Two-Pendulum Model of Propellant Slosh in Europa Clipper PMD Tank

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Outline

- Objective
- Background
- Results and literature verification
  - Mass
  - Frequency
  - Damping ratio
  - Hinge location
- Conclusions

Objective

Model propellant slosh for Europa Clipper using two pendulums such that controls engineers can predict slosh behavior during the mission.

BACKGROUND

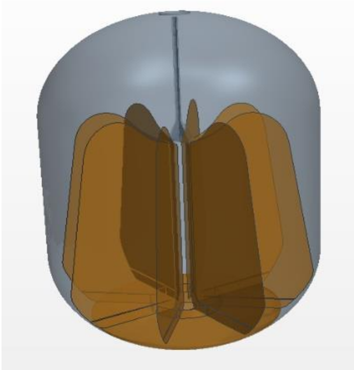
Motivation

- Importance of predicting propellant slosh
  - Sloshing changes CM (center of mass) of spacecraft and exerts forces and torques on spacecraft
  - Avoid natural frequencies of structures
  - Size ACS (Attitude Control Systems) thrusters to counteract forces and torques
- Can model sloshing fluid as two pendulums with specific parameters (mass, length, damping)

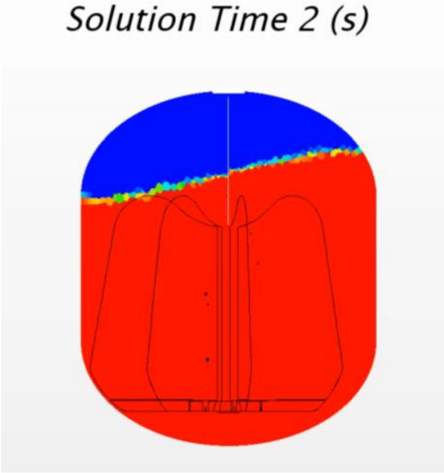
Background

- Europa Clipper tanks
  - Bipropellant system
  - Cylindrical with domed top and bottom
  - 8-vane PMD (propellant management device)
- CFD (computational fluid dynamics) data used as "real" slosh behavior
  - Have data for two propellants at three fill fractions each
  - Initial condition of 15 degree free surface offset, released and allowed to settle
  - CFD requires long computing time -> Need a computationally simple model

Notional tank and PMD



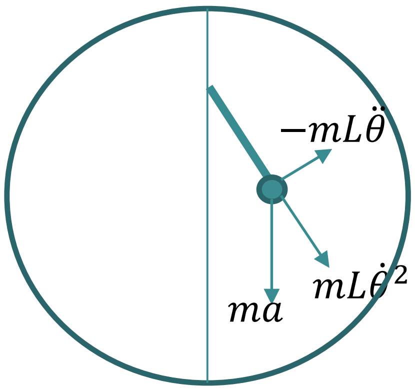
CFD Simulation



Background

- Pendulum model
  - Model fluid movement as two pendulums attached to central axis of the tank
  - For each CFD data set, find parameters: mass, frequency, damping ratio, attachment height

Forces exerted on tank by fluid



$$CM(t) = mLsin\theta(t)$$

$$= mLsin\,\theta_0 e^{-\xi\omega t}\left(\frac{\xi\omega}{\omega\sqrt{1-\xi^2}}\sin\left(\omega\sqrt{1-\xi^2}\,t\right) + \cos\left(\omega\sqrt{1-\xi^2}\,t\right)\right)$$

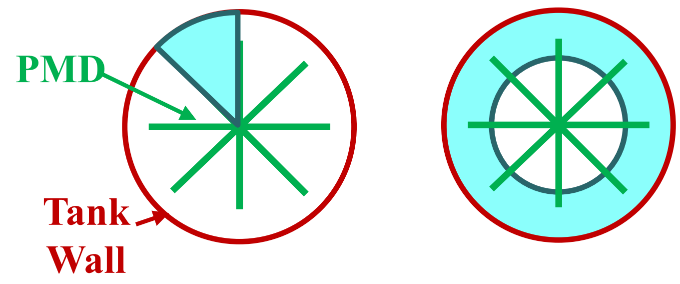
Existing Literature

- SP-106 (1966), SwRI (2000): Analytical equations and empirical correlations for damping and frequency
  - Includes bare cylindrical (no PMD), sector, and annular tanks

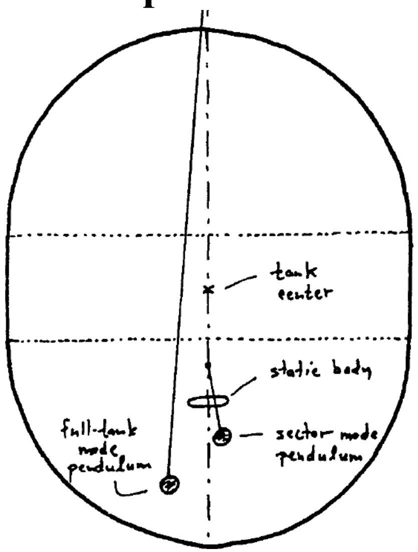
- Cassini slosh paper (1994): Two pendulum model
  - Slosh around PMD was modeled as combination of sector and annular slosh modes
  - Two separate pendulums to model two slosh modes
  - Static mass component at bottom that experiences little movement

Sector tank mode (top view)

Annular tank mode (top view)

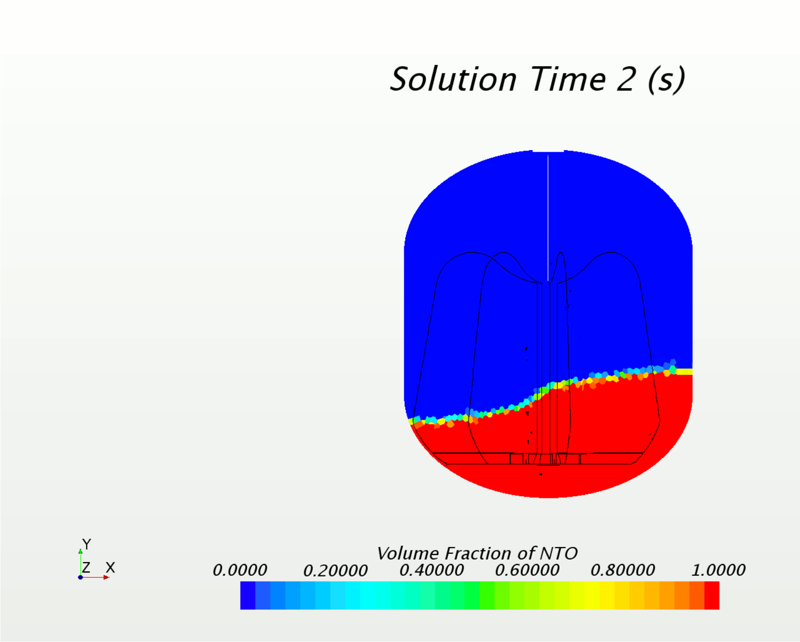


Cassini paper illustration of double pendulum model



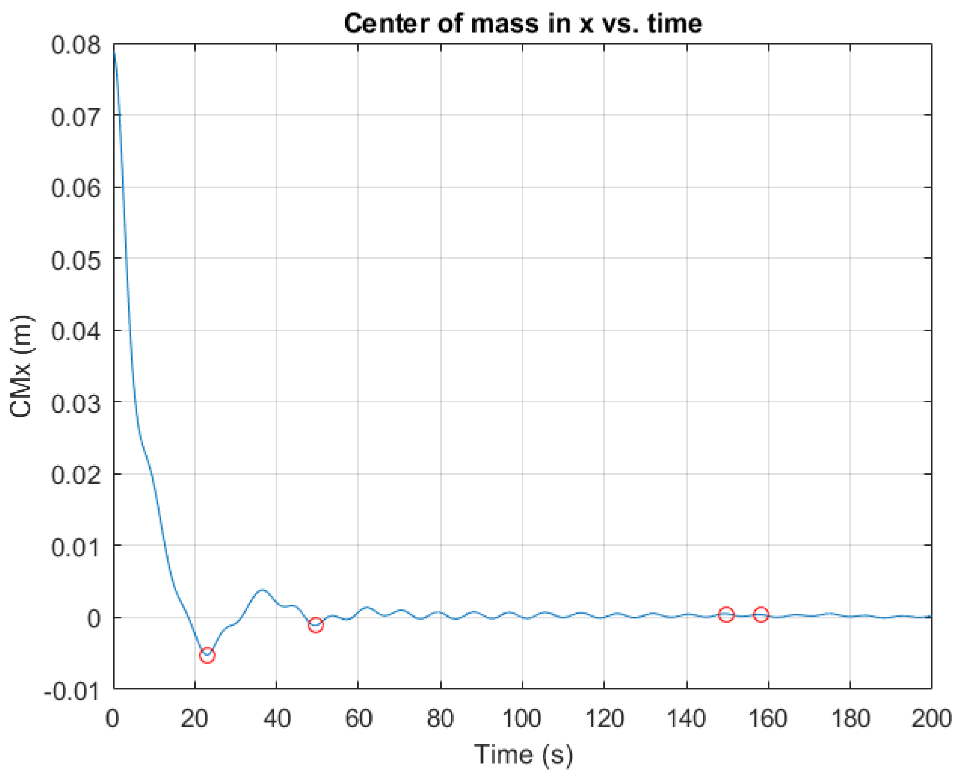
METHODS OVERVIEW

Generate CFD Data



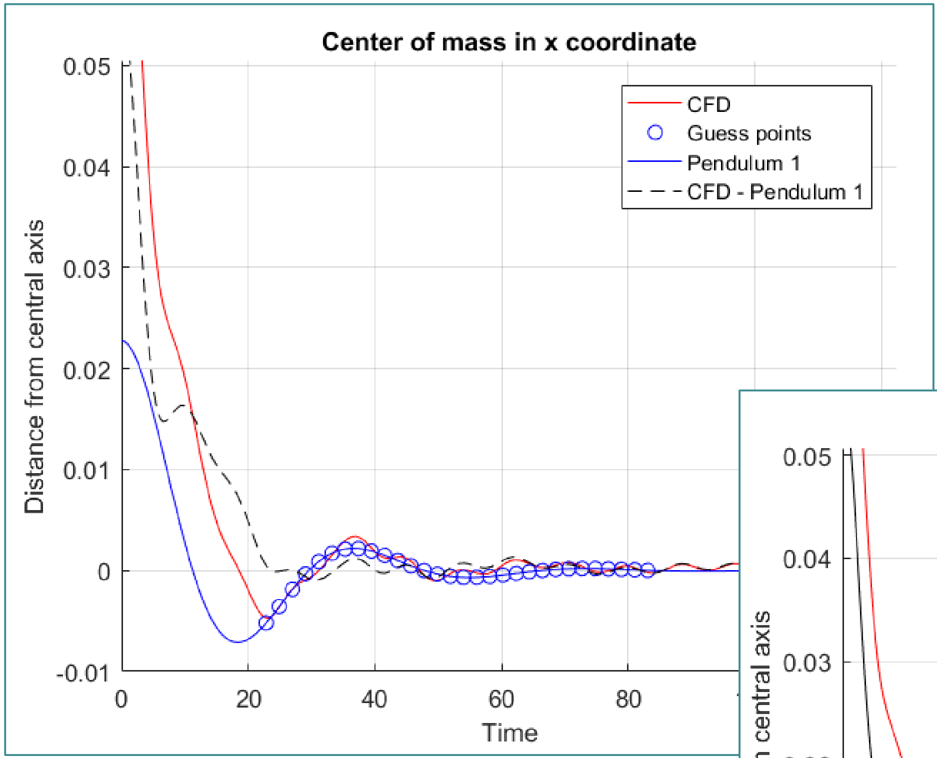
- Propellants: NTO and MMH
- Fill fractions: 25%, 50%, 85%
- Data: CM, Force, Moment (all 3 axes)

Find Initial Guesses

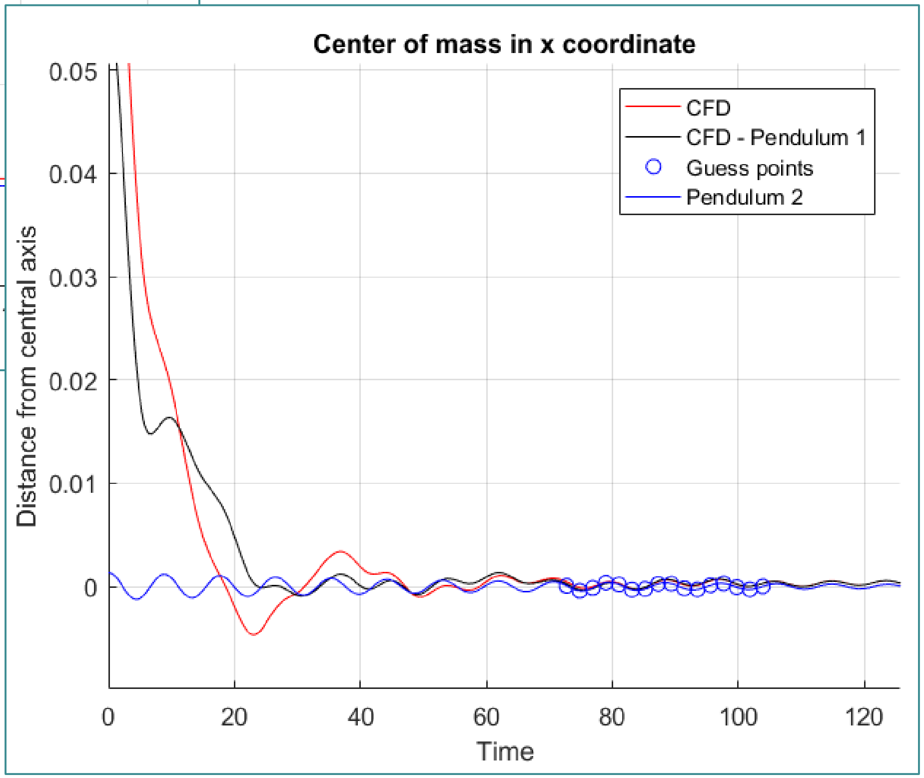


- Curve fitting by finding parameters in pendulum equation that most closely match CFD
- Trying to resolve CFD into two pendulums
- Peak-to-peak values ->
- Initial guesses for damping and frequency of each pendulum
- Note much higher damping before first peak

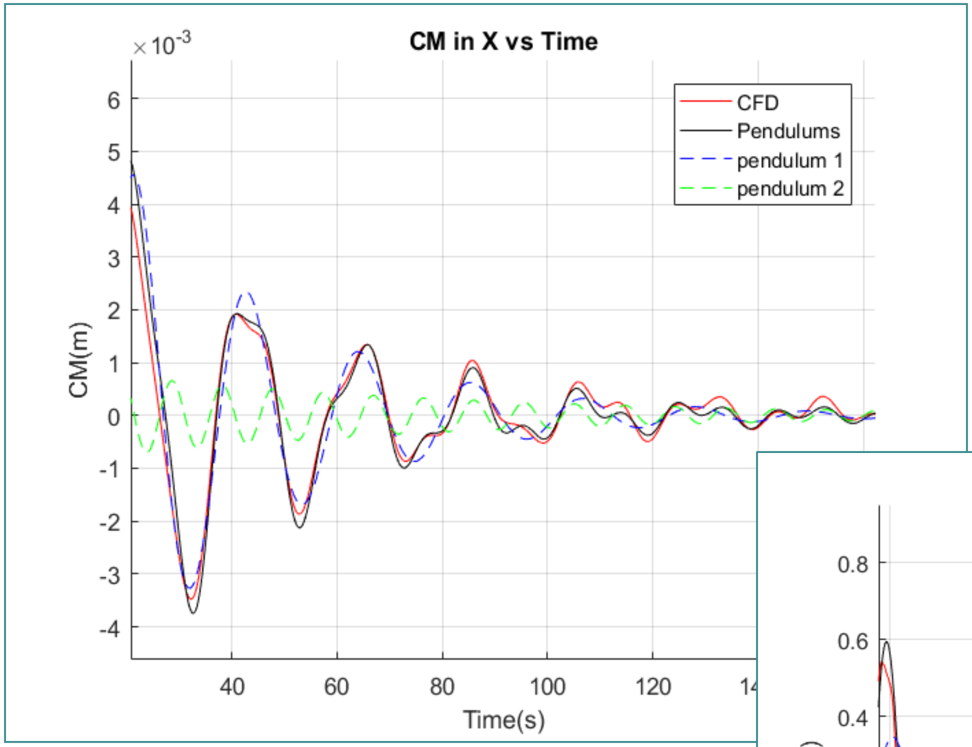
Find Parameters to Fit CM Data



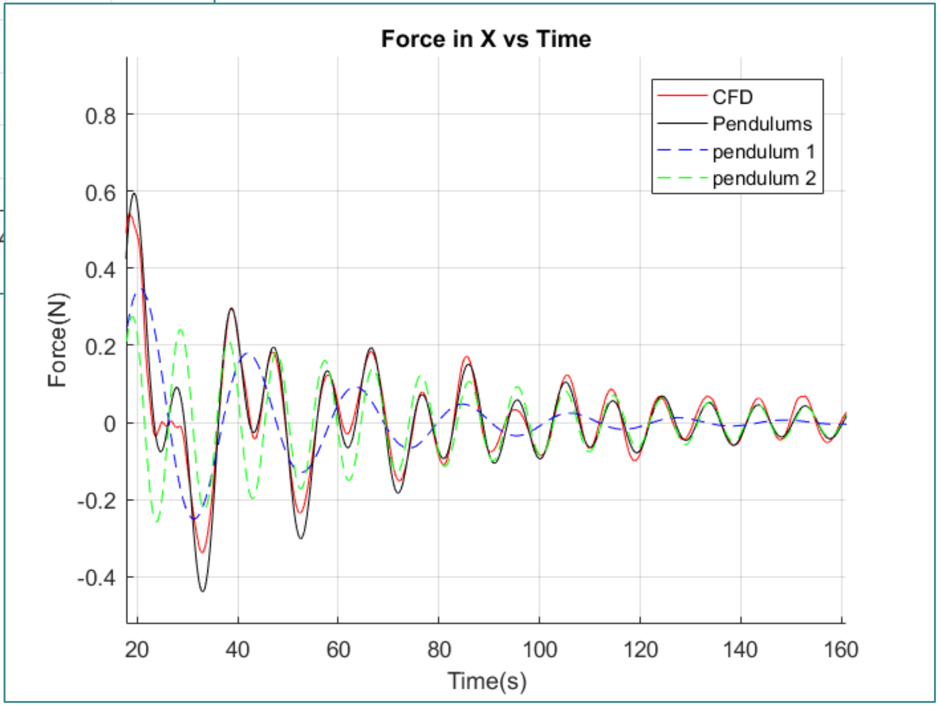
- Matlab's fsolve(x) ->
- Mass, damping, and frequency parameters to fit CMx CFD data
- Refine and iterate



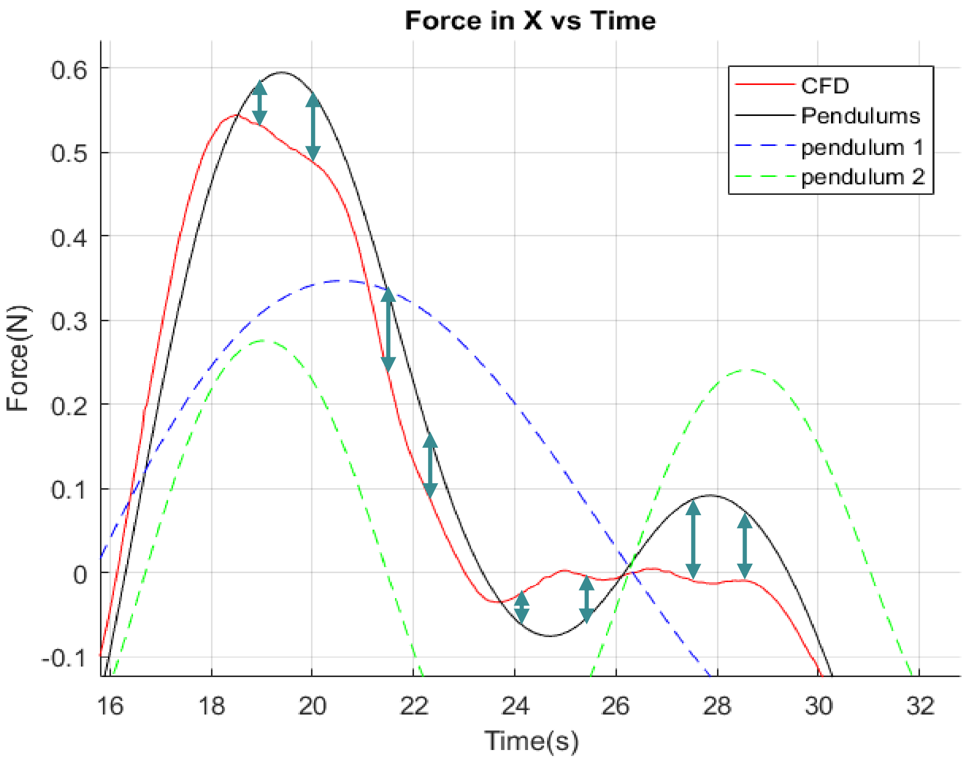
Compare Sum of Pendulums to CFD Data



- Sum of two pendulums generates model for propellant slosh
- Should match both CM and Force data



Mean Error in Force



- Metric to quantify accuracy of fit: mean absolute difference between CFD force and pendulum model force

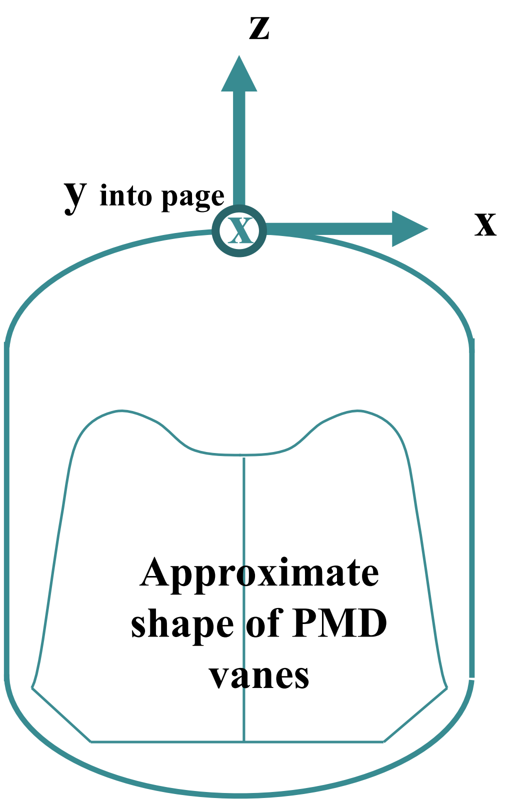
$$\frac{1}{n}\sum_{1}^{n} abs(CFD - pendulum)$$

- Select methods that minimize this

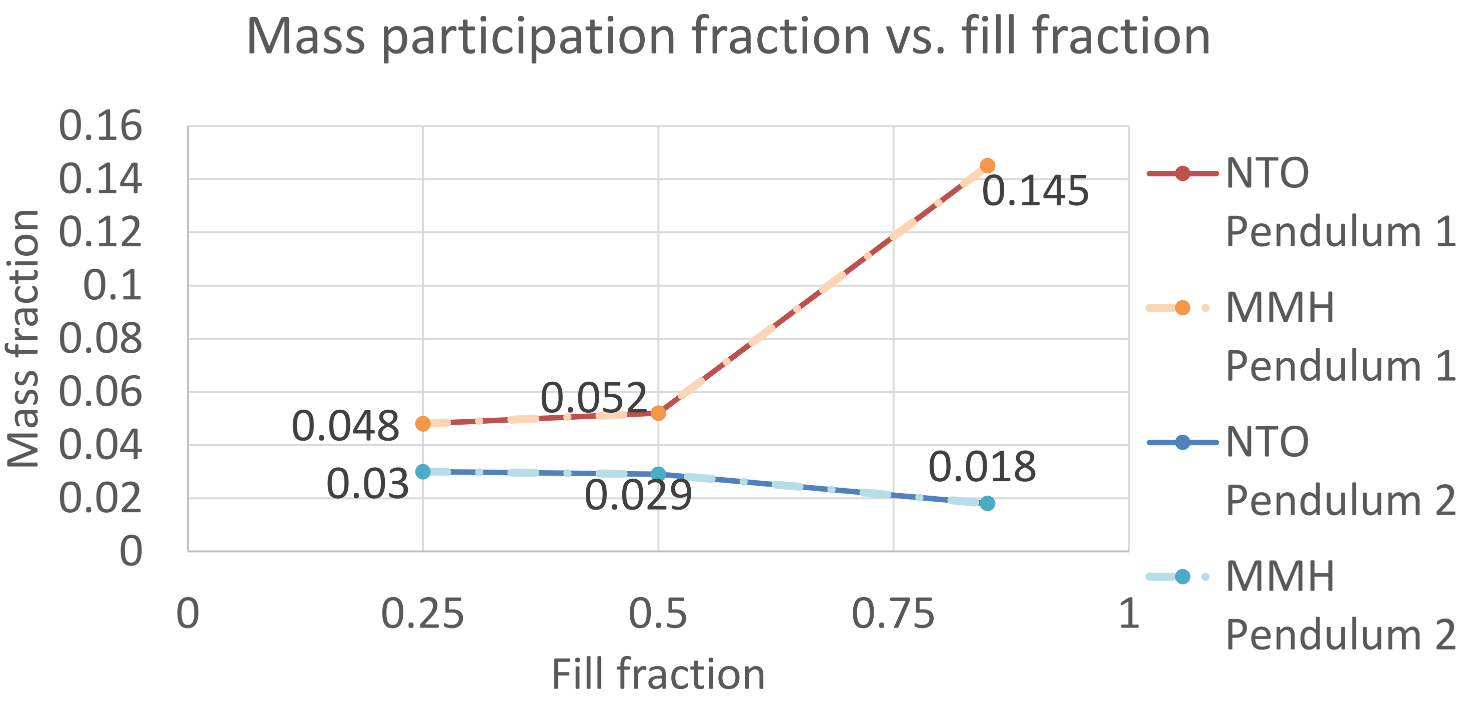
RESULTS AND LITERATURE COMPARISON

Basis for results

- Coordinate system – origin at top of tank
- Parameters prioritized fitting the behavior after the first peak
- Two pendulum model is an approximation only
  - PMD does not create a perfectly sector nor annular tank and is only a fraction of tank height
  - Parameters not constant over time
  - Model does not scale well with high fluid displacements

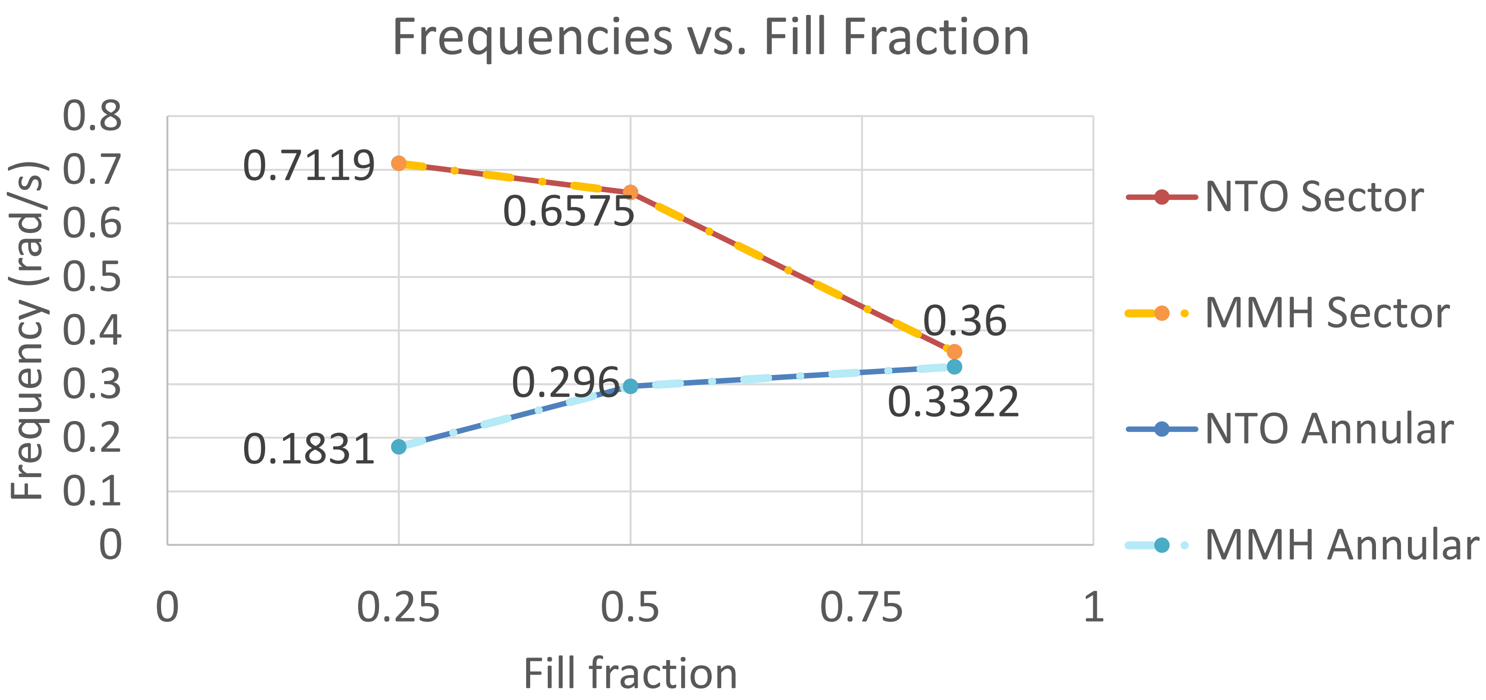


Mass Participation Fraction



- Pendulum mass as a fraction of total fluid mass
- Monotonic trends
- Mass fractions are identical between NTO and MMH
- Piecewise linear fit
  - First two fill fractions – fluid partially submerges PMD, sloshing occurs between vanes
  - Last fill fraction – fluid completely submerges PMD, different slosh behavior

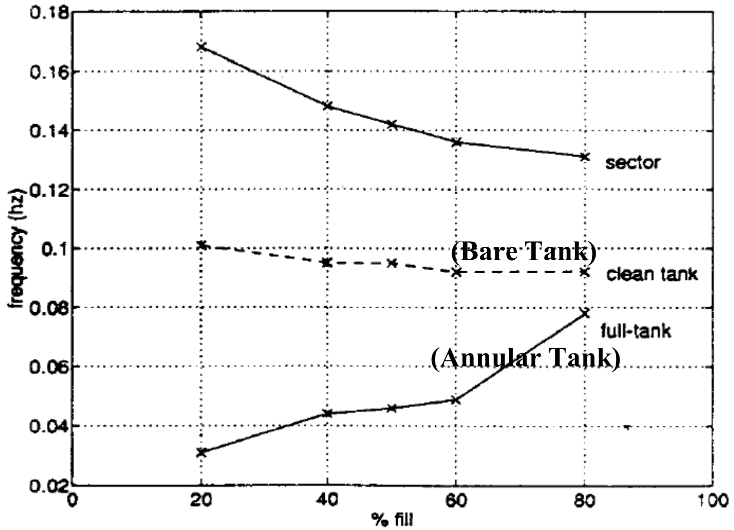
Frequency



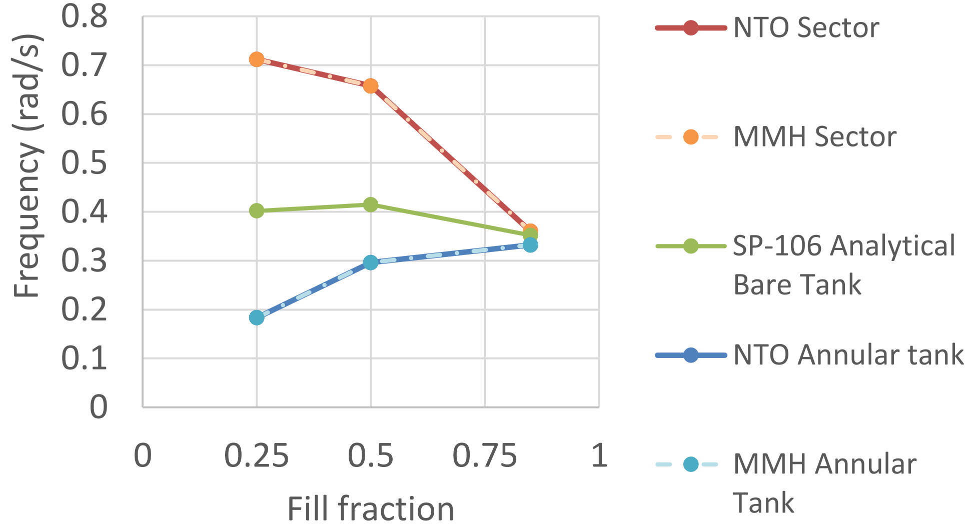
- Function of pendulum's length and acceleration
- Monotonic trends
- Frequencies are identical between NTO and MMH
- Frequencies for the two pendulums converge as fill fraction increases
  - Sector and annular slosh modes become less distinct as PMD becomes fully submerged

Frequency - Literature Comparison 1

Cassini Paper Frequencies vs. Fill Fraction

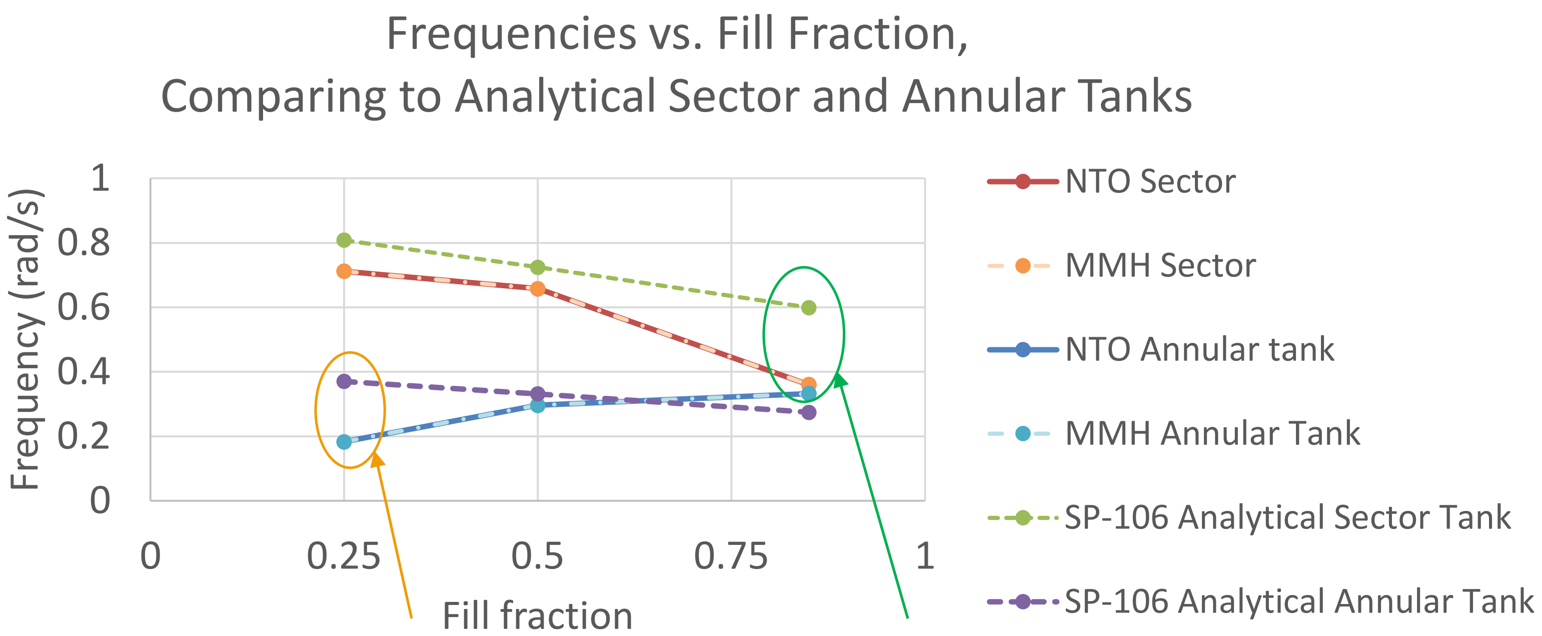


Frequencies vs. Fill Fraction, Comparing to SP-106 Bare Tank



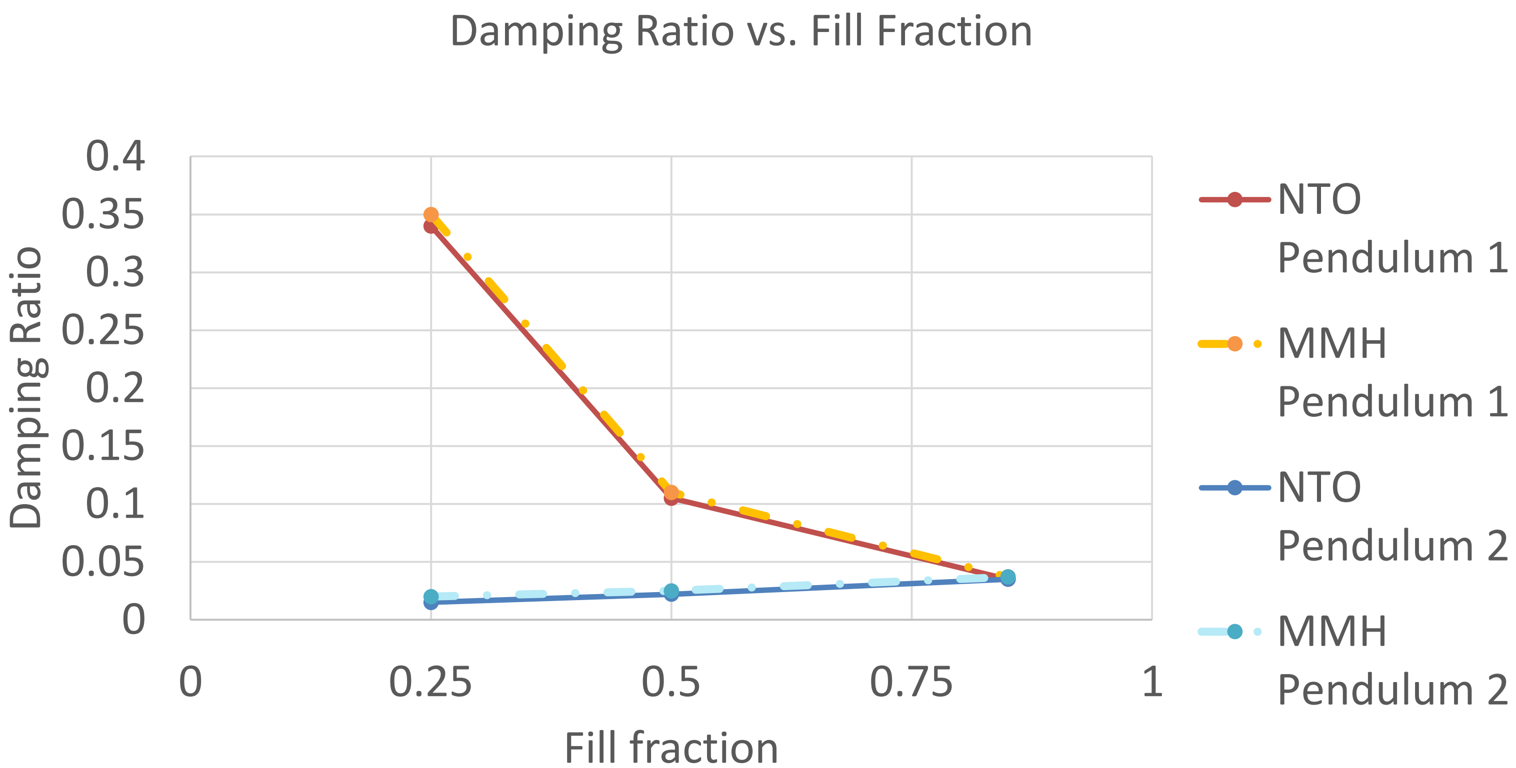
- Left: Cassini paper referenced SP-106 for an analytical equation for slosh frequency in a bare tank (cylindrical tank with no PMD) and compared it to the frequencies of their two pendulums
- Right: Similar trends to Cassini found in Europa pendulum model frequencies
- Sector and annular slosh modes converge towards bare tank frequency as PMD becomes more submerged (fully submerged at 85% fill fraction for Europa tank)

Frequency – Literature Comparison 2



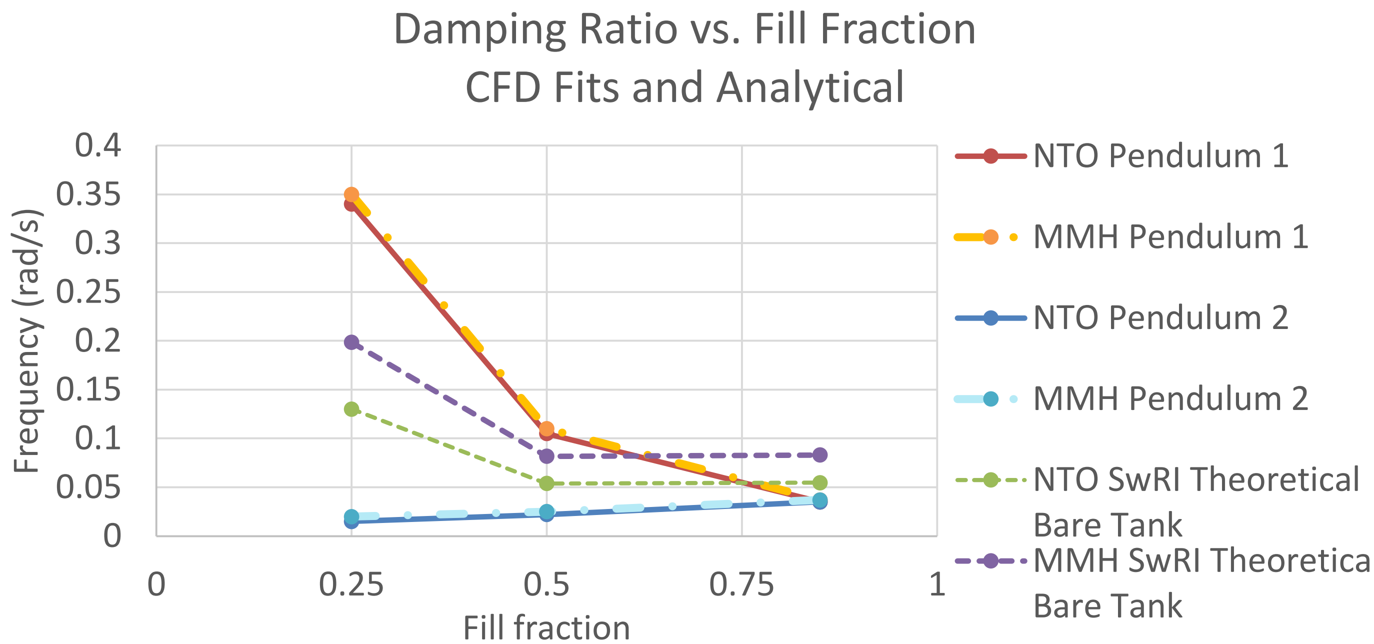
- SP-106 references tables (Bauer, 1963) for an analytical equations for sector and annular slosh frequency
- Function of acceleration, geometry, and fluid height
- Pendulum frequencies are close to analytical equation frequencies
- Differences between analytical and pendulum fits due to:
  - PMD is not exactly a sector/annular tank
  - Half-dome bottom approximated as flat bottom – at 25% fill fraction, sloshing fluid is almost entirely in the dome
  - PMD doesn’t include entire height of tank – at 85% fill fraction, PMD is completely submerged

Damping Ratio

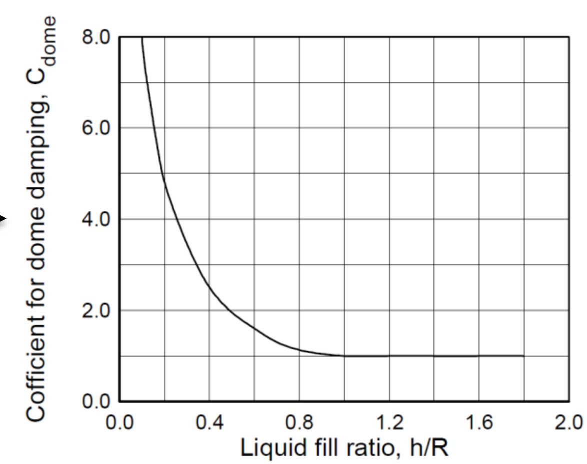


- Monotonic trends
- Slightly higher damping ratio for higher dynamic viscosity (MMH)

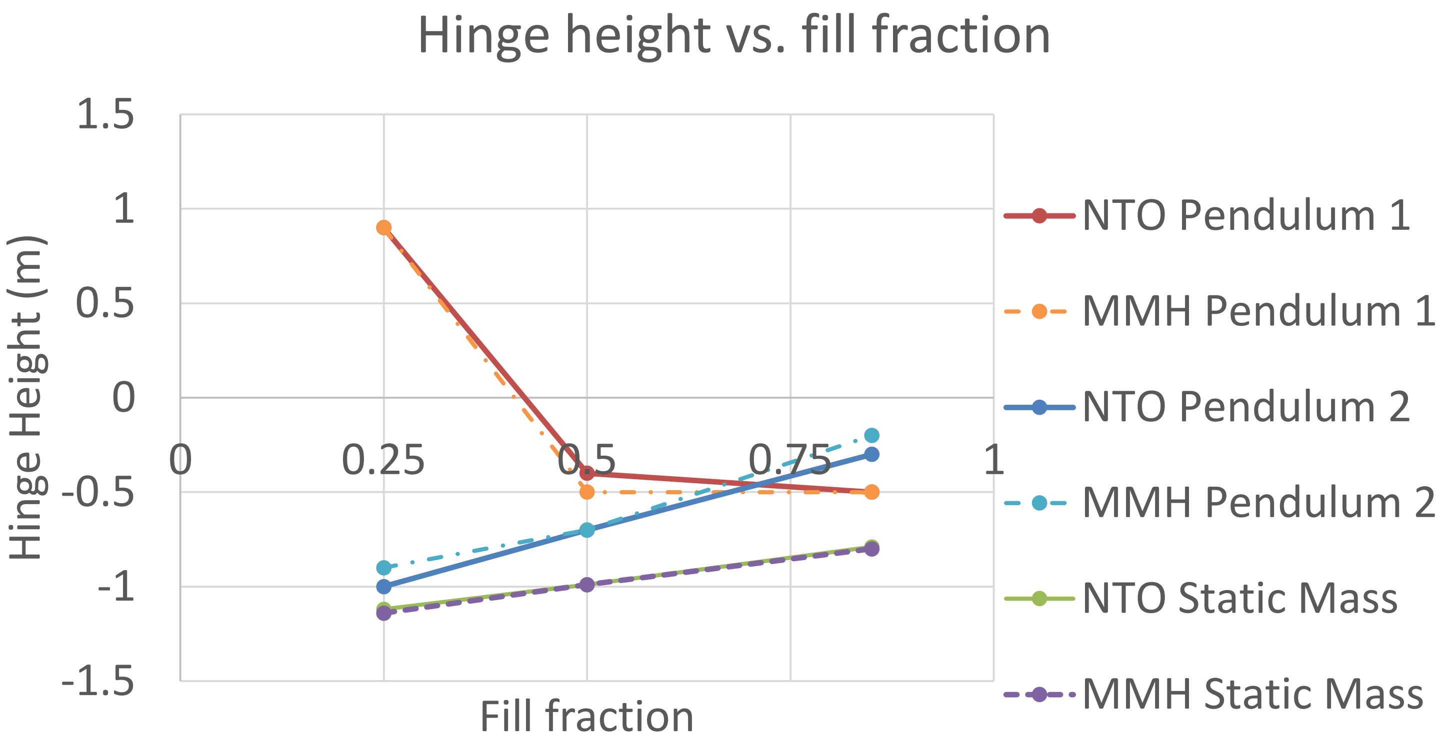
Damping Ratio – Comparison 1



- Mikishev and Dorozhkin found correlation for damping in a bare tank
- Function of geometry, acceleration, viscosity, and fluid height
- Scales by correction coefficient for domed bottom →
- Pendulum damping within order of magnitude of analytical prediction
- Pendulum damping less sensitive to viscosity than analytical prediction – viscous vs. drag forces



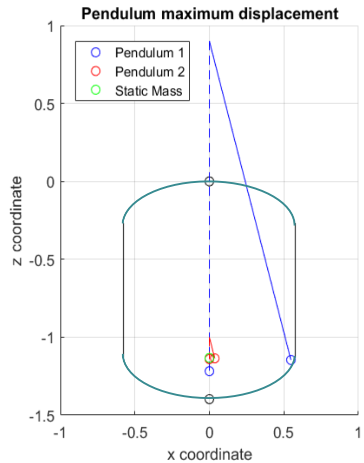
Length and Hinge Location



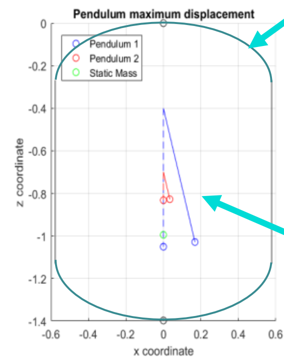
- Origin is top of tank
- Pendulum bobs stay within fluid
- Monotonic values for pendulum heights
- NTO and MMH heights are close but not identical

Length and Hinge Location

NTO 25% fill



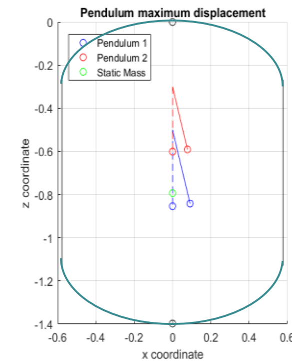
NTO 50% fill



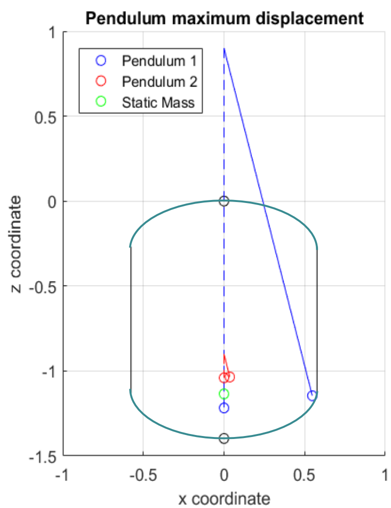
Approximate tank wall

Pendulum at 15 degree offset

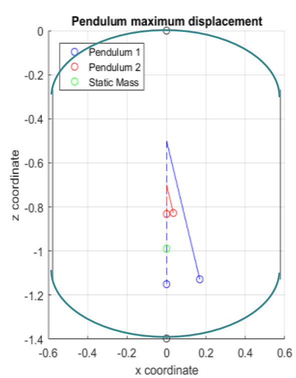
NTO 85% fill



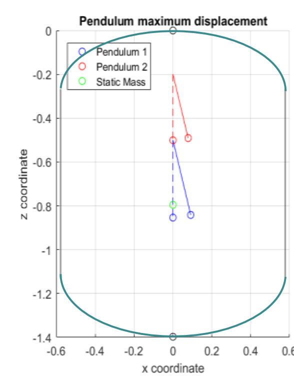
MMH 25% fill



MMH 50% fill

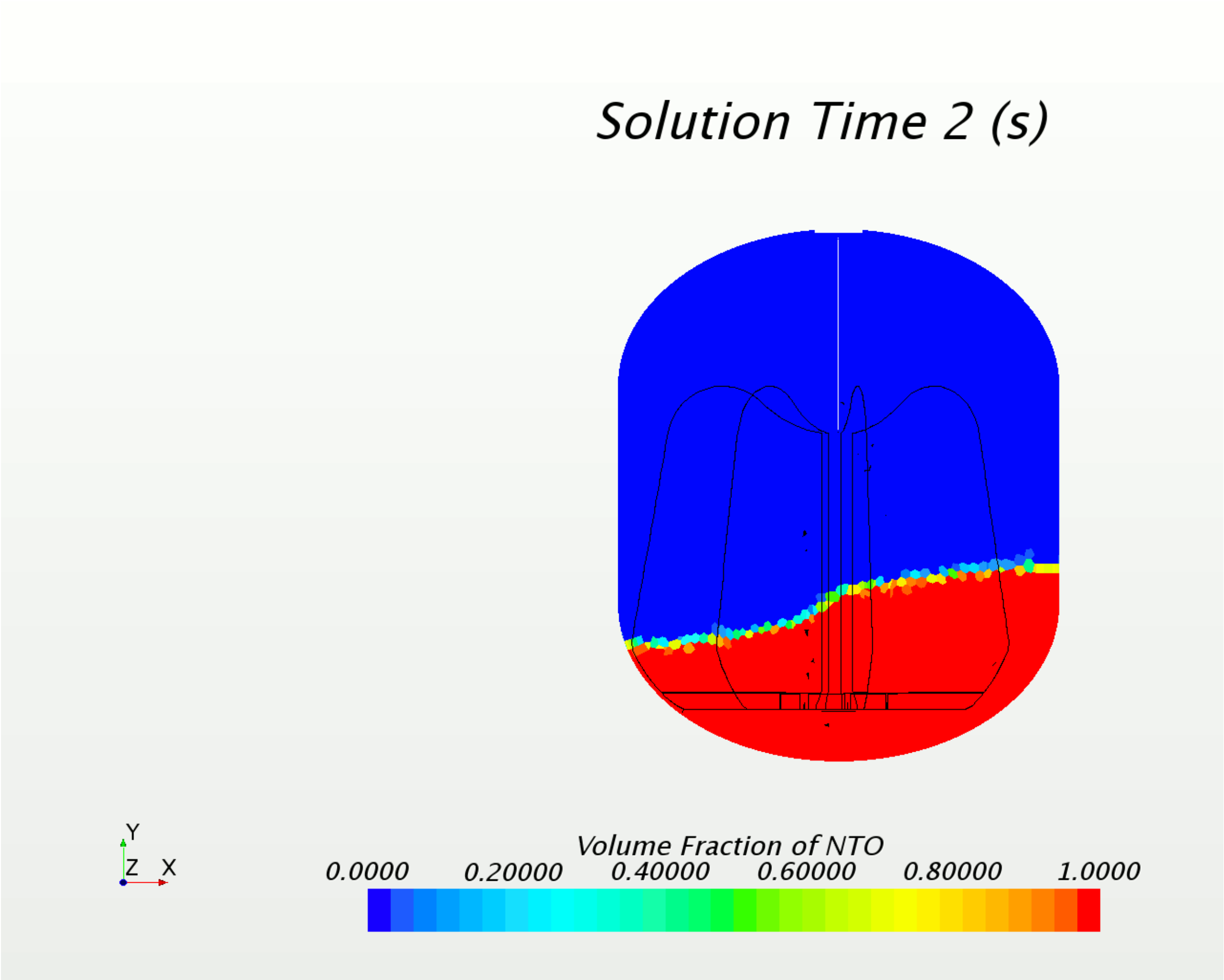


MMH 85% fill

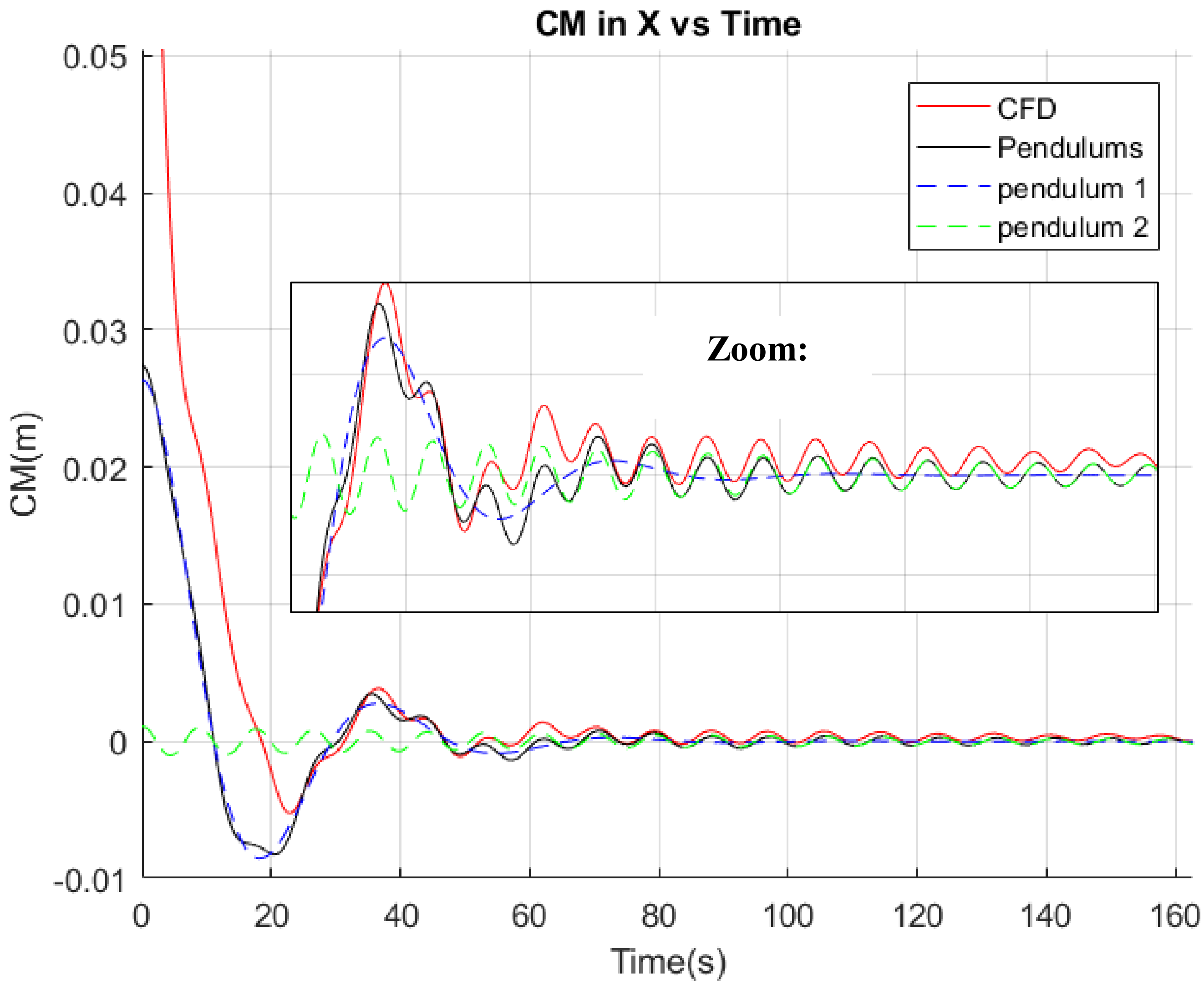


PLOTS COMPARING PENDULUM MODELS AND CFD DATA

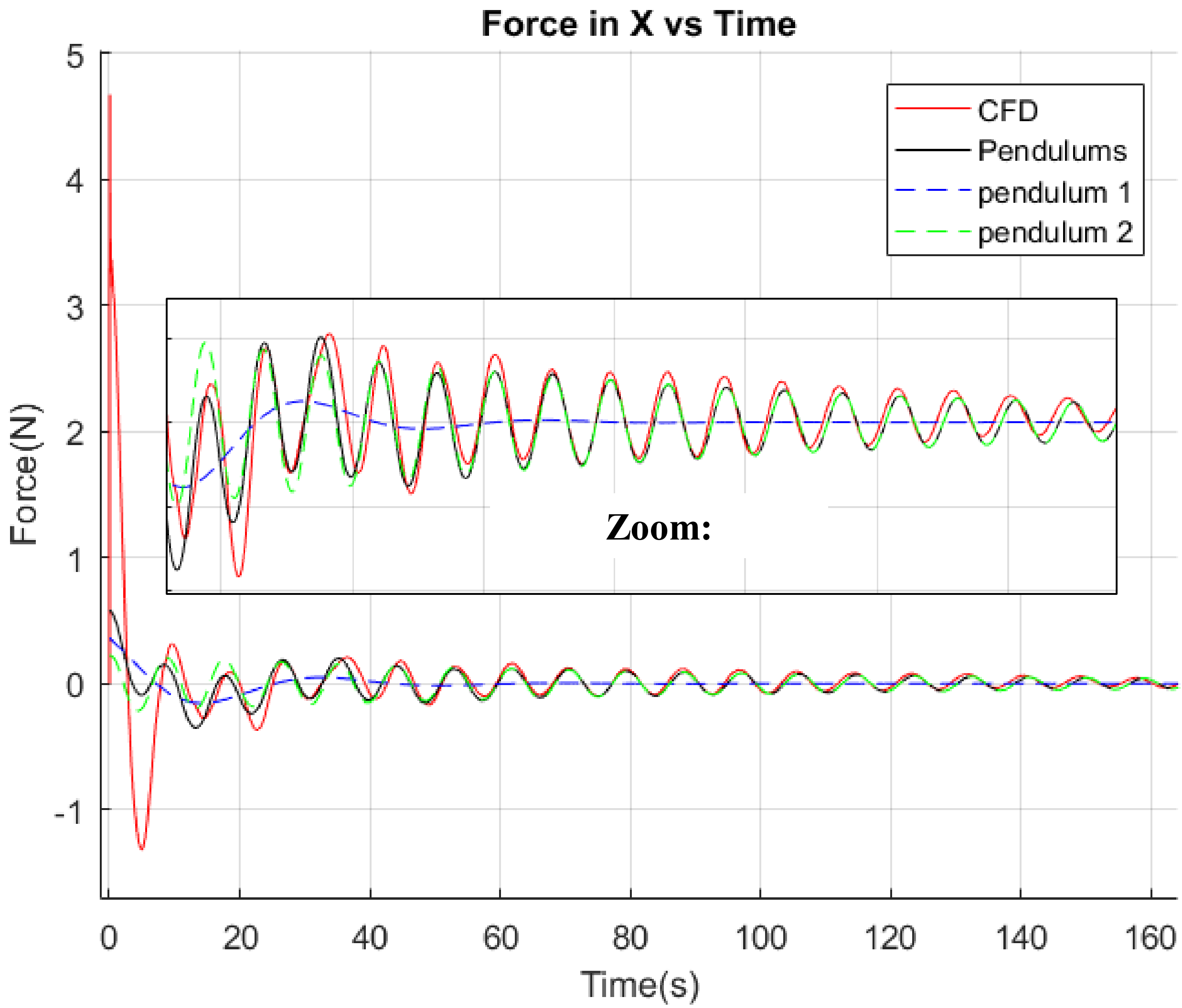
NTO 25% Fill Fraction



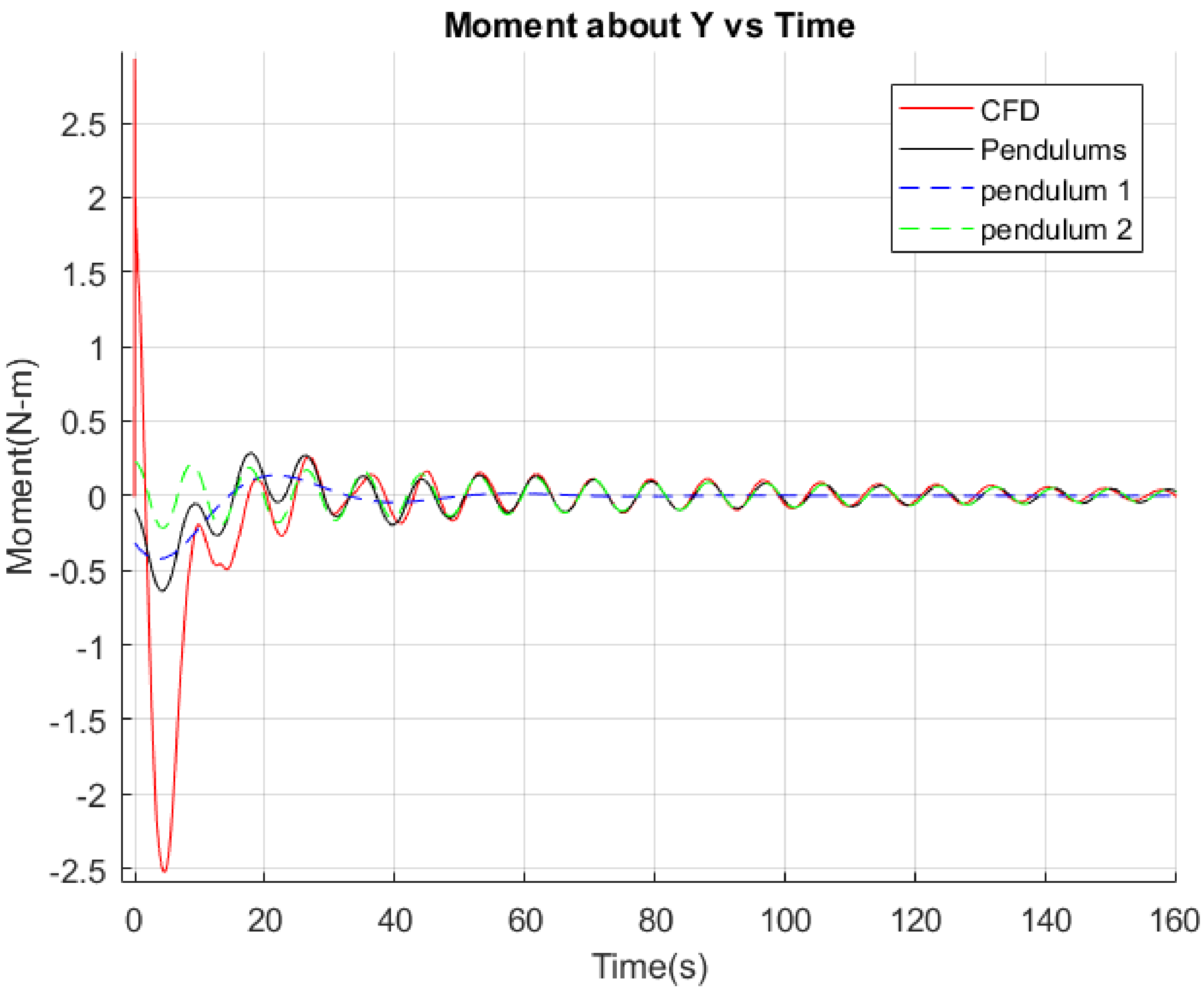
NTO 25% Fill Fraction



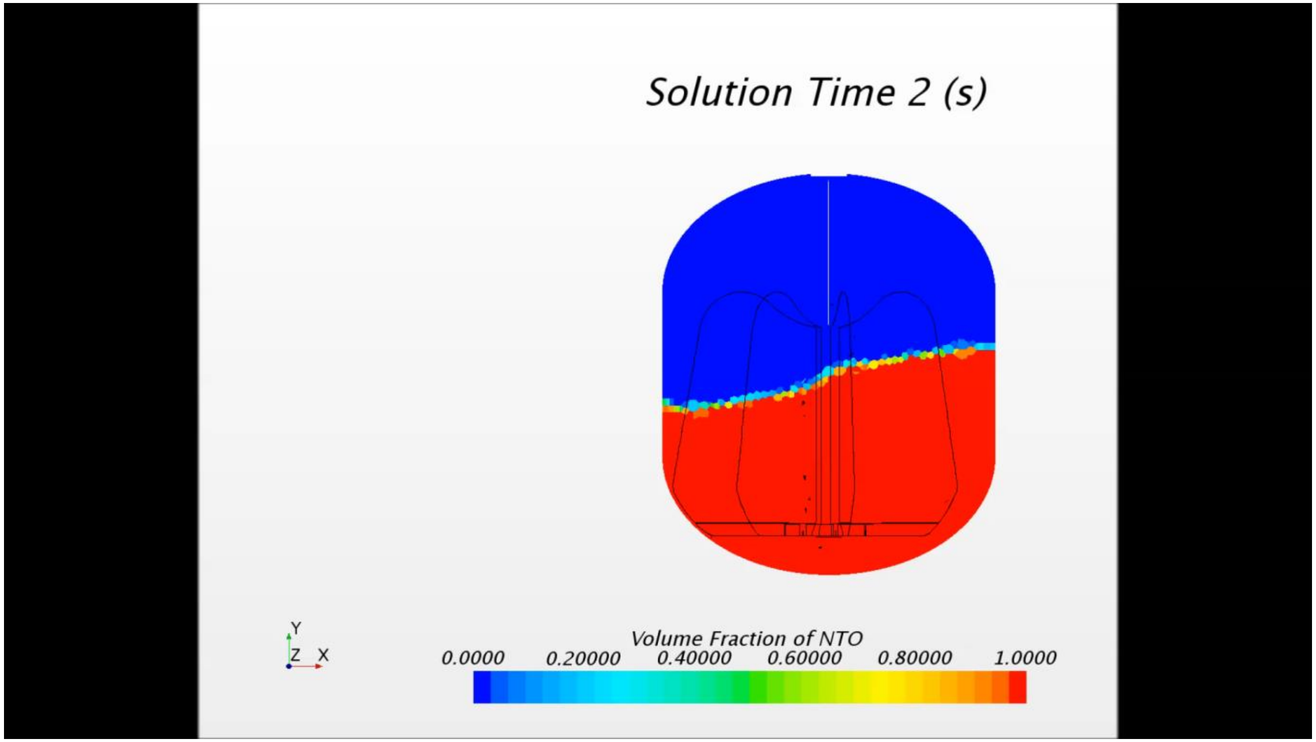
NTO 25% Fill Fraction



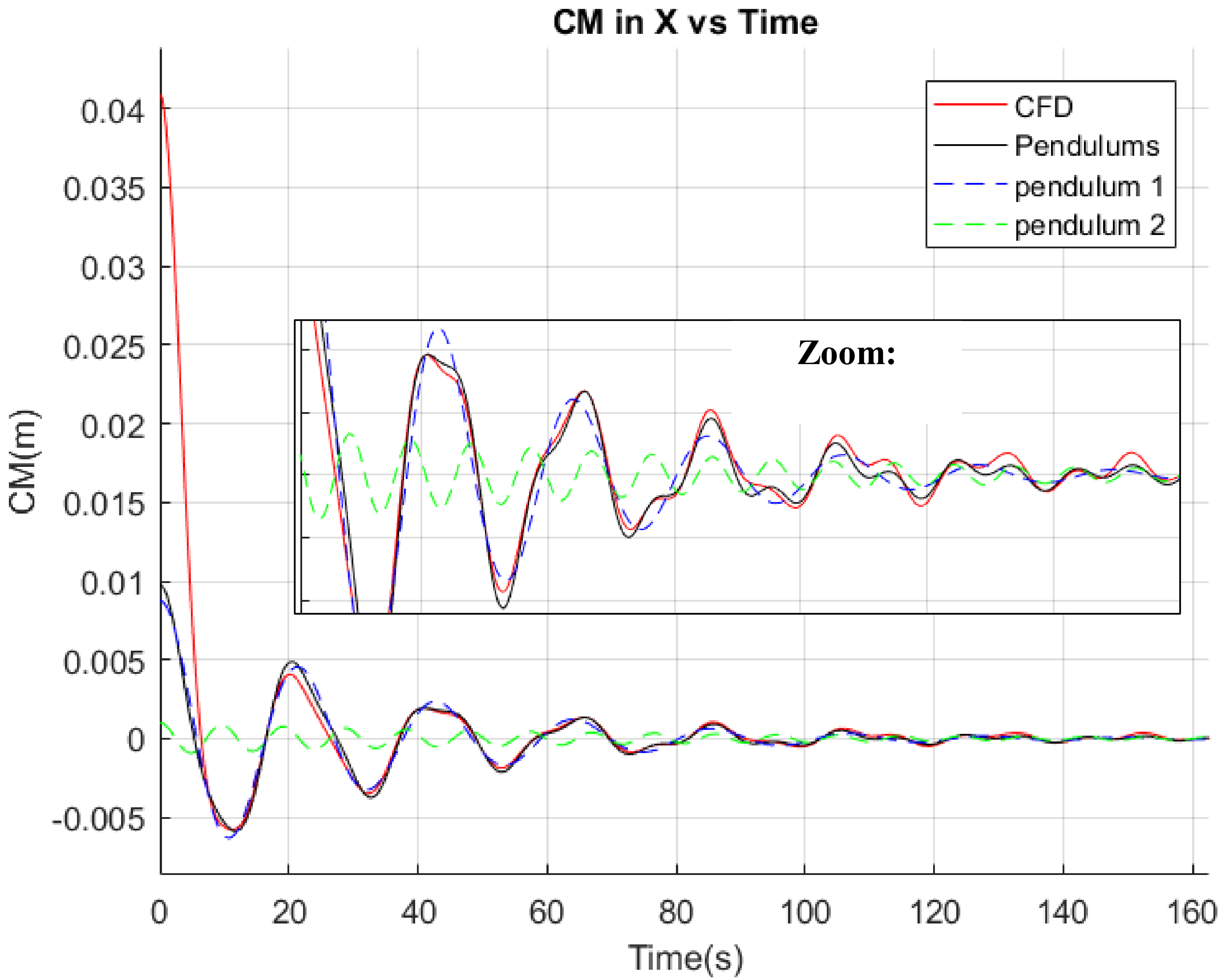
NTO 25% Fill Fraction



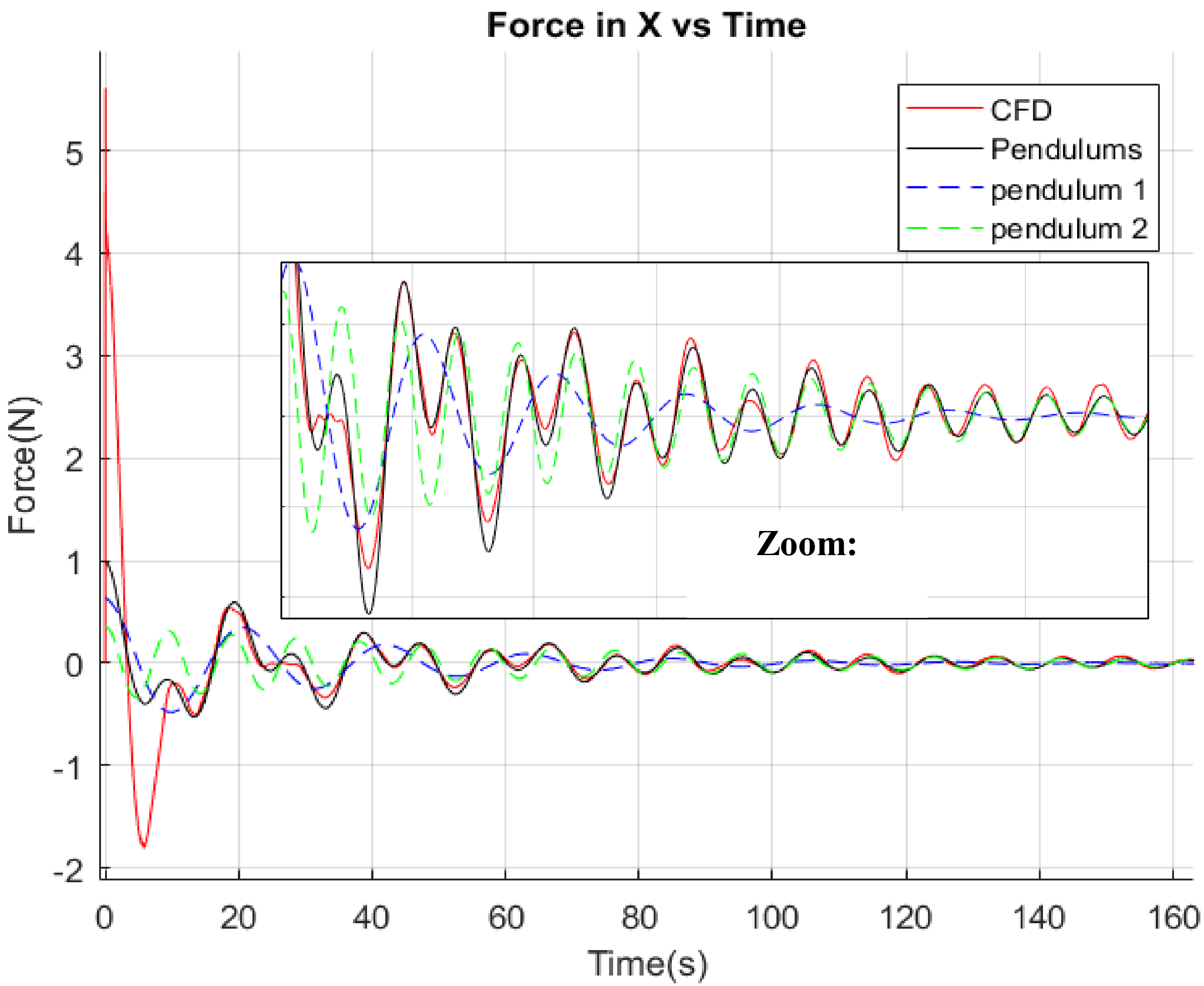
NTO 50% Fill Fraction



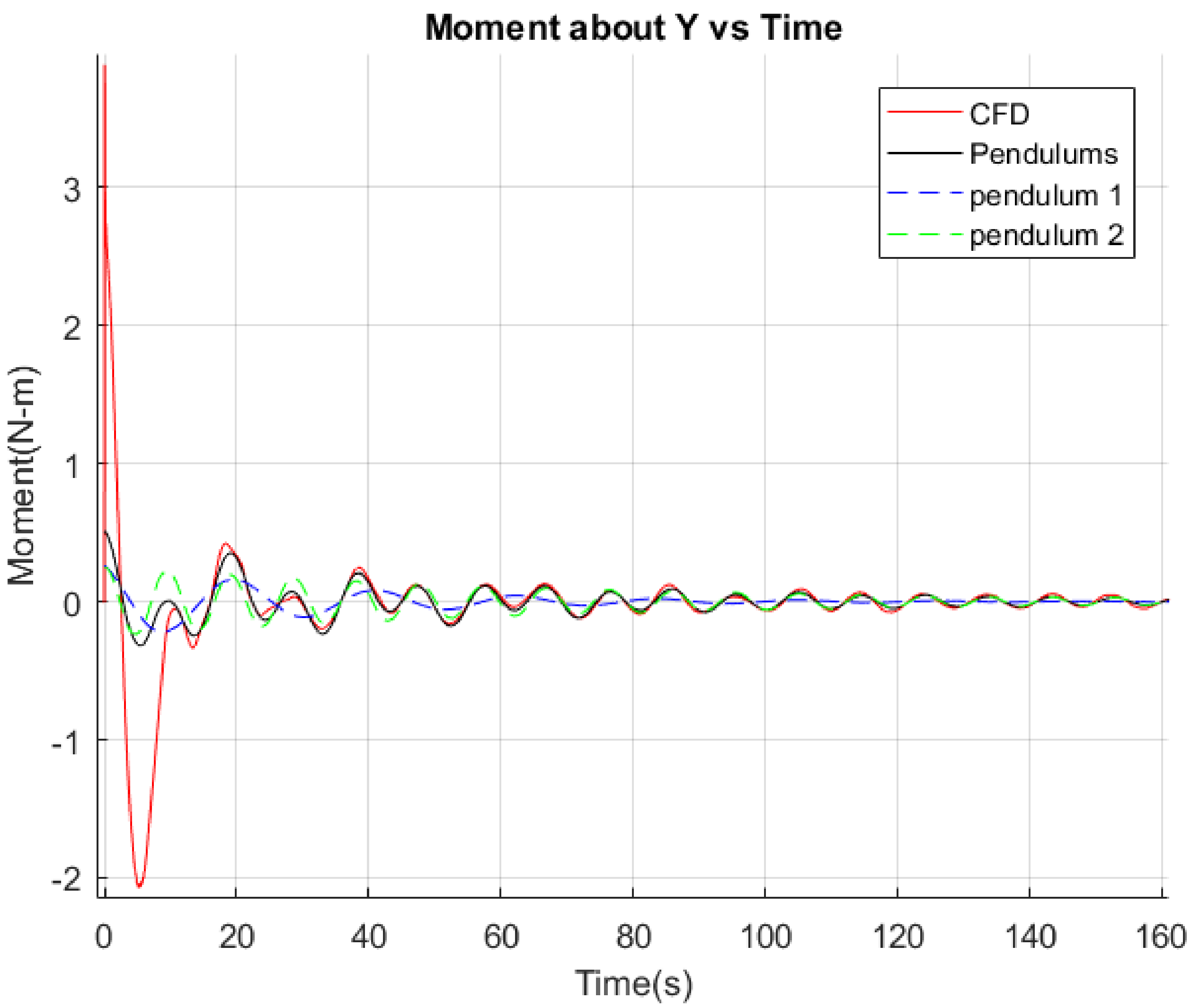
NTO 50% Fill Fraction



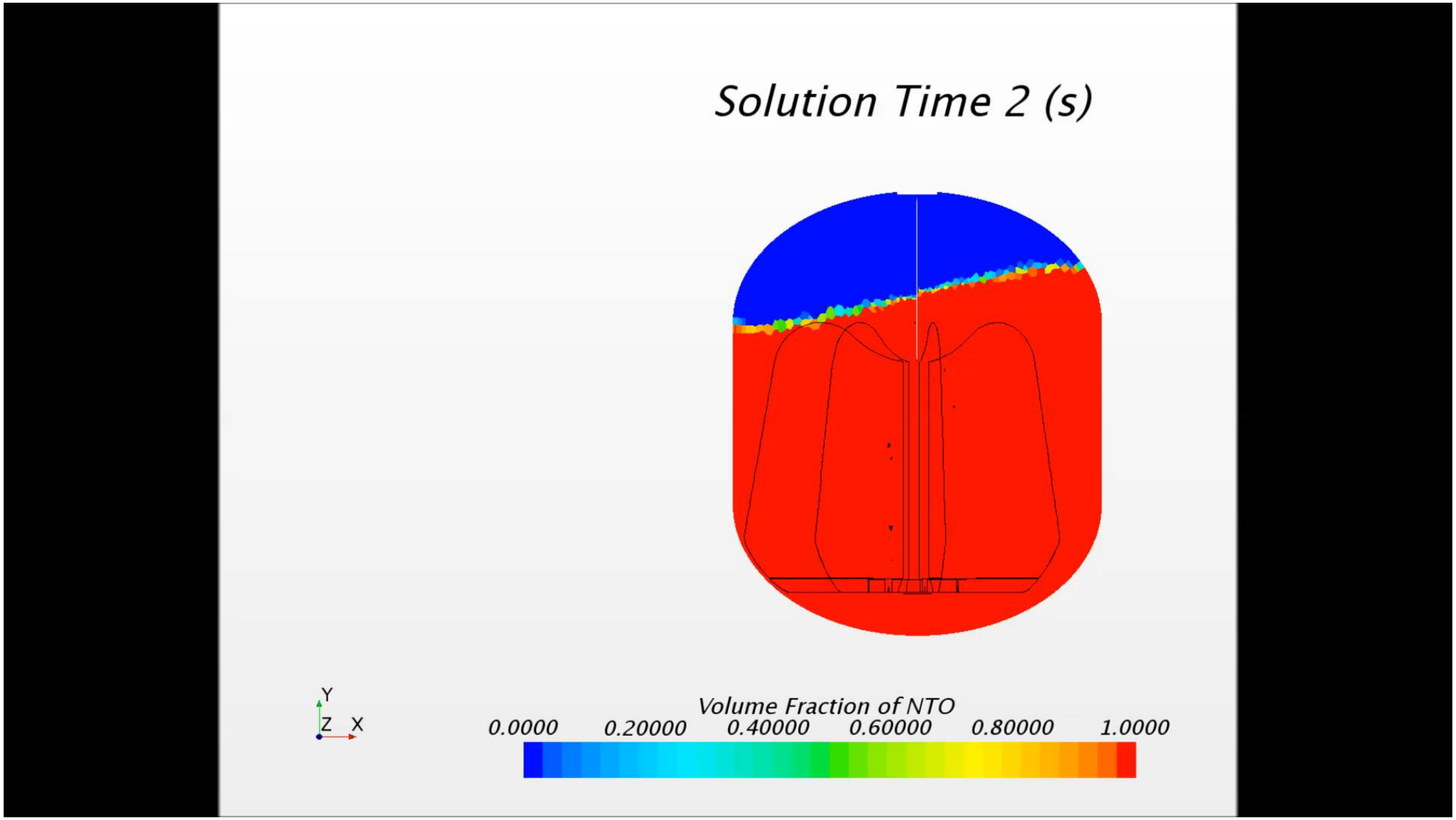
NTO 50% Fill Fraction



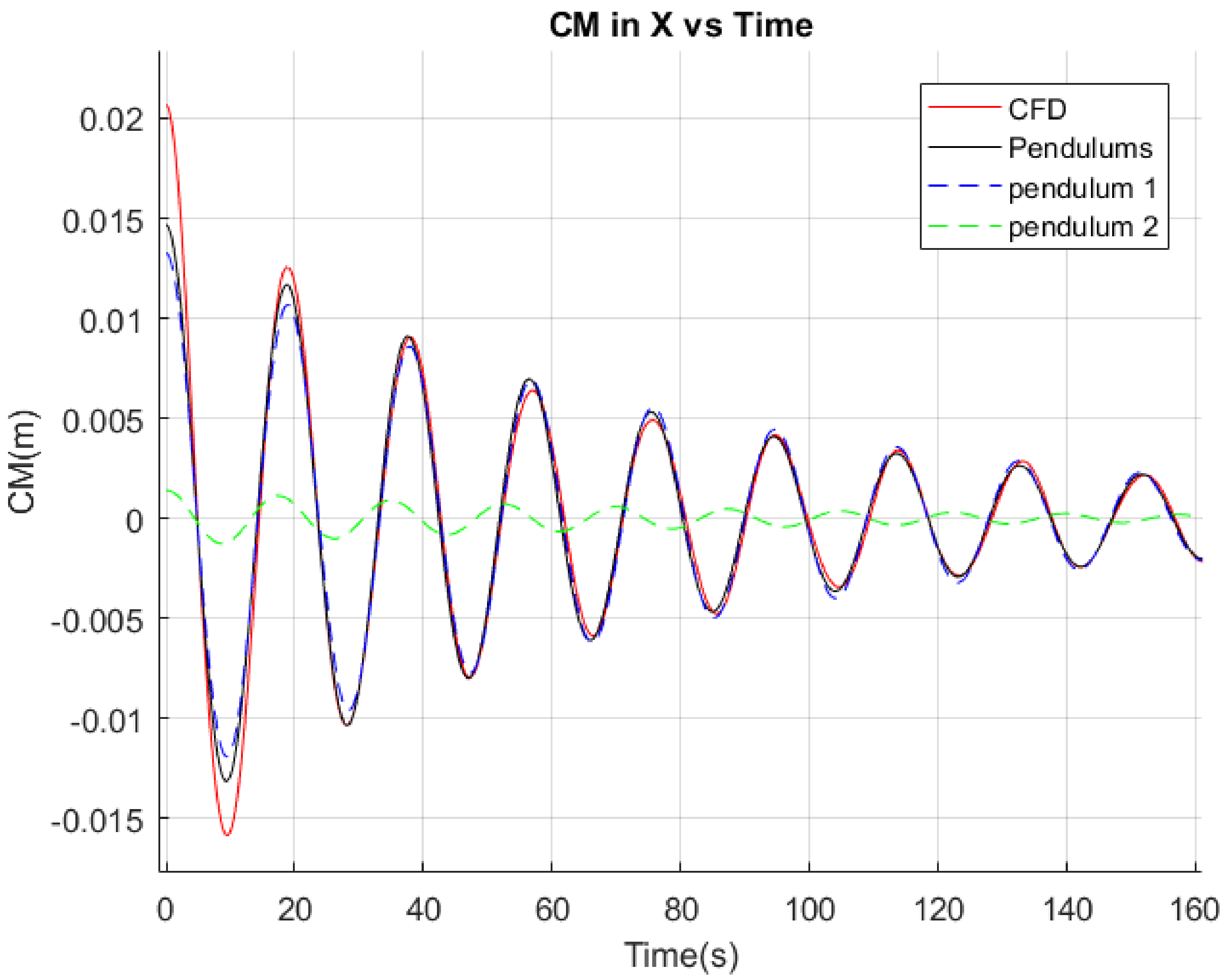
NTO 50% Fill Fraction



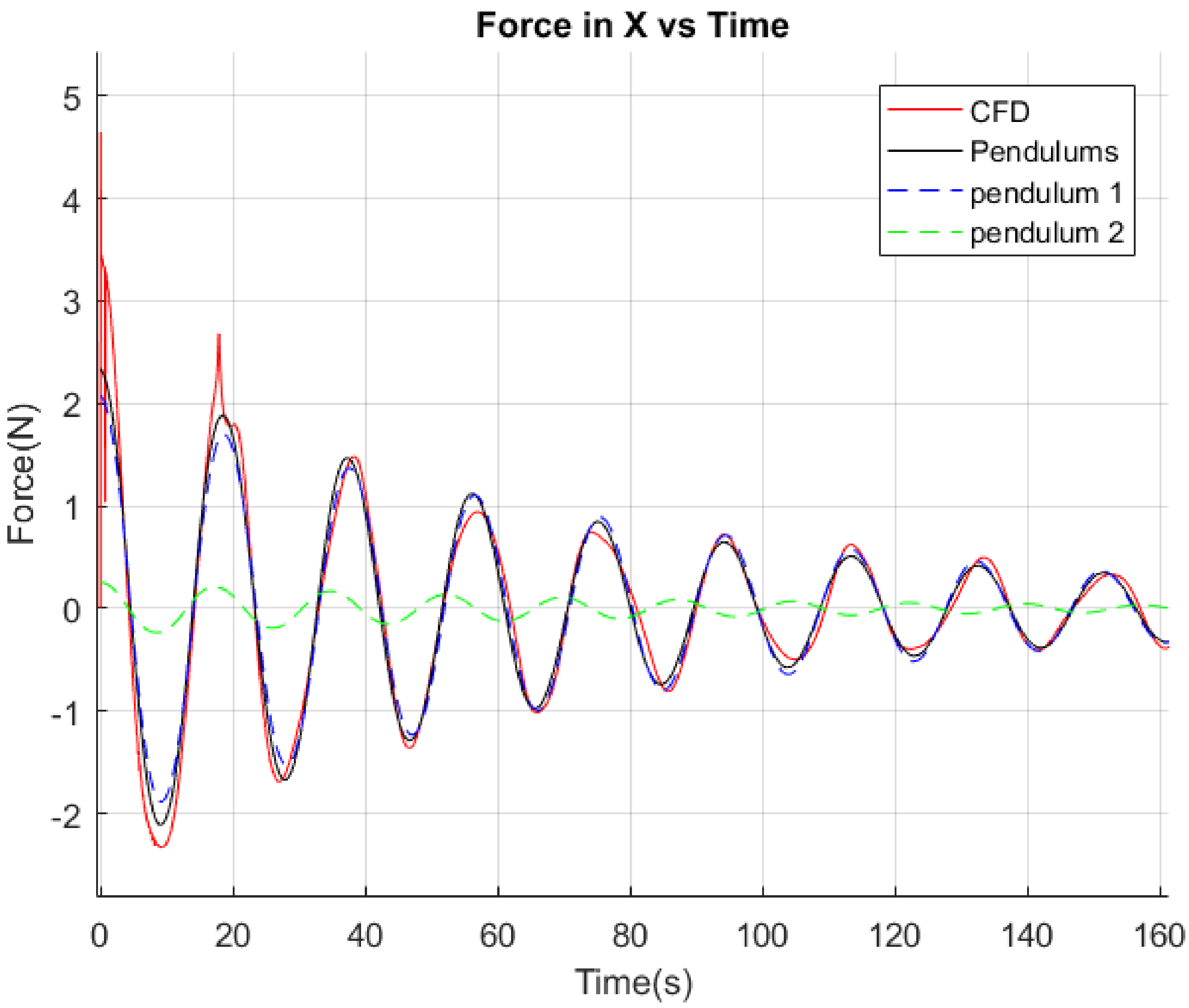
NTO 85% Fill Fraction



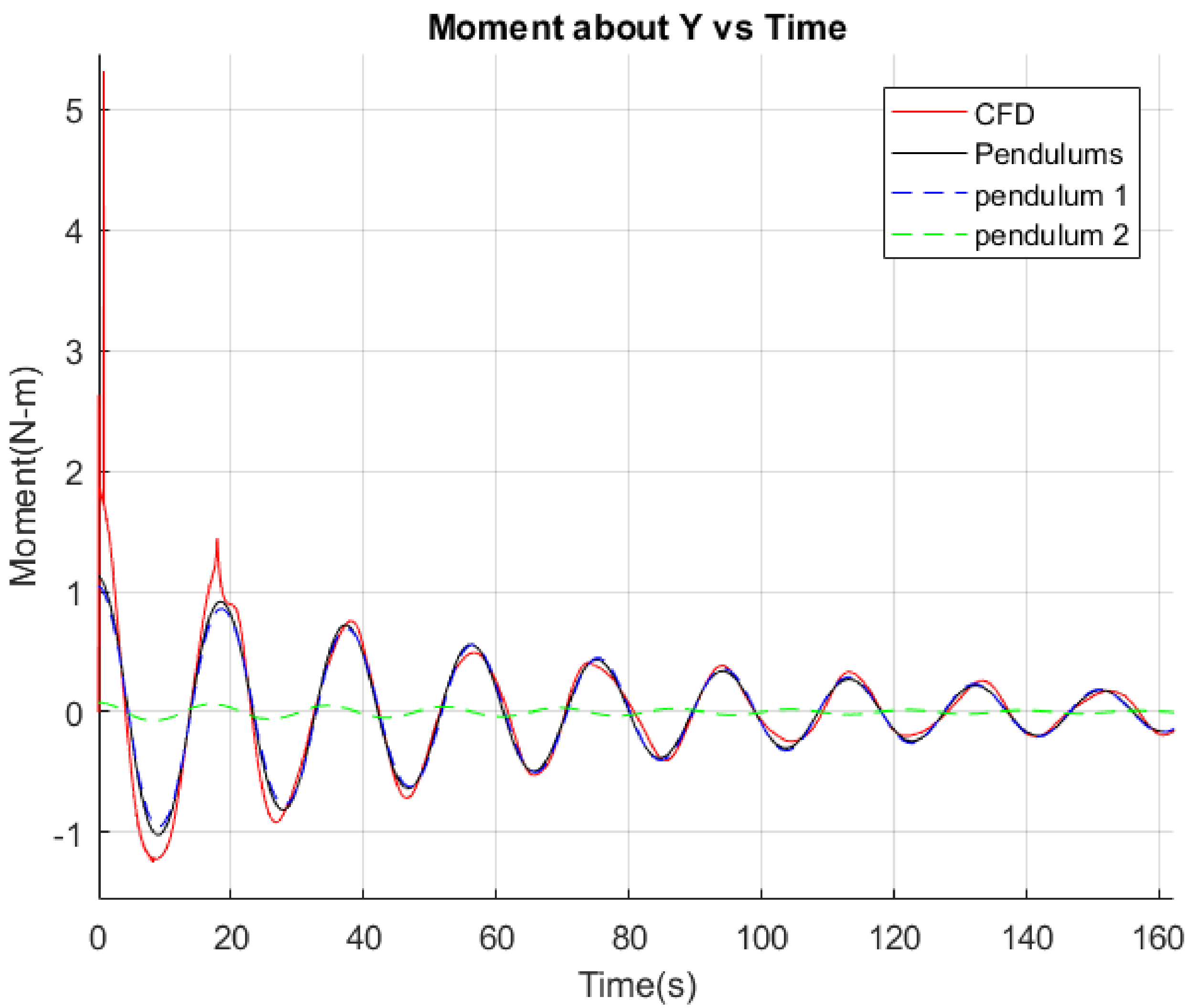
NTO 85% Fill Fraction



NTO 85% Fill Fraction



NTO 85% Fill Fraction



Summary of Parameters

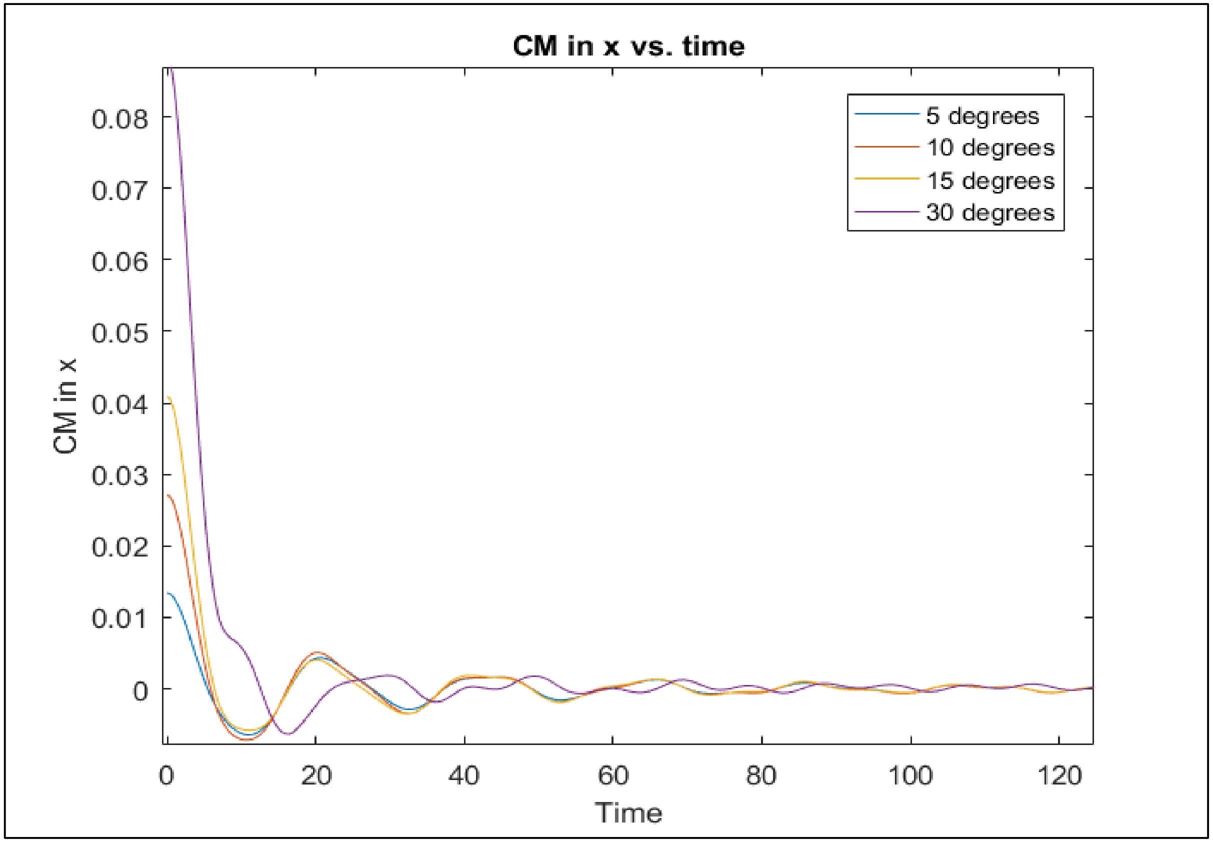
	NTO (nitrogen tetroxide)			MMH (monomethyl hydrazine)		
	25% fill	50% fill	85% fill	25% fill	50% fill	85% fill
Mass fraction1	0.048	0.052	0.145	0.048	0.052	0.145
Mass fraction 2	0.03	0.029	0.018	0.03	0.029	0.018
Mass 1 (kg)	20.09	44.49	210.87	12.12	26.69	126.53
Mass 2 (kg)	12.56	24.81	26.18	7.58	14.89	15.71
Frequency 1 (rad/s)	0.1831	0.296	0.3322	0.1831	0.296	0.3322
Frequency 2 (rad/s)	0.7119	0.6575	0.36	0.7119	0.6575	0.36
Damping Ratio 1	0.34	0.105	0.035	0.35	0.11	0.037
Damping Ratio 2	0.015	0.022	0.035	0.02	0.025	0.037
Hinge Height 1 (m)	0.9	-0.4	-0.5	0.9	-0.5	-0.5
Hinge Height 2 (m)	-1.0	-0.7	-0.3	-0.9	-0.7	-0.2
Static Mass Height (m)	-1.12	-0.99	-0.79	-1.14	-0.99	-0.8
Mean Force Error from t=0	0.0716	0.075	0.1055	0.0398	0.0447	0.0679
Mean Force Error from First Peak	0.0241	0.018	0.0775	0.0118	0.0119	0.0518

CONCLUSIONS

Accuracy of Fit

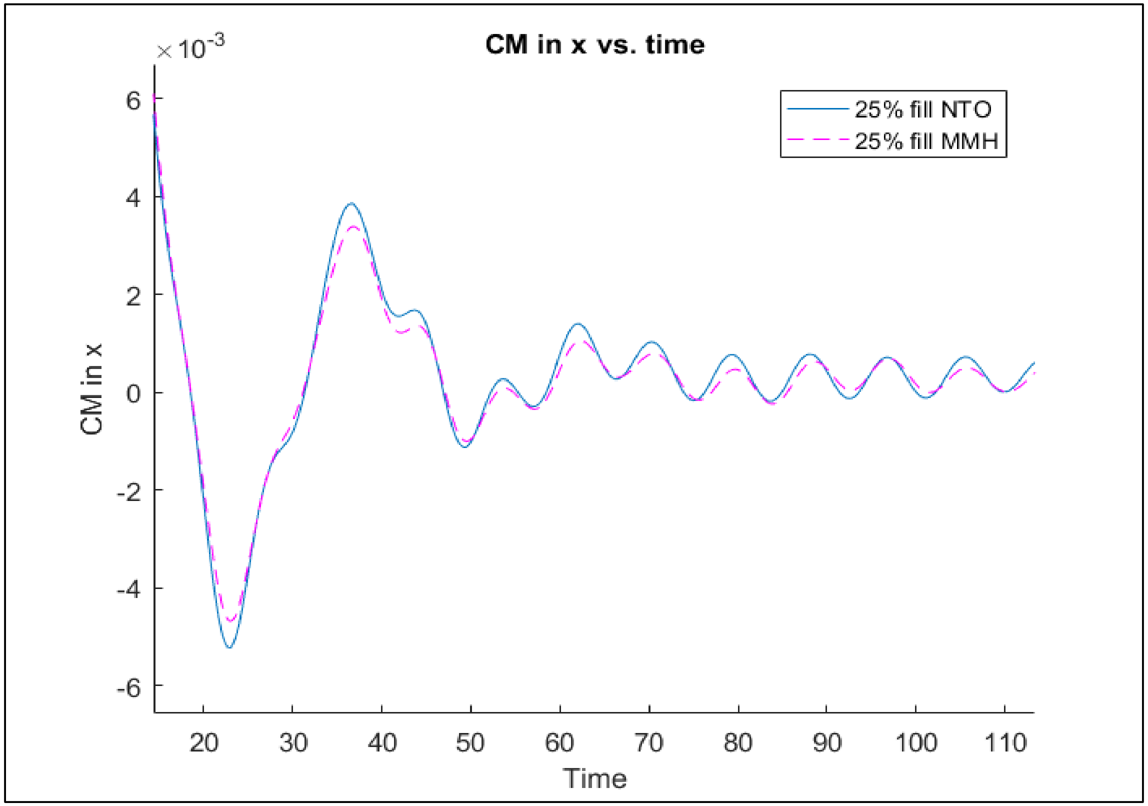
- Two-pendulum model can accurately capture either before or after first peak
- High confidence on frequencies except 85% fill pendulum 2
- Moderate confidence on mass, damping, and hinge location
  - Sometimes several sets of parameters could have provided good matching to CFD
  - Selected parameters that made physical sense
- Model parameters may reflect inaccuracies in CFD
- Pendulum model does not scale well for high fluid disturbance angles
- Damping is actually a function of time and distance traversed by moving fluid
  - Pendulum model assumes damping is constant over time

Observations to Note



- Small initial fluid displacements: Changes have little impact on long-term CFD results
- Large initial displacements: behavior differs drastically

Observations to Note



- Changing density (NTO vs MMH) only slightly changes damping, has little impact on CFD results

Areas for Further Investigation

- Find literature to support mass fraction parameters
- Potentially to capture first peak – add third pendulum with damping ratio of one
- Validate with more CFD data:
  - At intermediate fill fractions
  - At different initial fluid offset angles - 5 degree offset is more conservative than 15, will be used for deliverable in May
- Validate with experiments

Thank You

Sources

- Abramson, N.H.: The Dynamic Behavior of Liquids in Moving Containers. NASA SP-106, 1966
- Bauer, H.F.: Tables and Graphs of Zeros of Cross Product Bessel Functions. MTP-AERO-63-50 NASA-MSFC, June 1963
- Dodge, F.T.: The New "Dynamic Behavior of Liquids in Moving Containers". Southwest Research Institute, 2000
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