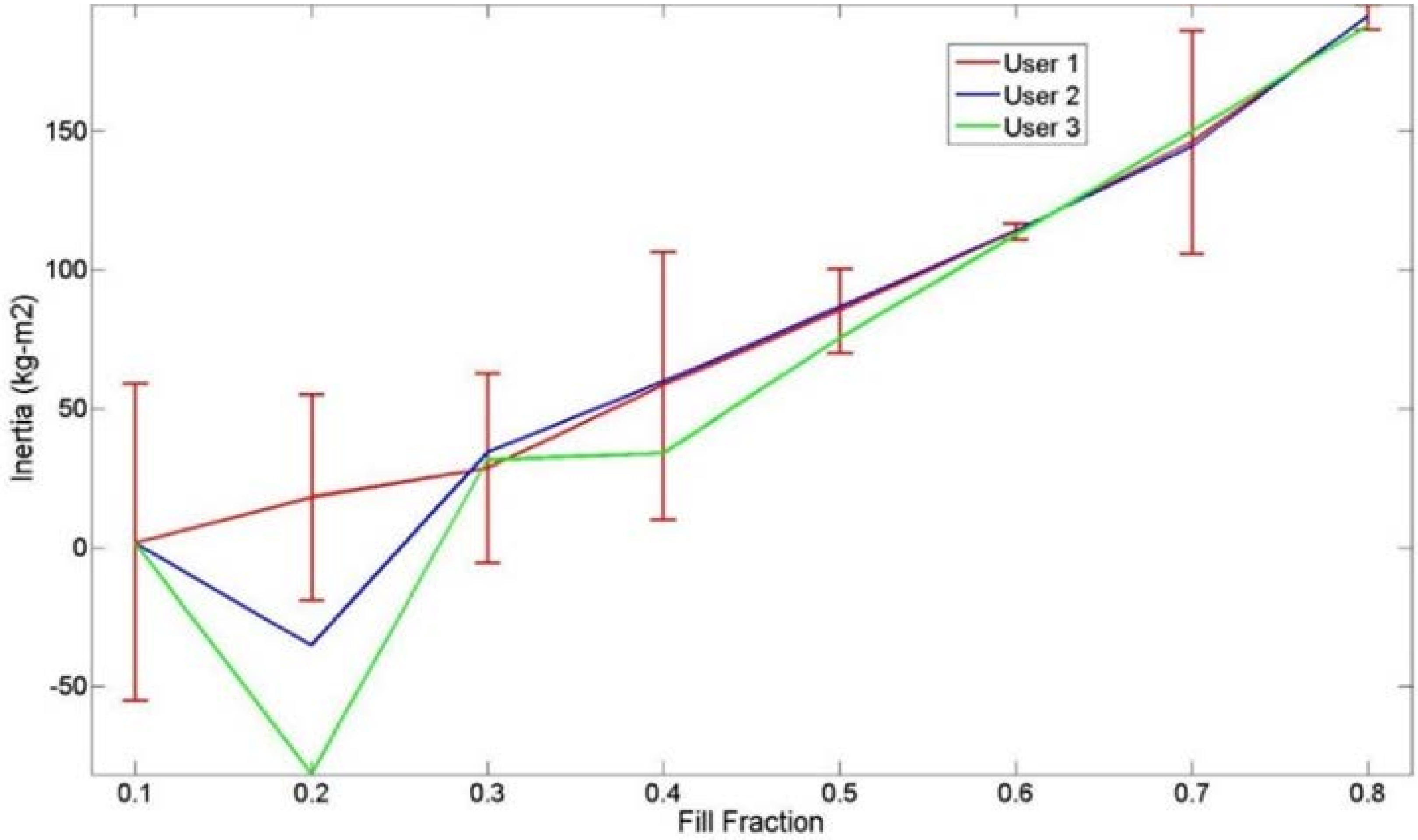
Static Mass Versus Fill Fraction



Static Vertical Axis Moment of Inertia Versus Fill Fraction



Static Horizontal Axis Moment of Inertia Versus Fill Fraction



Uncertainty Summary

- Significant uncertainty in the results
- Values obtained by uncertainty analysis appear to be sufficient in nearly all cases
- Input variable most likely at fault when uncertainty bars don’t encompass differences in the user results is the input pendulum angle due to large uncertainties in this value

Conclusion

- Mechanical models found for both high and low-g cases
- Reasonable differences between users show repeatability of processes
- Trends found between fill fractions to allow easy interpolation for inputs to attitude control system software
- Changes in trend behavior occur at locations where PMD and tank geometry change most rapidly

References

[1] Michell, R. C. et. al., “Engineering Properties of Rocket Propellants,” Air Force Rocket Propulsion Laboratory, AD-771 580, Springfield, VA, November 1973.

[2] Dodge, F. T., “The New “Dynamic Behavior of Liquids In Moving Containers,”” Southwest Research Institute, San Antonio, TX, 2000.

[3] Enright, P. J. and Wong, E. C., “Propellant Slosh Models for the Cassini Spacecraft,” *AIAA Astrodynamics Conference,* Scottsdale, AZ, USA, 1994, pp. 186-195.

[4] Ng, W. and Benson, D., "Two-Pendulum Model of Propellant Slosh in Europa Clipper PMD Tank," Thermal and Fluids Analysis Workshop, Report Number GSFC-E-DAA-TN45416, August 2017.

[5] Brakke, K., "Surface Evolver Overview," *Surface Evolver Documentation* [online], http://facstaff.susqu.edu/brakke/evolver/html/intro.htm#overview [retrieved 19 May 2018].