TFAWS Interdisciplinary Paper Session

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

Wanyi Ng & David Benson,
NASA GSFC, 597, Civil Servants, Authors

Presented By
Wanyi Ng

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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

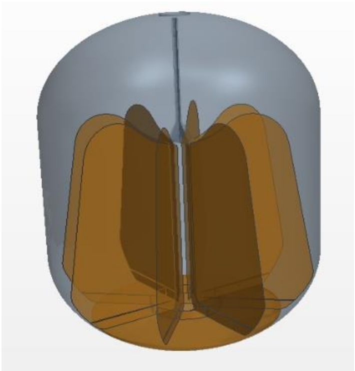
Motivation

- 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

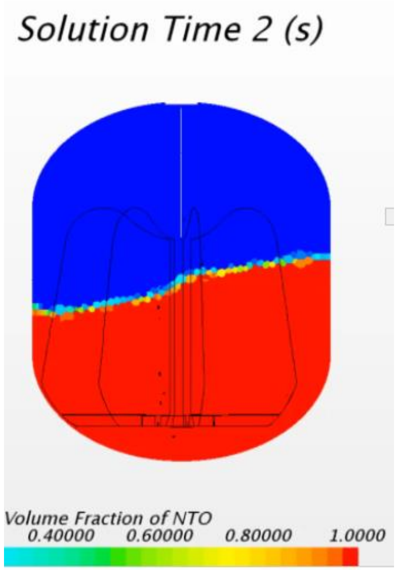
- **Europa Clipper tanks**
  - **Bipropellant system**
  - **Cylindrical with domed top and bottom**
  - **8-vane PMD (propellant management device)**

Notional tank and PMD



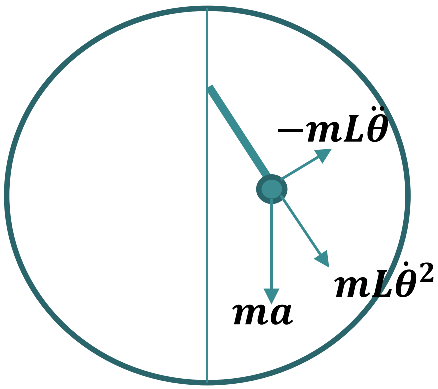
- **CFD (computational fluid dynamics) data used as "real" slosh behavior**
  - **Have data for two propellants at three fill fractions each**
  - **Initial condition of 15 degree free surface offset, released and allowed to settle**
  - **CFD requires long computing time -> Need a computationally simple model**

CFD Simulation



- **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 by fluid on tank



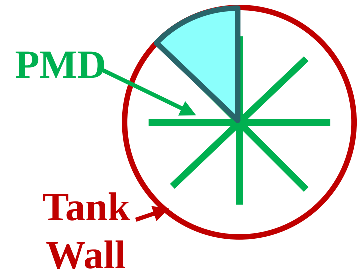
$$CM(t) = mLsin\theta(t)$$

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

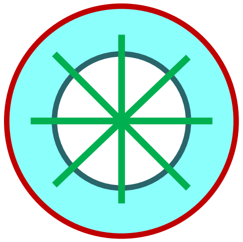
Existing Literature

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

Sector tank mode (top view)

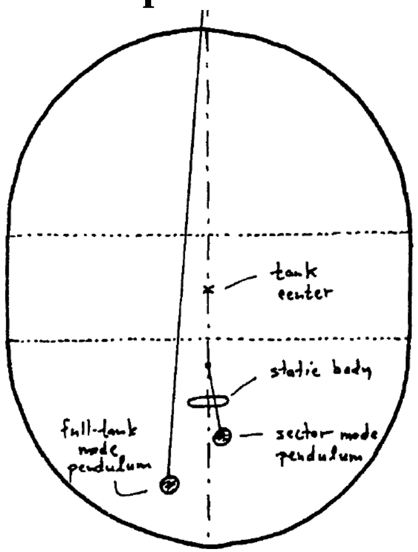


Annular tank mode (top view)



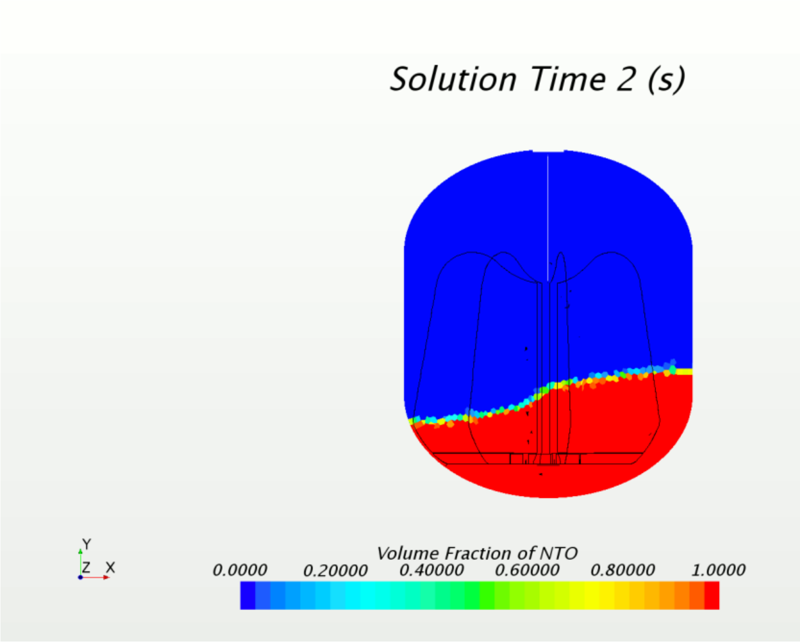
- **Cassini slosh paper (1994): Two pendulum model**
  - Slosh around PMD was modeled as combination of sector and annular slosh modes
  - Two separate pendulums to model two slosh modes
  - Static mass component at bottom that experiences little movement

Cassini paper illustration of double pendulum model



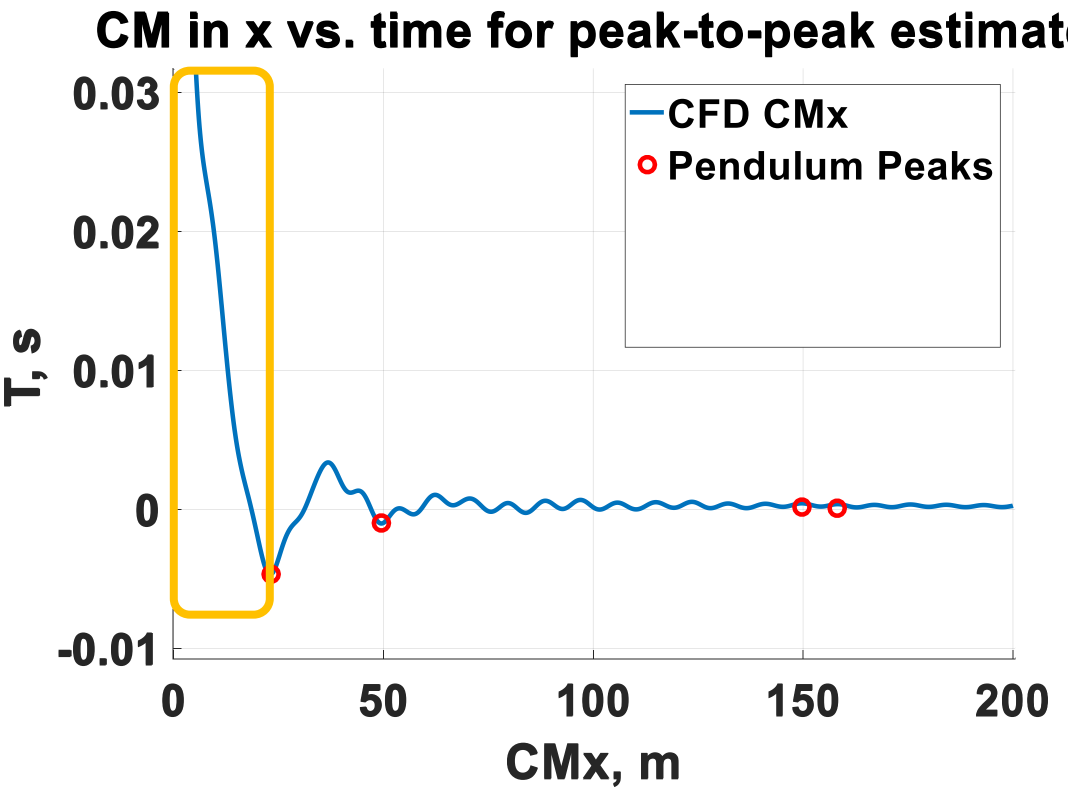
METHODS OVERVIEW

Generate CFD Data



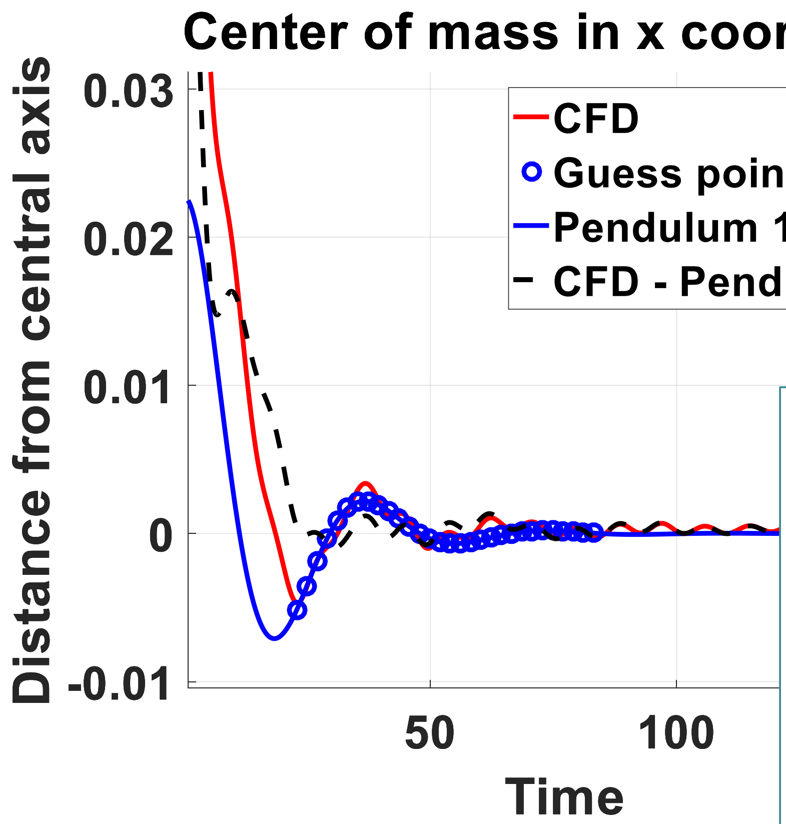
- Propellants: NTO and MMH
- Fill fractions: 25%, 50%, 85%
- Data: CM, Force, Moment (all 3 axes)

Find Initial Guesses

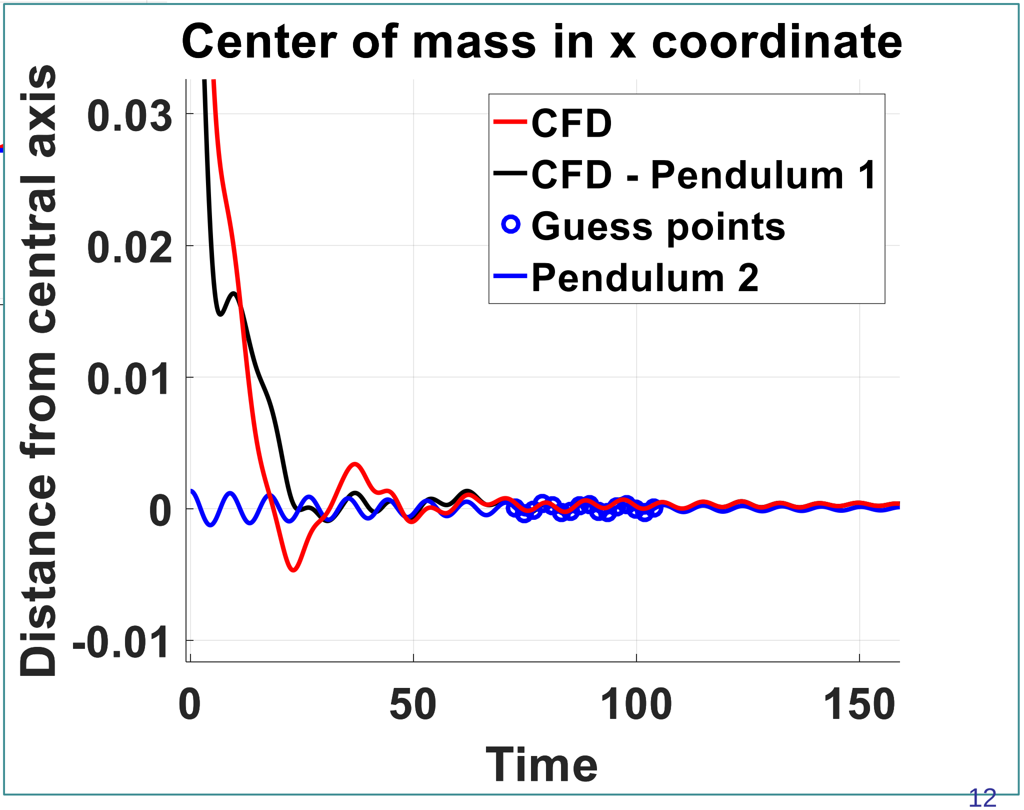


- Curve fitting by finding parameters in pendulum equation that most closely match CFD
- Trying to resolve CFD into two pendulums
- Peak-to-peak values
- -> Initial guesses for damping and frequency of each pendulum
- Note much higher damping before first peak

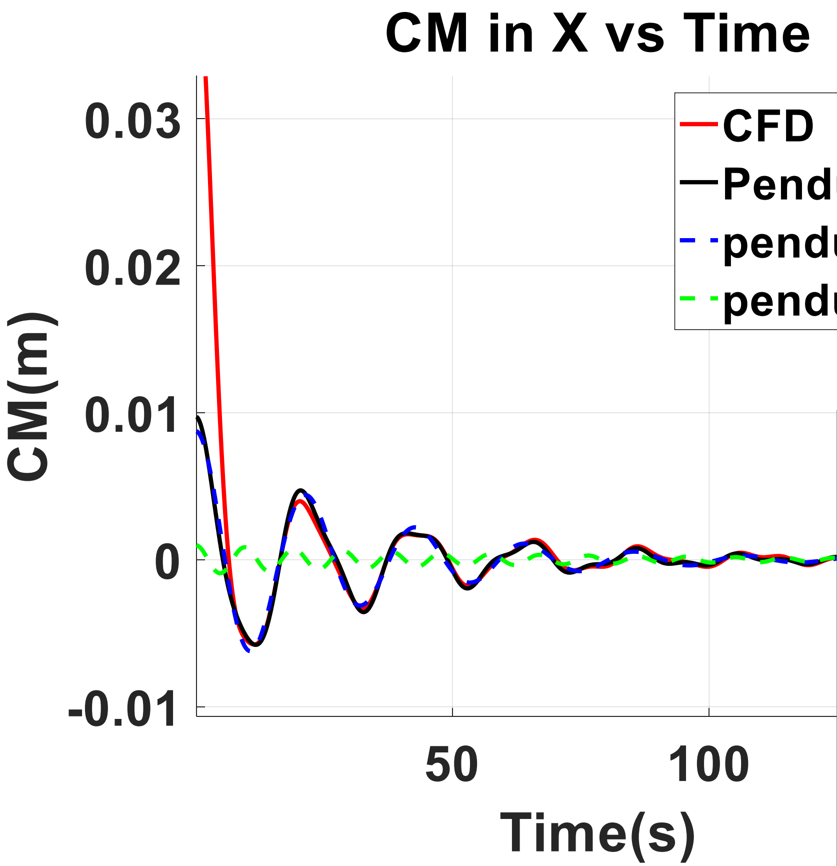
Find Parameters to Fit CM Data



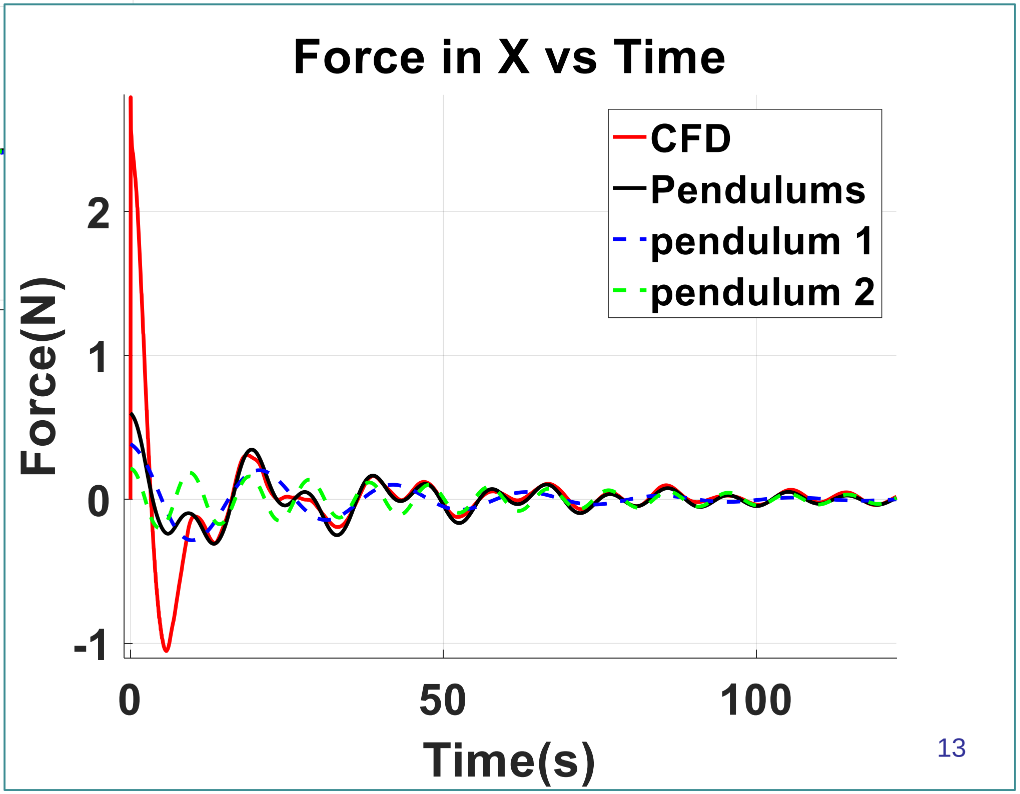
- Matlab's fsolve(x)
- -> Mass, damping, and frequency parameters to fit CMx CFD data
- Refine and iterate



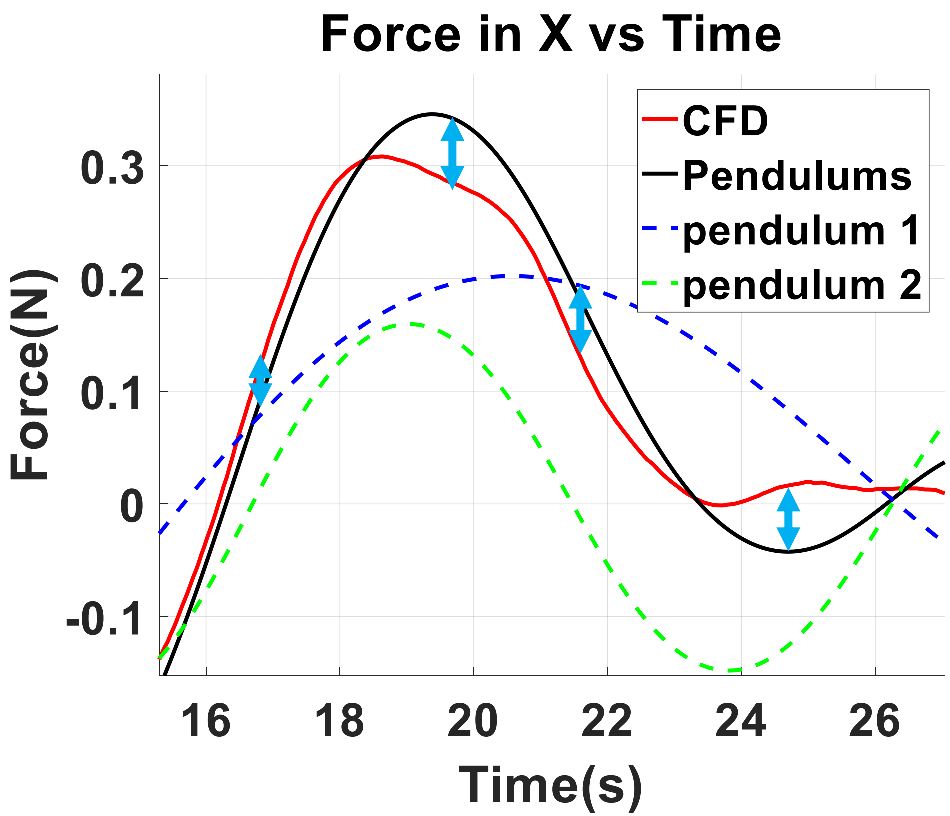
Compare Sum of Pendulums to CFD Data



- 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

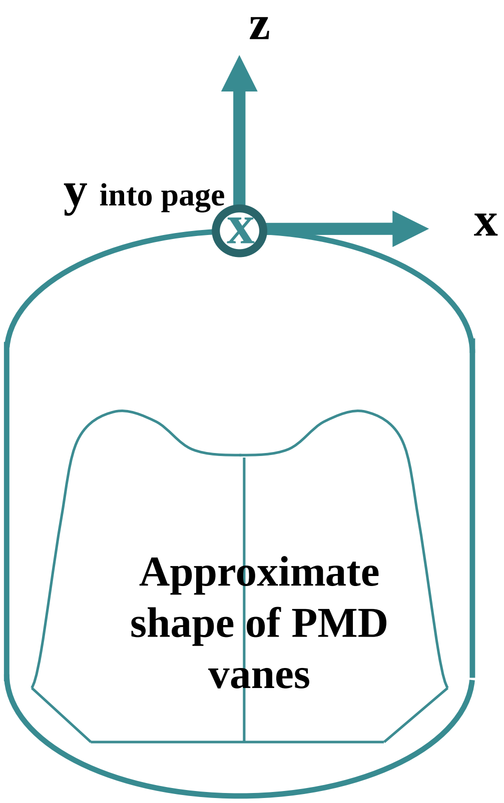
$$\frac{1}{n}\sum_{1}^{n} abs(CFD - pendulum)$$

- Select methods that minimize this

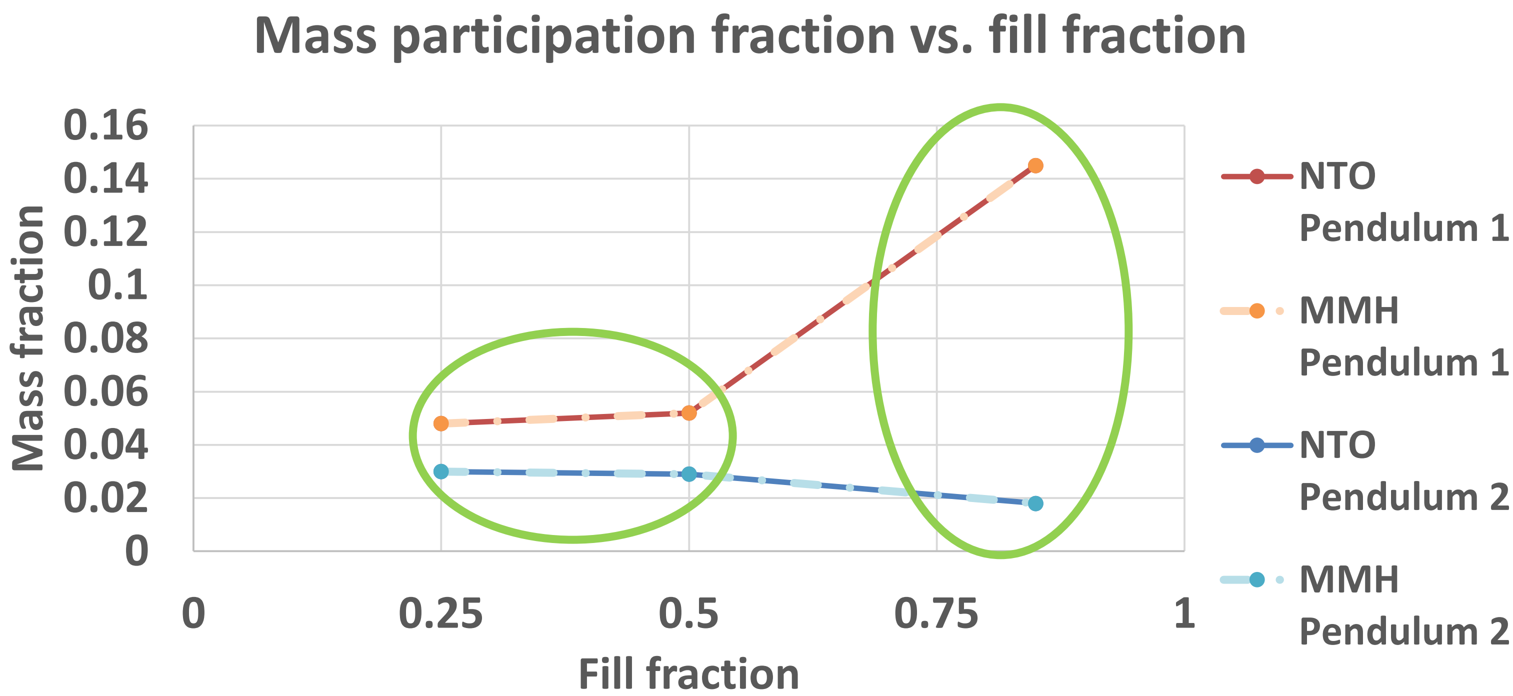
RESULTS AND LITERATURE COMPARISON

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

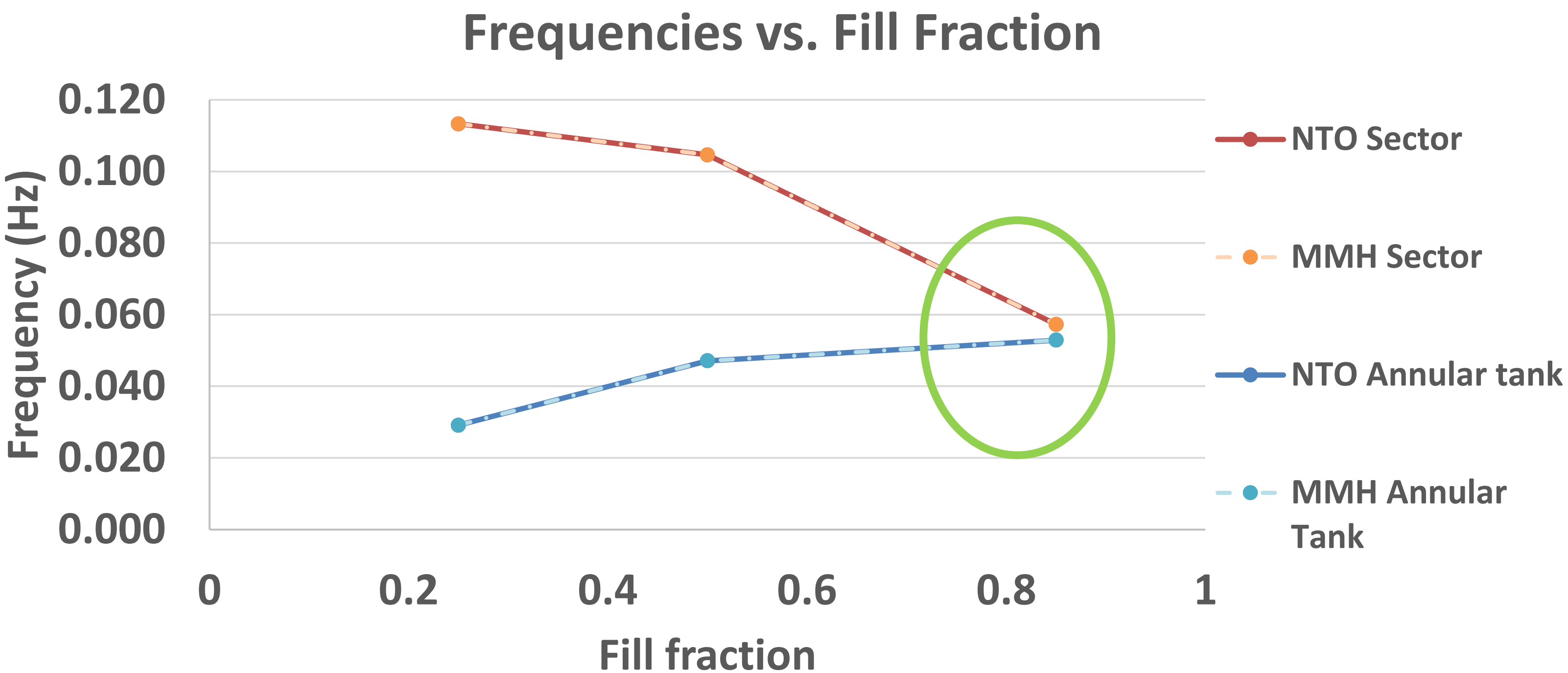


Mass Participation Fraction



- **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**

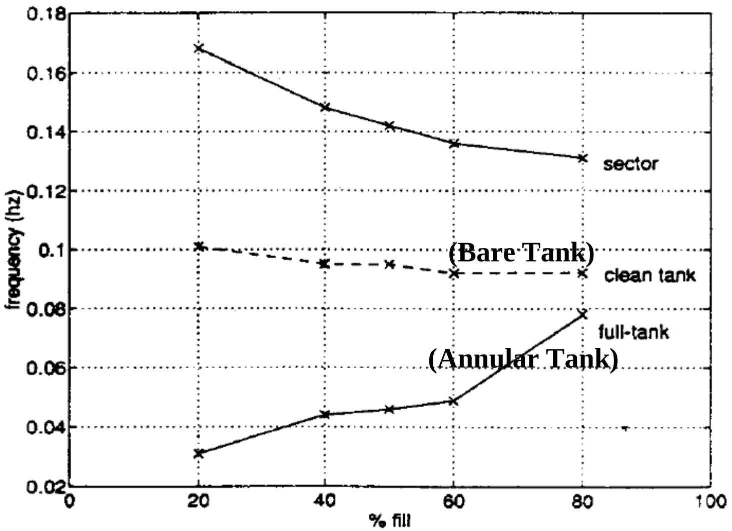
Frequency

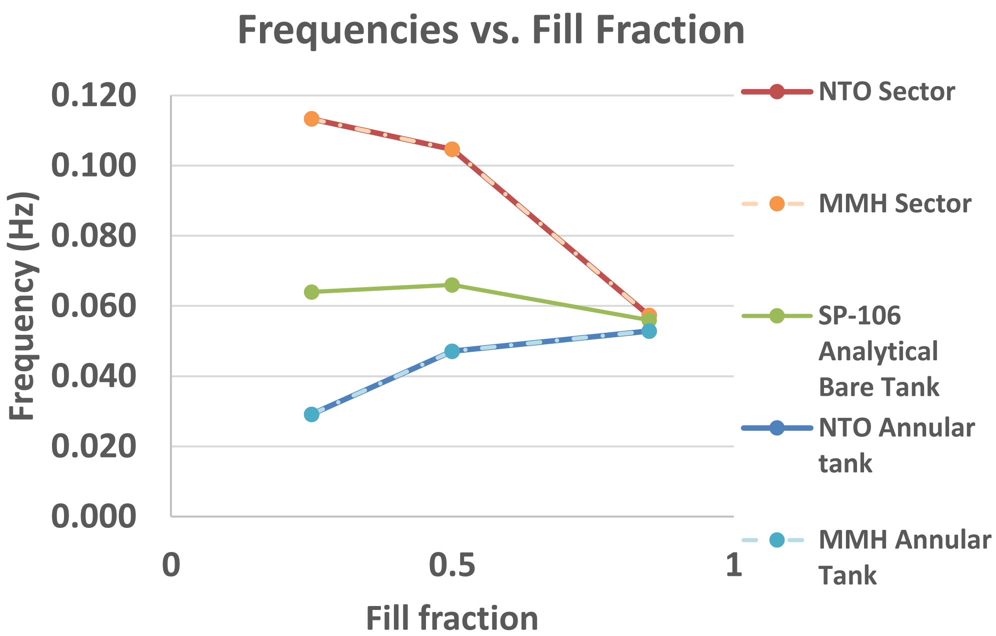


- Function of pendulum's length and acceleration
- Monotonic trends
- Frequencies are identical between NTO and MMH
- Frequencies for the two pendulums converge as fill fraction increases
  - Sector and annular slosh modes become less distinct as PMD becomes fully submerged

Frequency - Literature Comparison 1

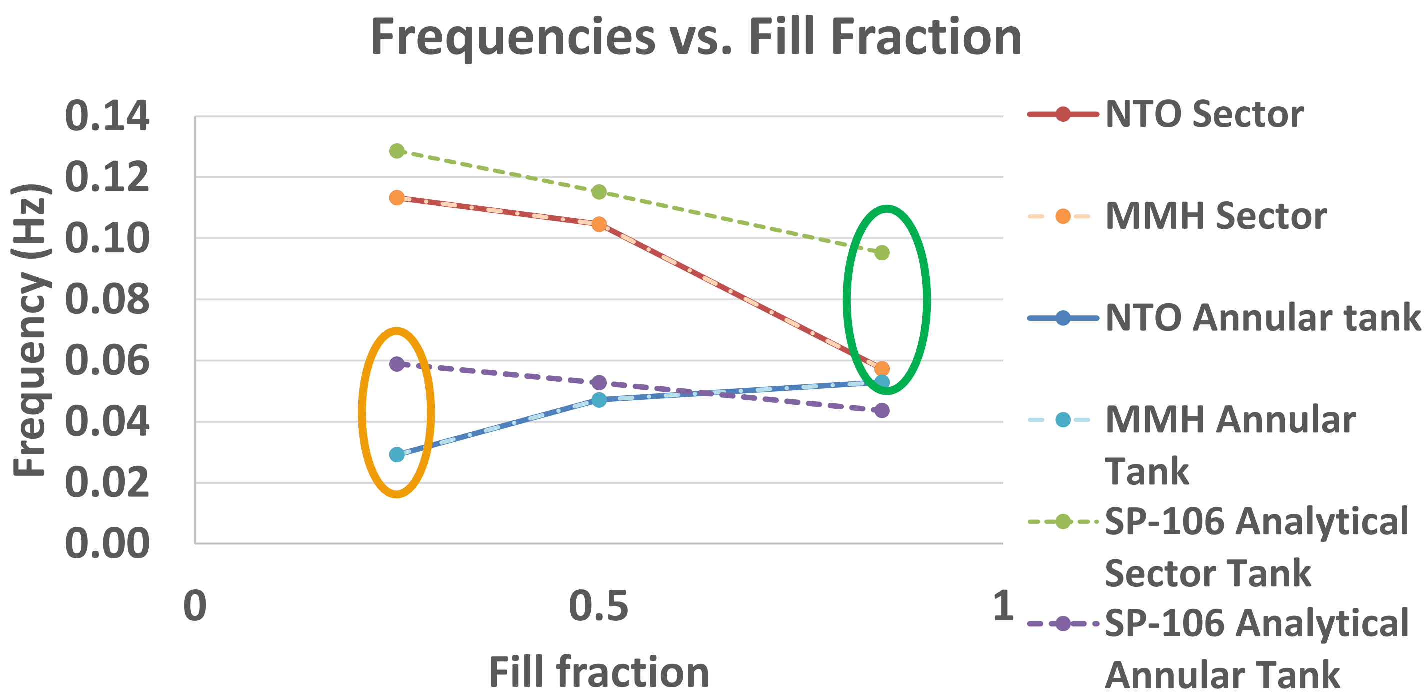
Cassini Paper Frequencies vs. Fill Fraction





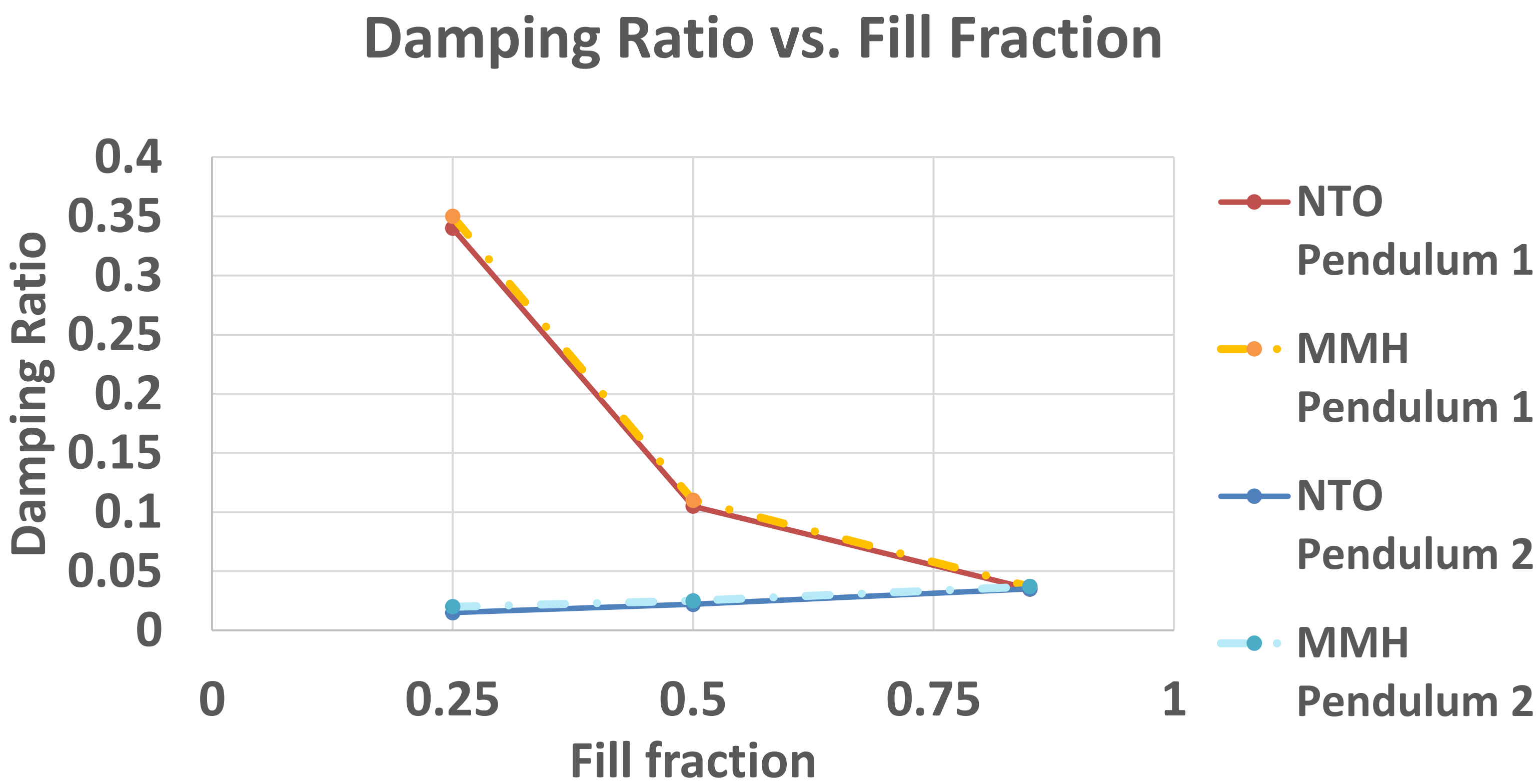
- Left: Cassini paper referenced SP-106 for an analytical equation for slosh frequency in a bare tank (cylindrical tank with no PMD) and compared it to the frequencies of their two pendulums
- Right: Similar trends to Cassini found in Europa pendulum model frequencies
- Sector and annular slosh modes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

Frequency – Literature Comparison 2



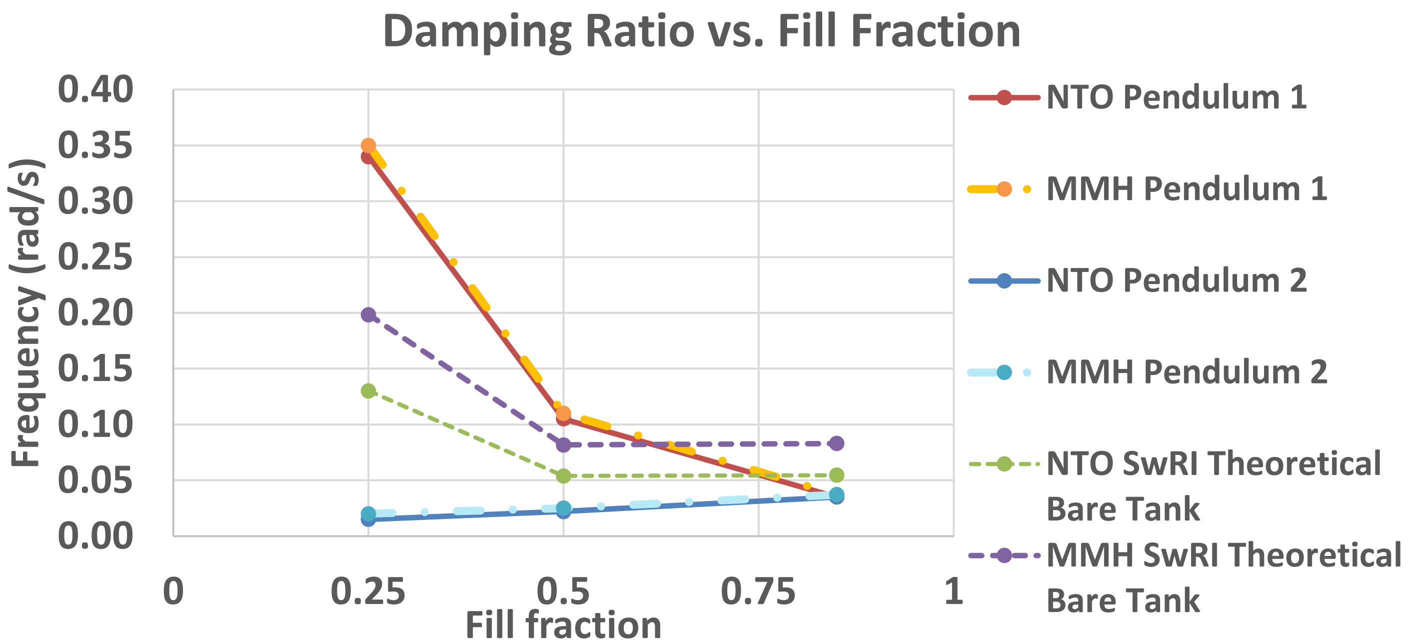
- SP-106 references tables (Bauer, 1963) for an analytical equations for sector and annular slosh frequency
- Function of acceleration, geometry, and fluid height
- Pendulum frequencies are close to analytical equation frequencies
- Differences between analytical and pendulum fits due to:
  - PMD is 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

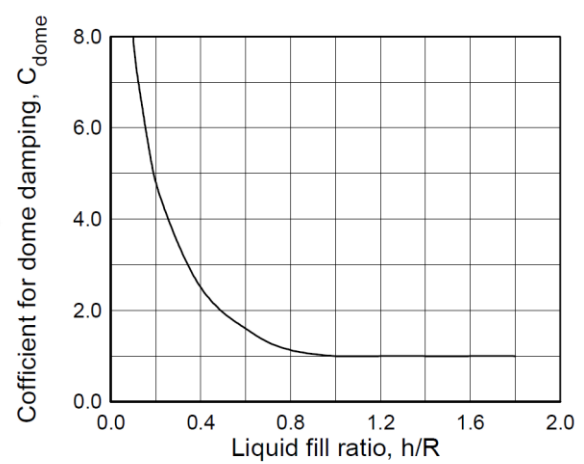


- Monotonic trends
- Slightly higher damping ratio for higher dynamic viscosity (MMH)

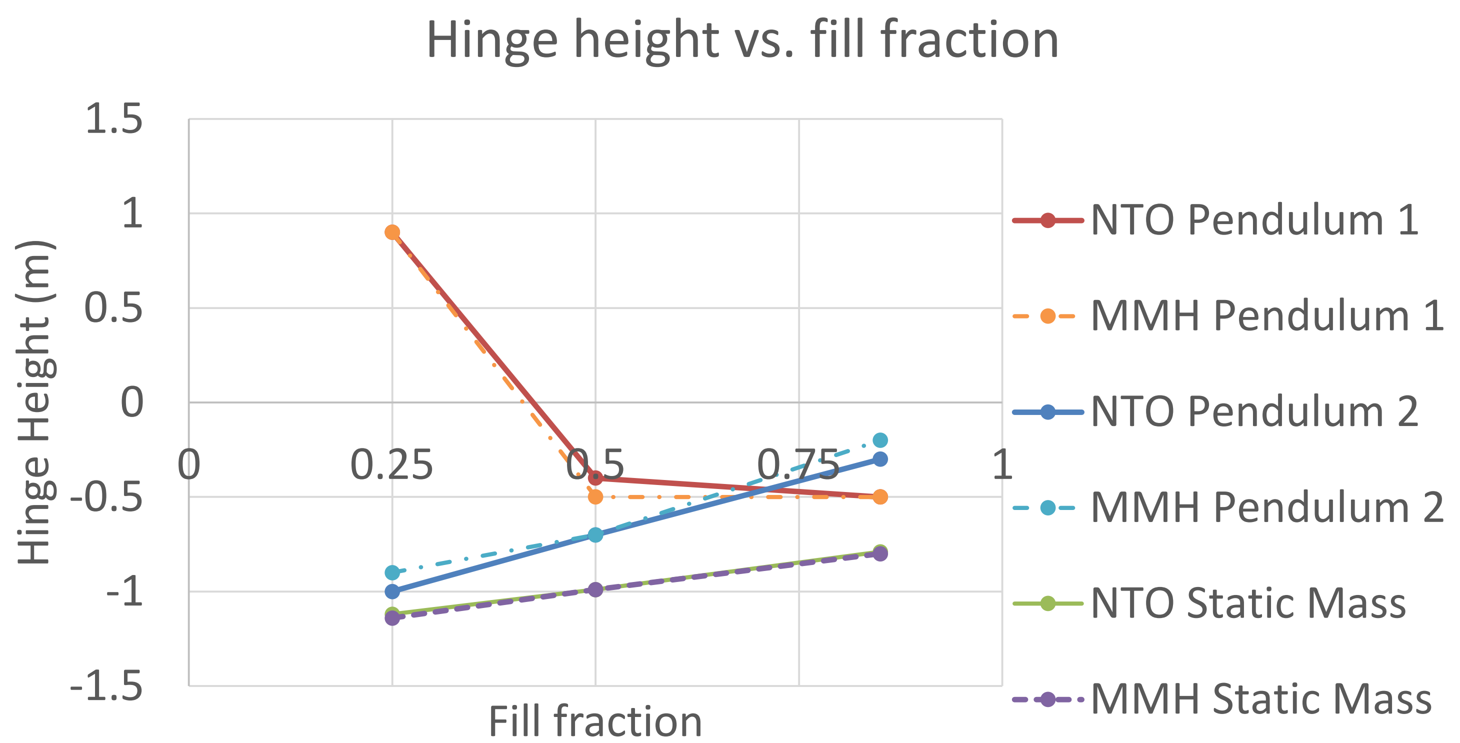
Damping Ratio – Comparison 1



- 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



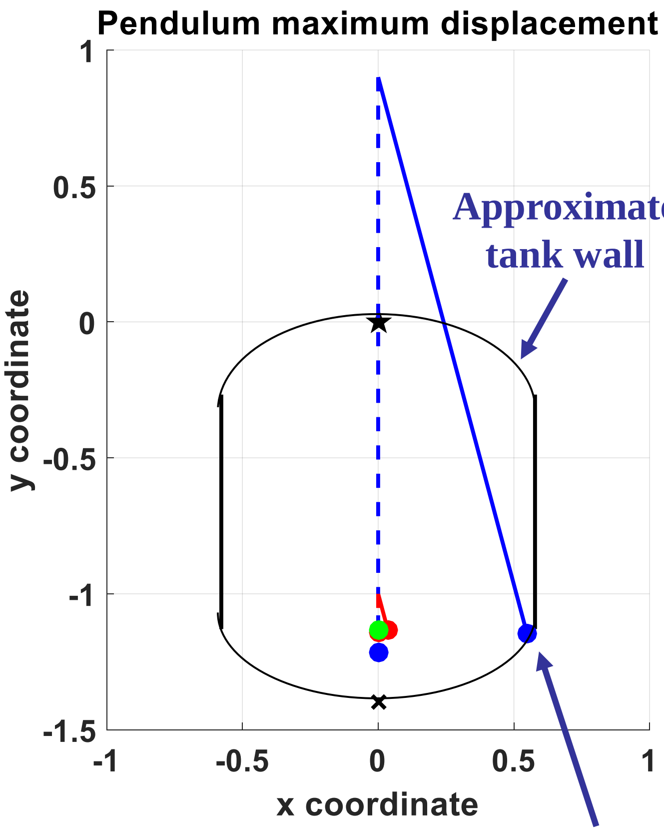
Length and Hinge Location



- **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

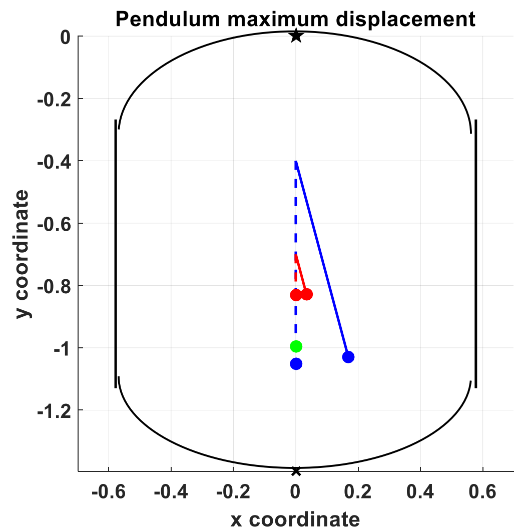
NTO 25% fill



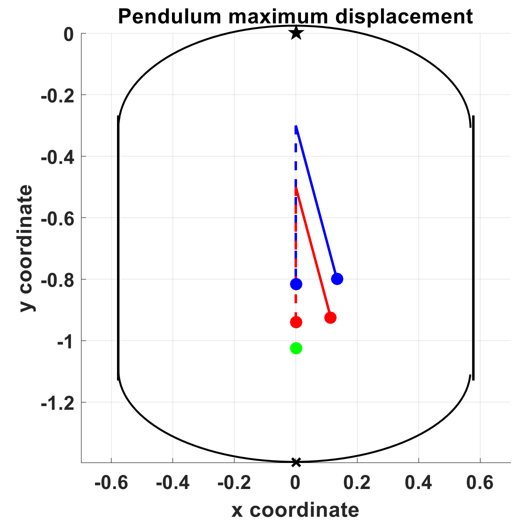
Approximate tank wall

Pendulum at 15 degree offset

NTO 50% fill

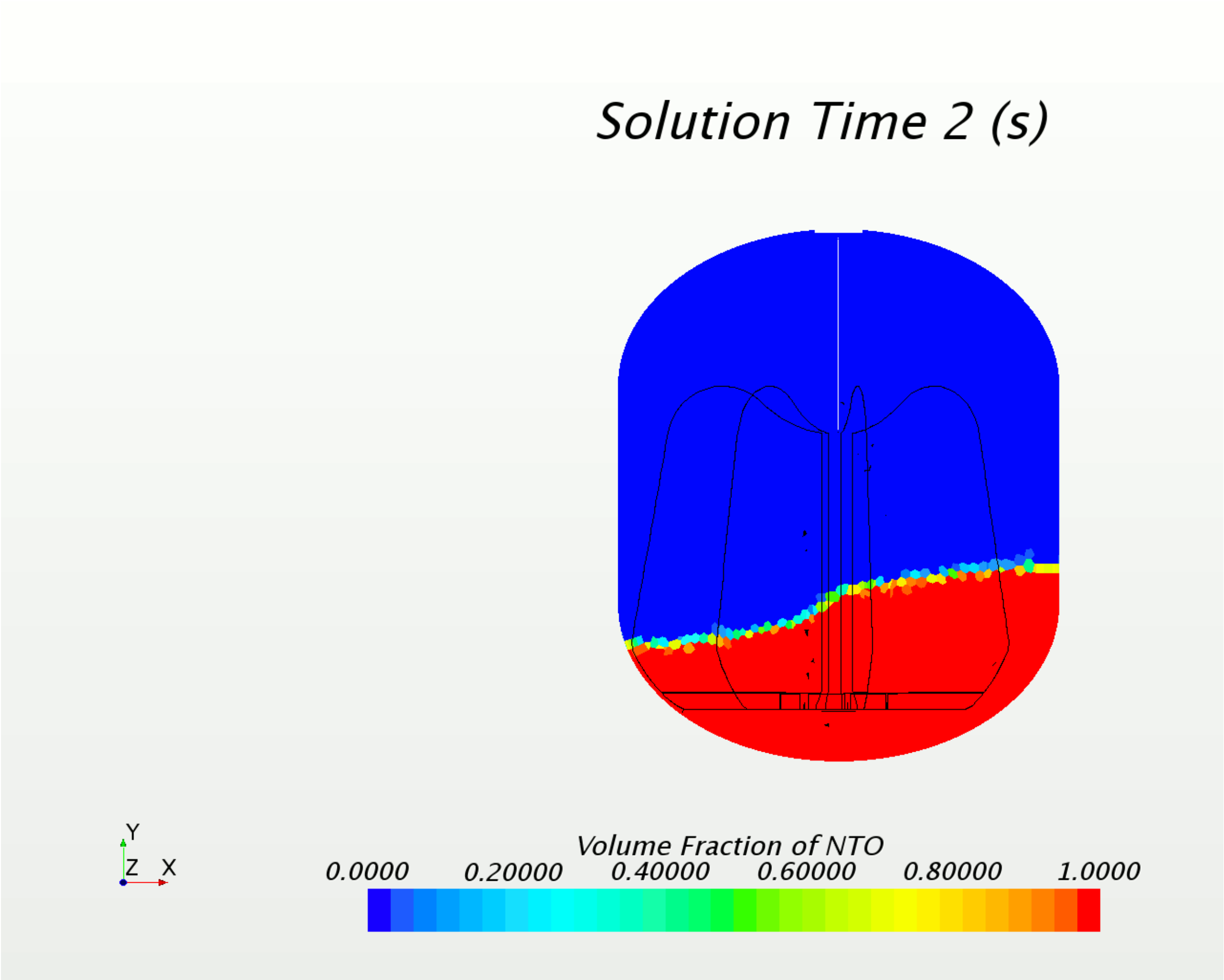


NTO 85% fill

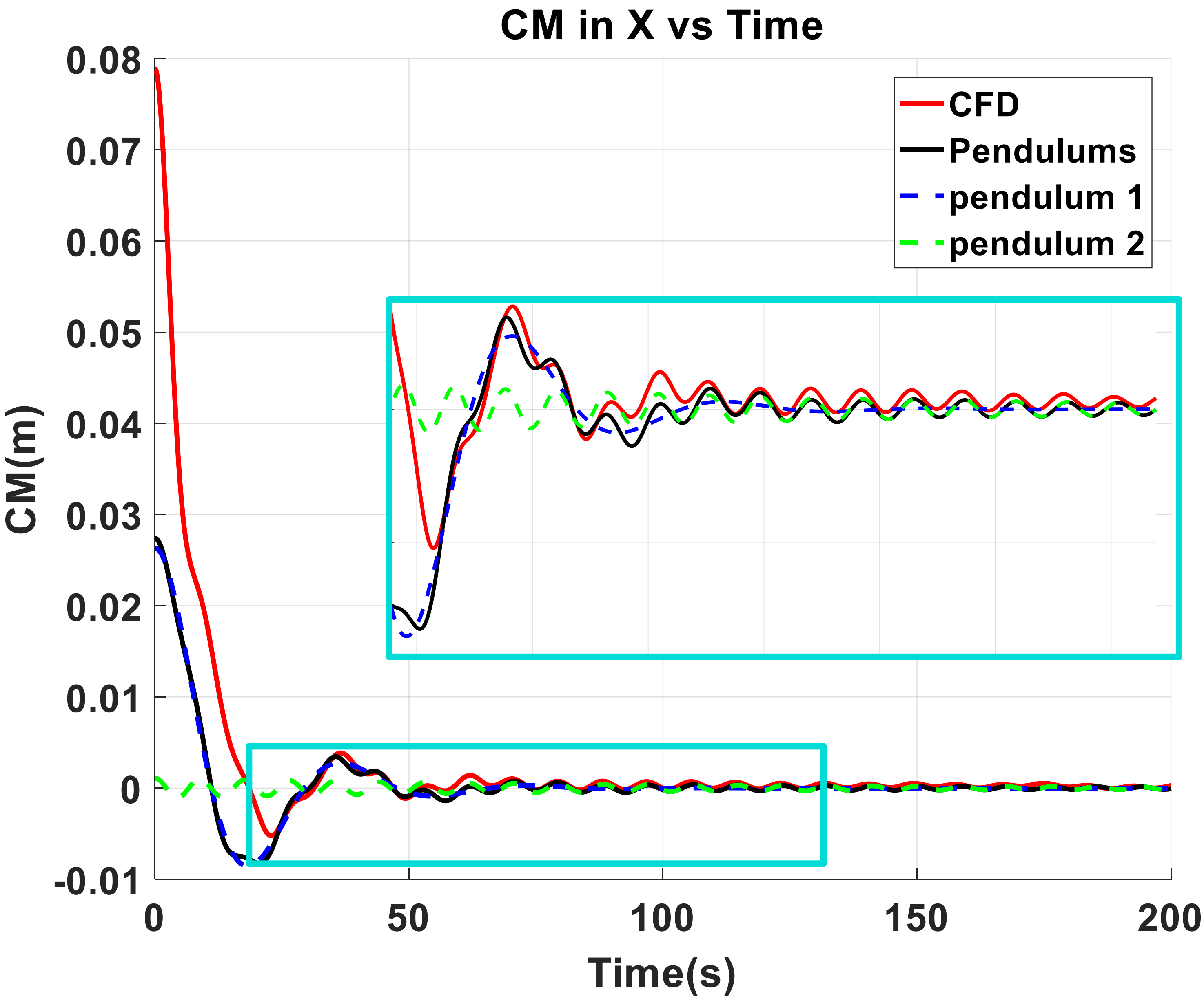


PLOTS COMPARING PENDULUM MODELS AND CFD DATA

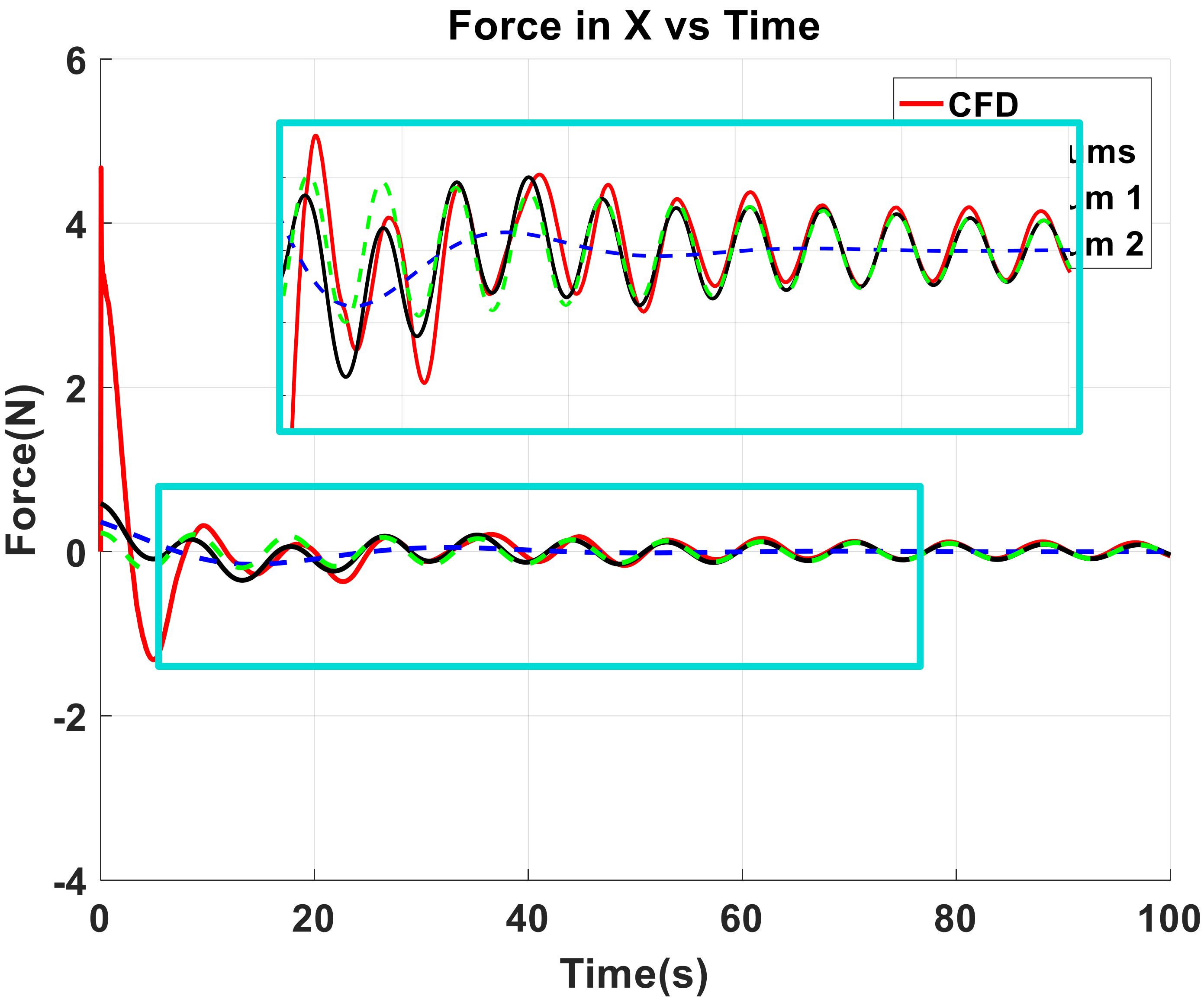
NTO 25% Fill Fraction



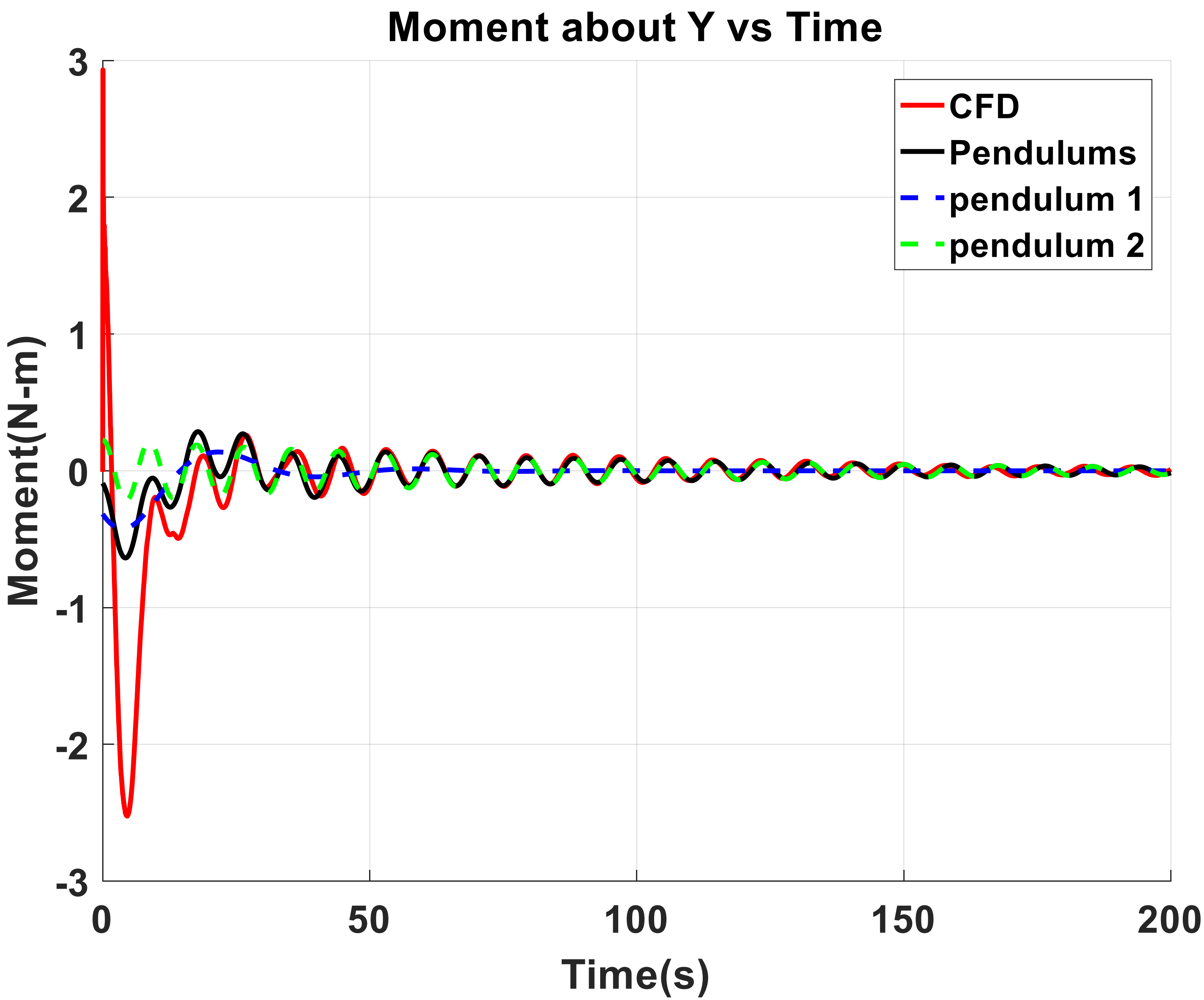
NTO 25% Fill Fraction



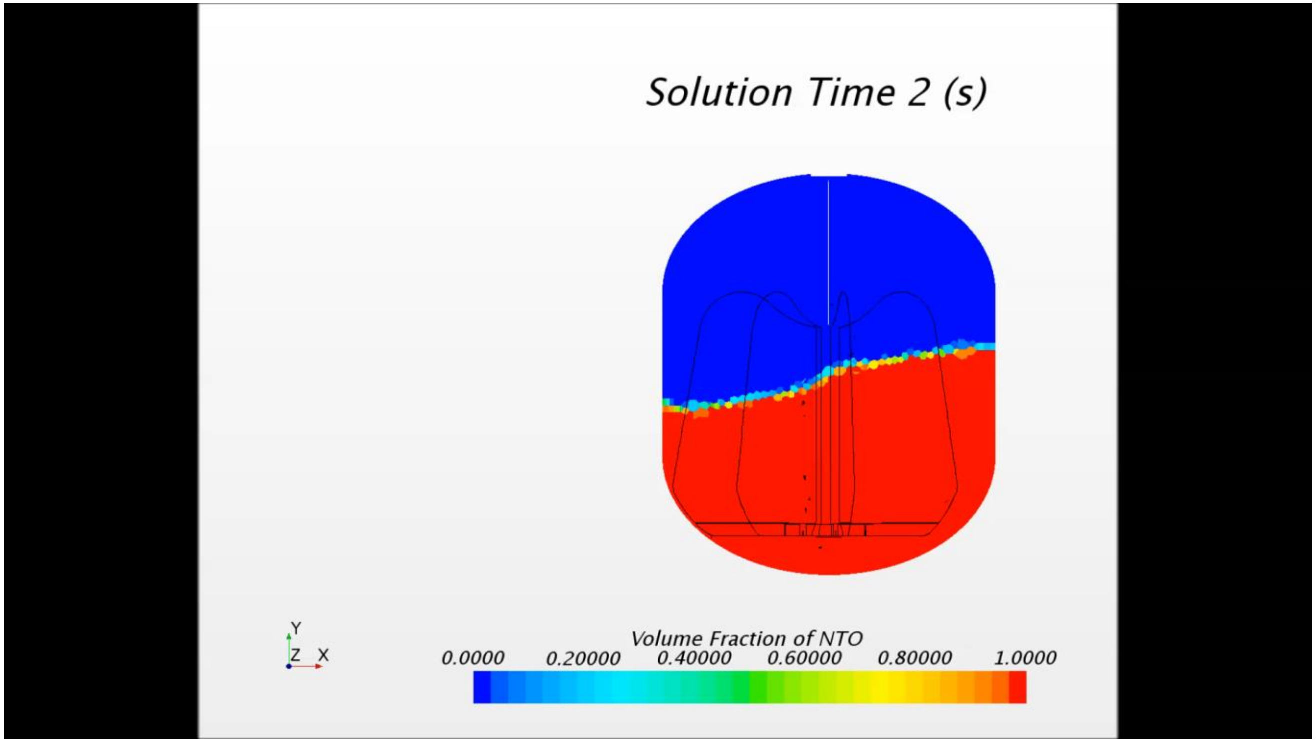
NTO 25% Fill Fraction



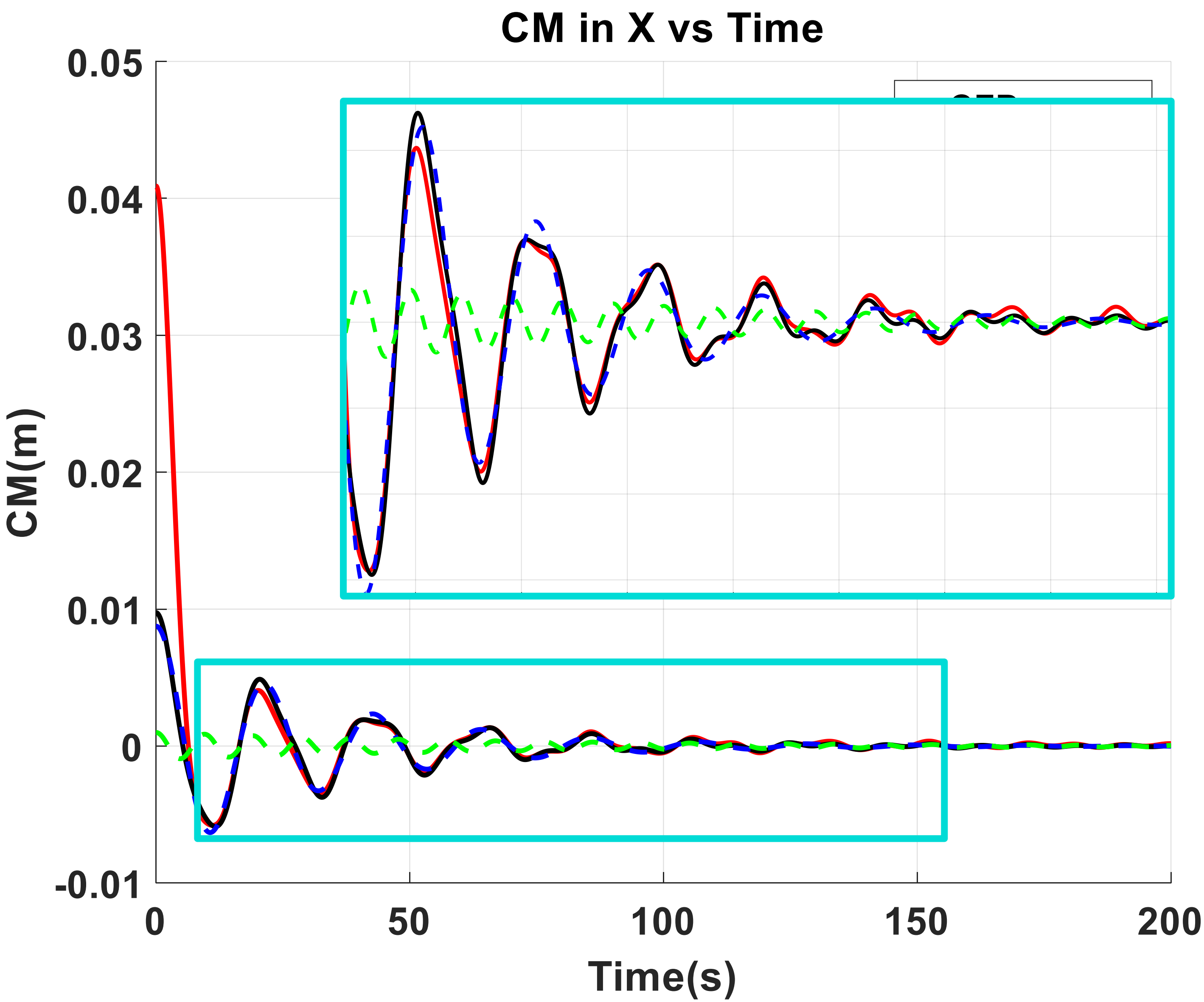
NTO 25% Fill Fraction



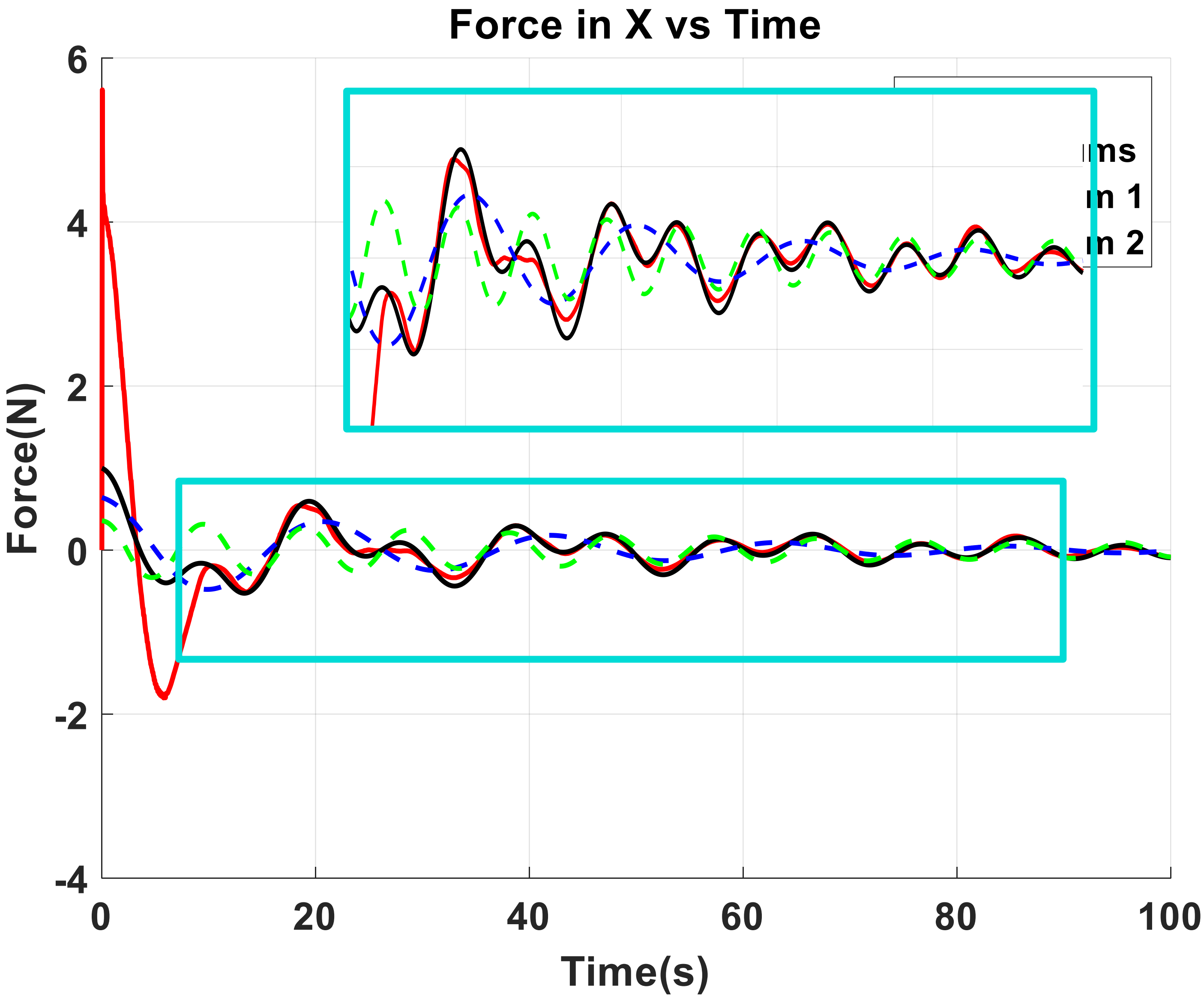
NTO 50% Fill Fraction



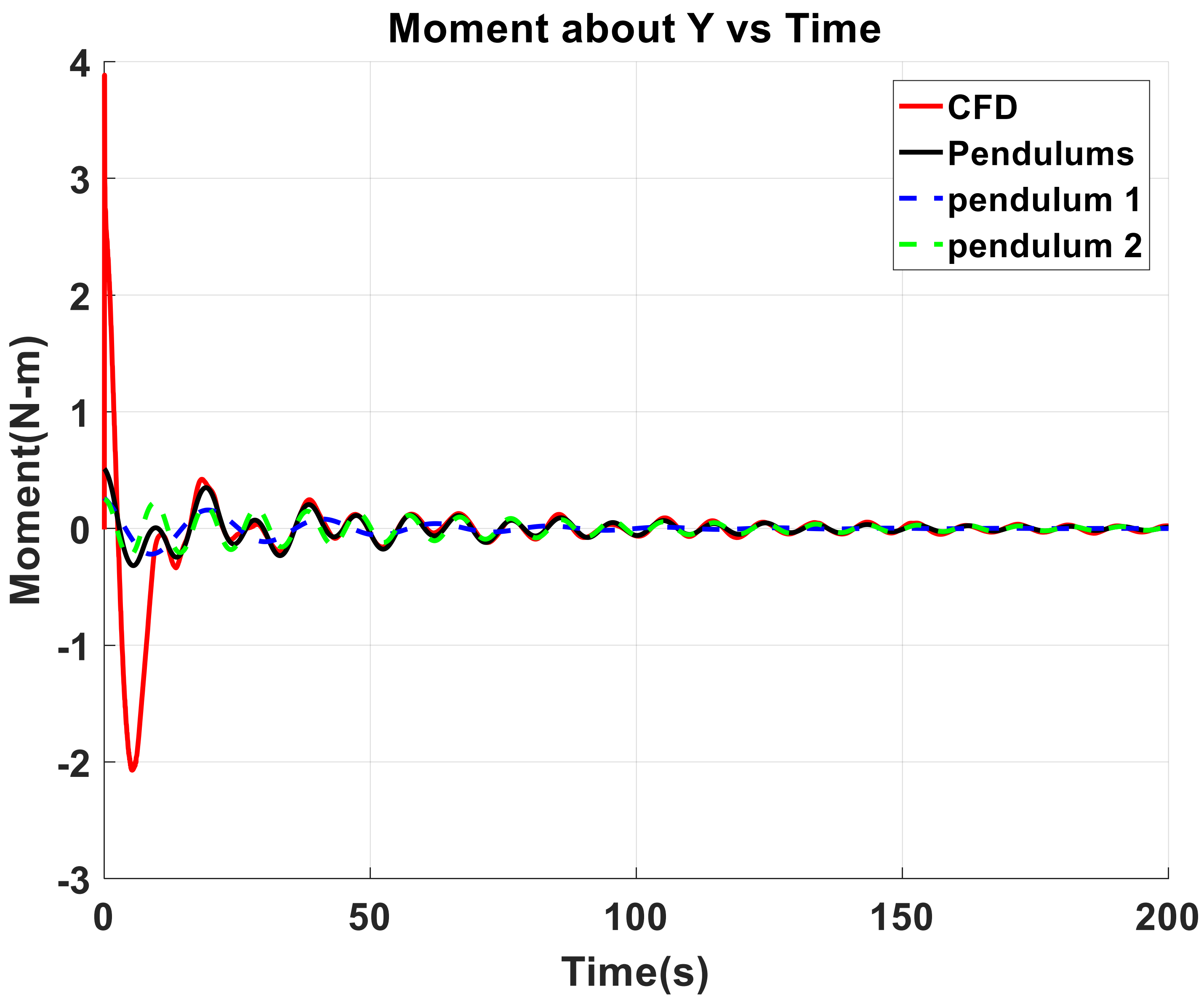
NTO 50% Fill Fraction



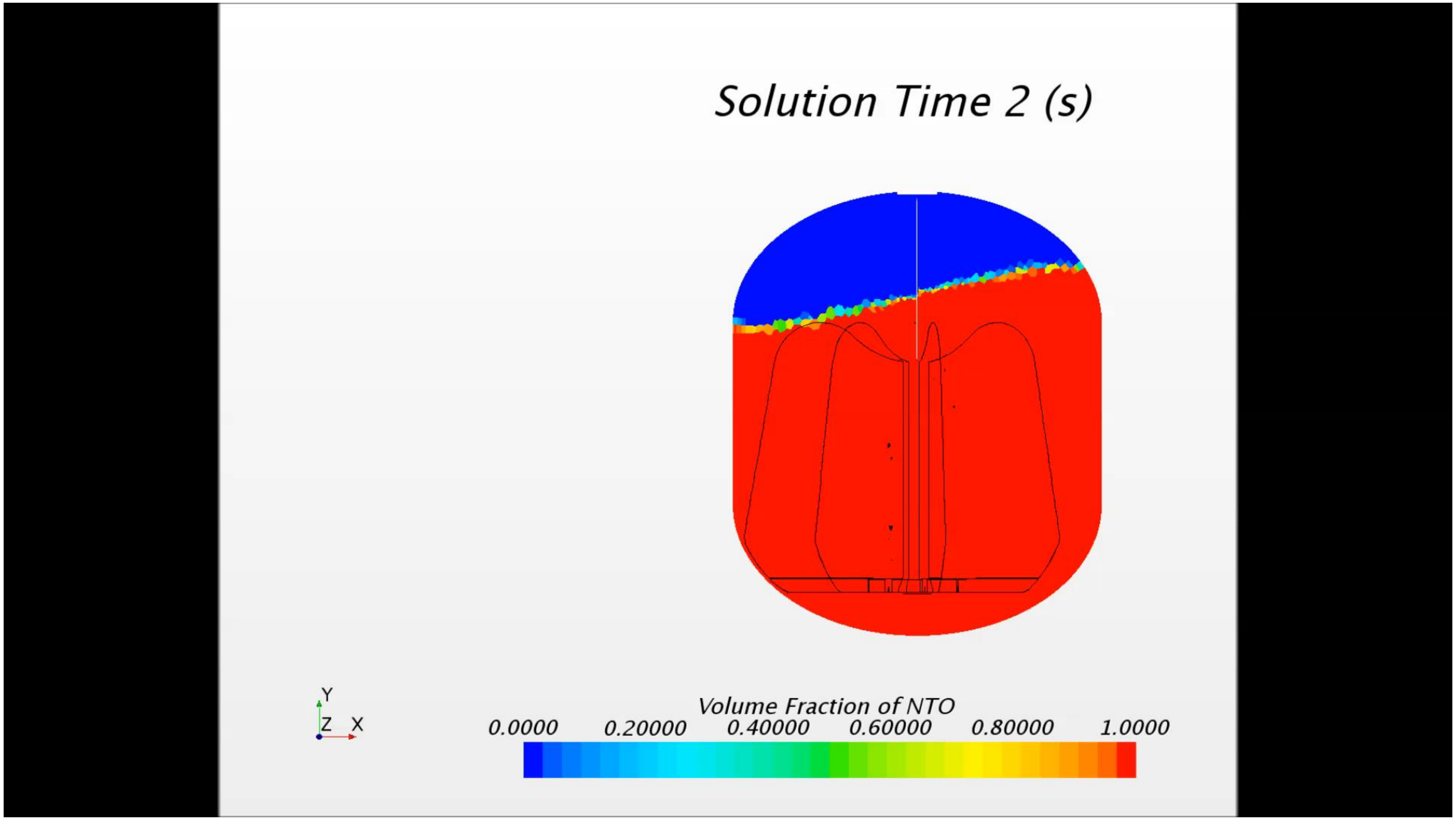
NTO 50% Fill Fraction



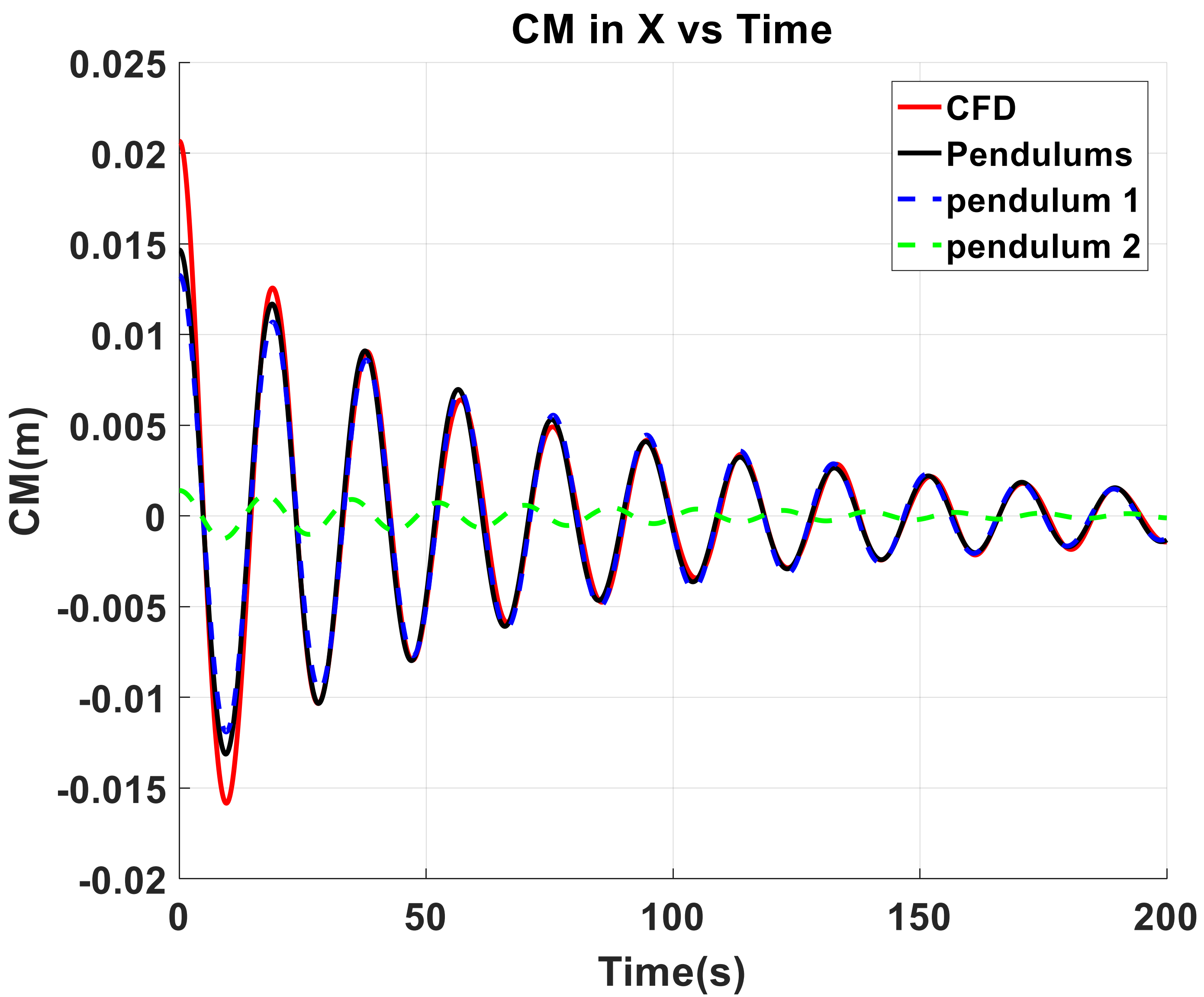
NTO 50% Fill Fraction



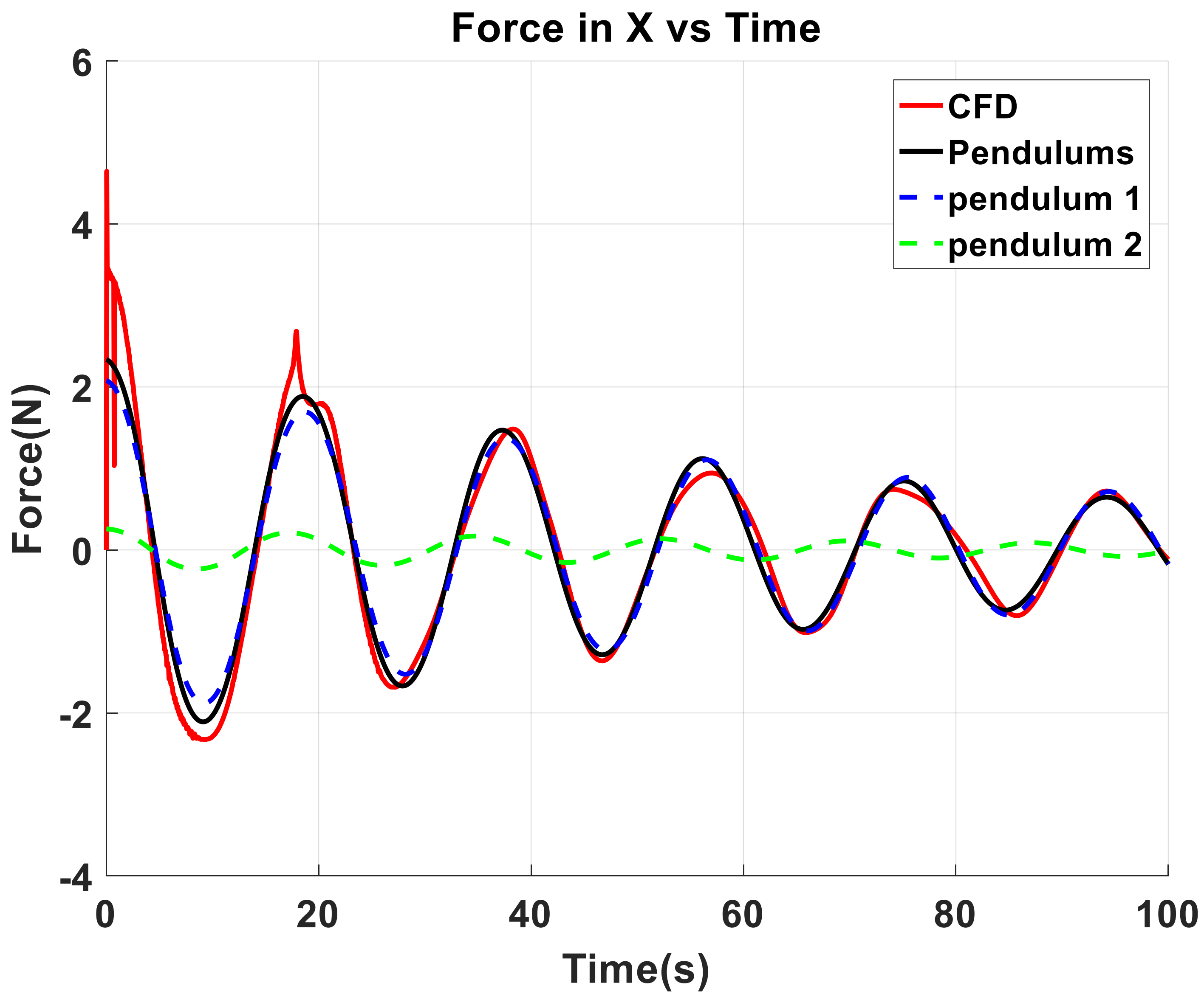
NTO 85% Fill Fraction



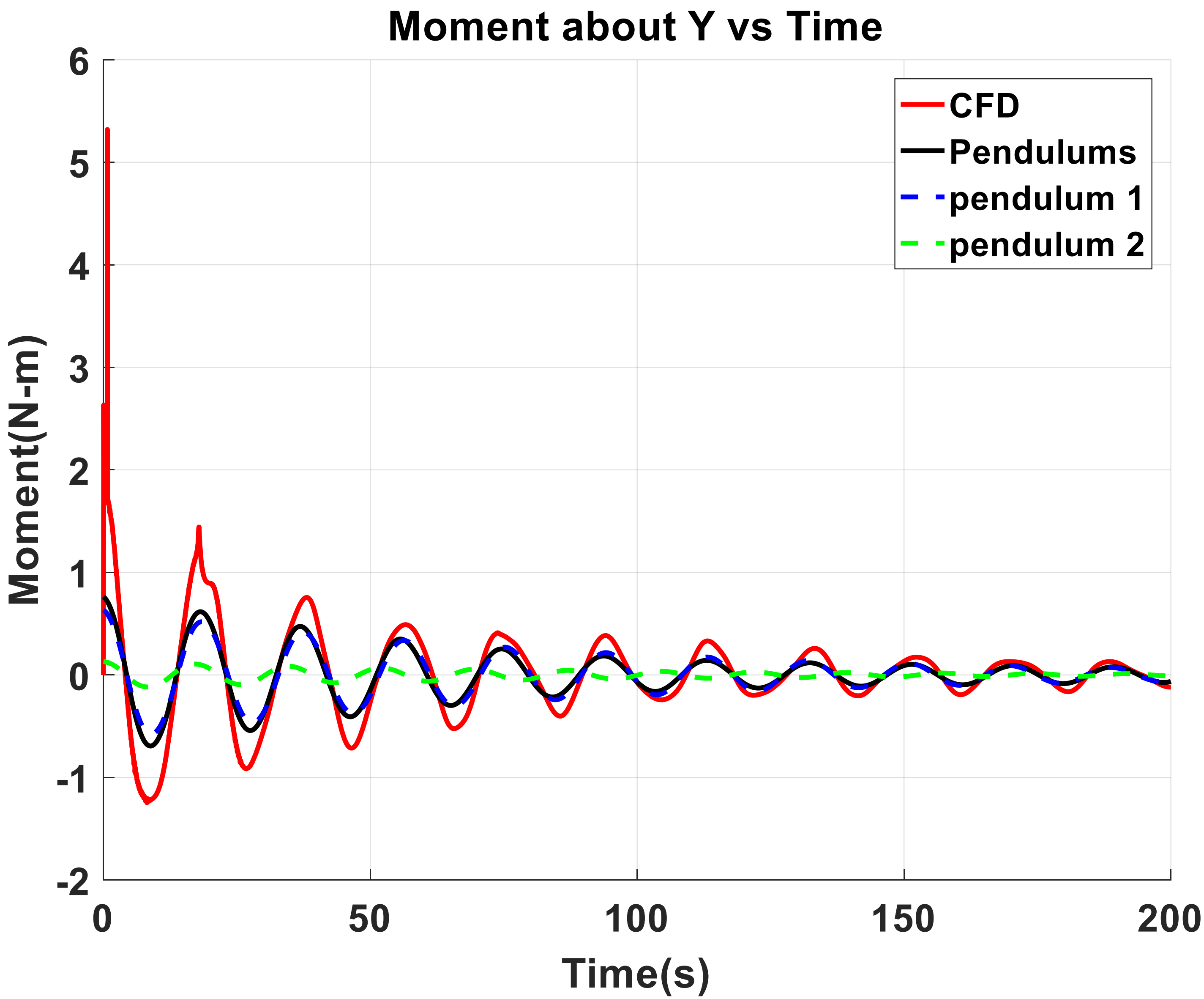
NTO 85% Fill Fraction



NTO 85% Fill Fraction



NTO 85% Fill Fraction



Summary of Parameters

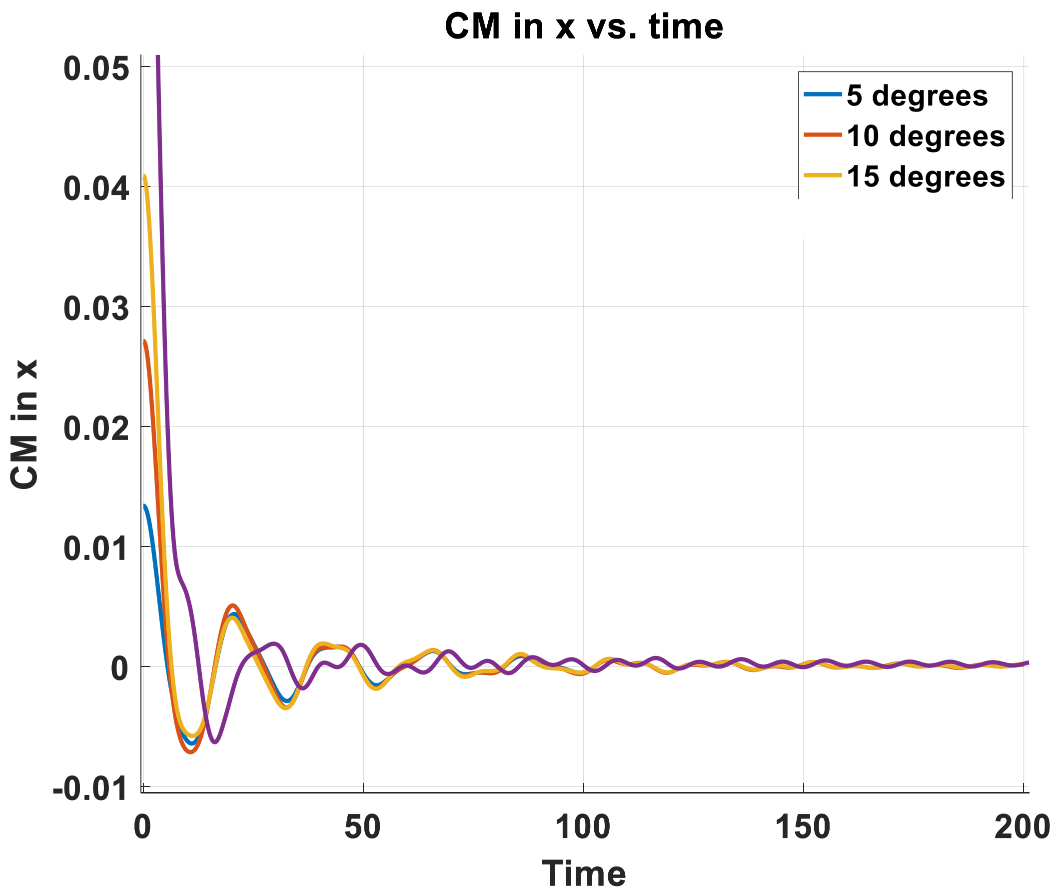
	NTO (nitrogen tetroxide)			MMH (monomethyl hydrazine)		
	25% fill	50% fill	85% fill	25% fill	50% fill	85% fill
Mass fraction1	0.048	0.052	0.145	0.048	0.052	0.145
Mass fraction 2	0.03	0.029	0.018	0.03	0.029	0.018
Mass 1 (kg)	20.09	44.49	210.87	12.12	26.69	126.53
Mass 2 (kg)	12.56	24.81	26.18	7.58	14.89	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

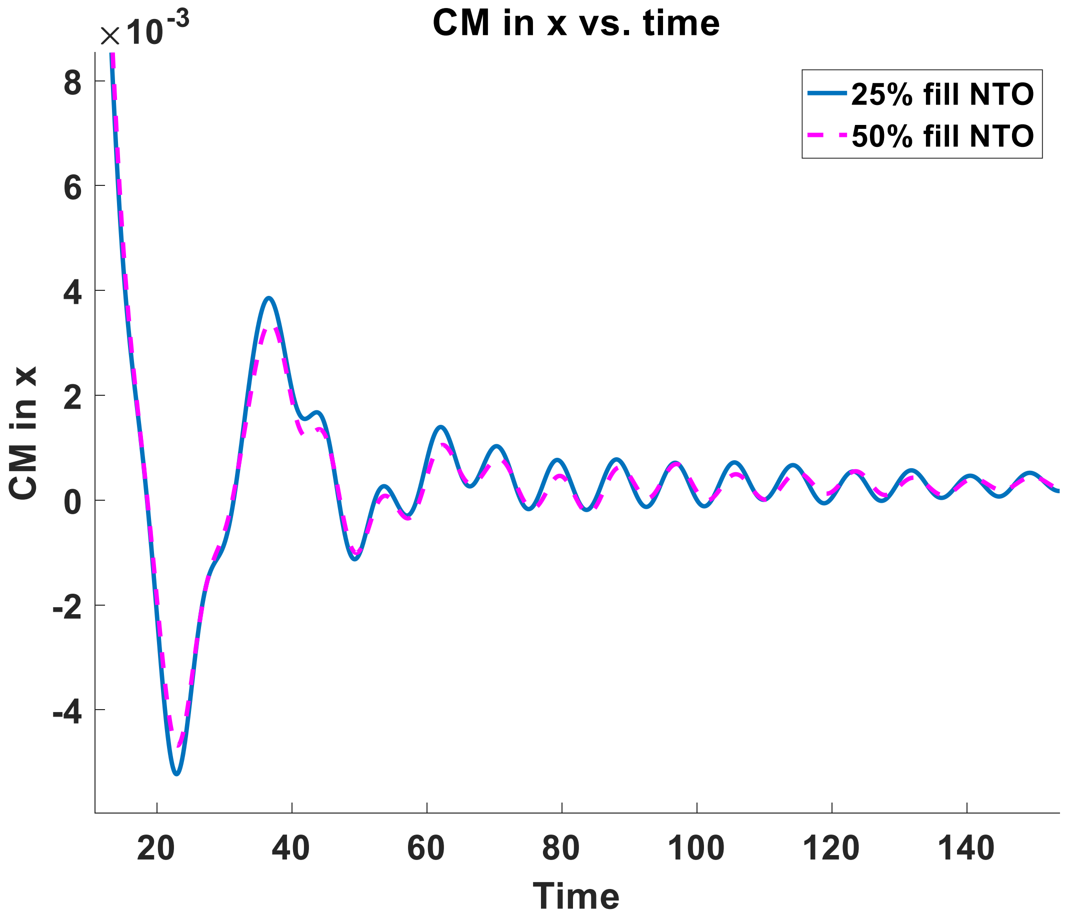
- Two-pendulum model can accurately capture either before or after first peak
- High confidence on frequencies except 85% fill pendulum 2
- Moderate confidence on mass, damping, and hinge location
  - Sometimes several sets of parameters could have provided good matching to CFD
  - Selected parameters 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 mocel 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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