Validation of Slosh Modeling Approach Using STAR-CCM+

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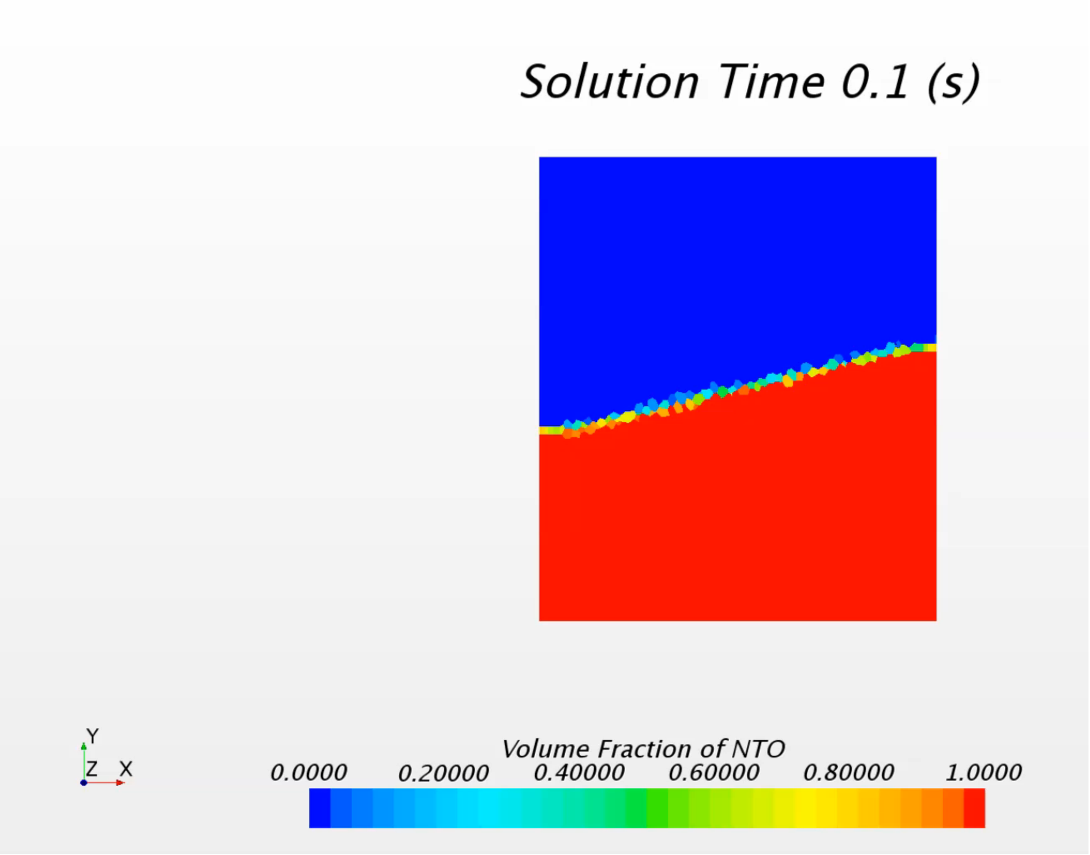
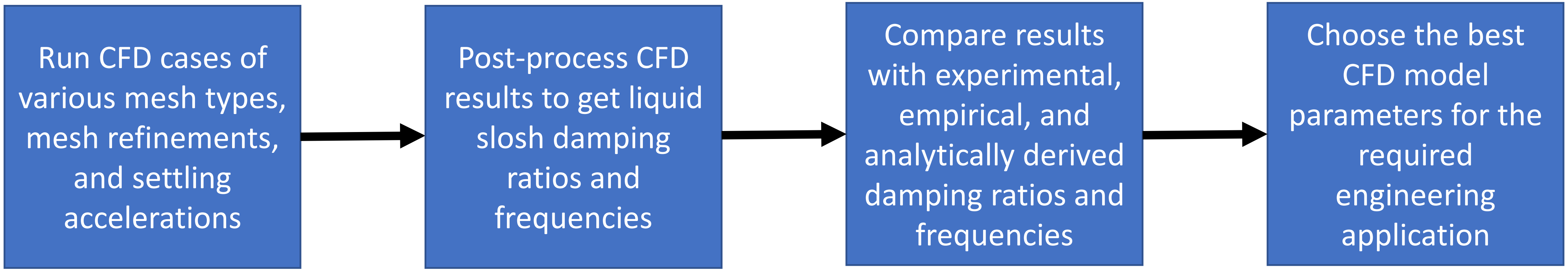
Background

- Slosh is movement of a liquid in a container
- For a spacecraft, propellant slosh is excited by thrusters, momentum wheels, launch vehicle motion, spacecraft separation from launch vehicle, and deployments
- Propellant slosh exerts forces and torques on the spacecraft, as well as shifting the spacecraft center of mass
- Inadequate knowledge of propellant can lead to loss of science observation time, and in extreme cases, a loss of the spacecraft
- NASA’s Europa Clipper mision uses STAR-CCM+, a commercially available computational fluid dynamics (CFD) tool, to model slosh



Validation Approach



Run CFD cases of various mesh types, mesh refinements, and settling accelerations

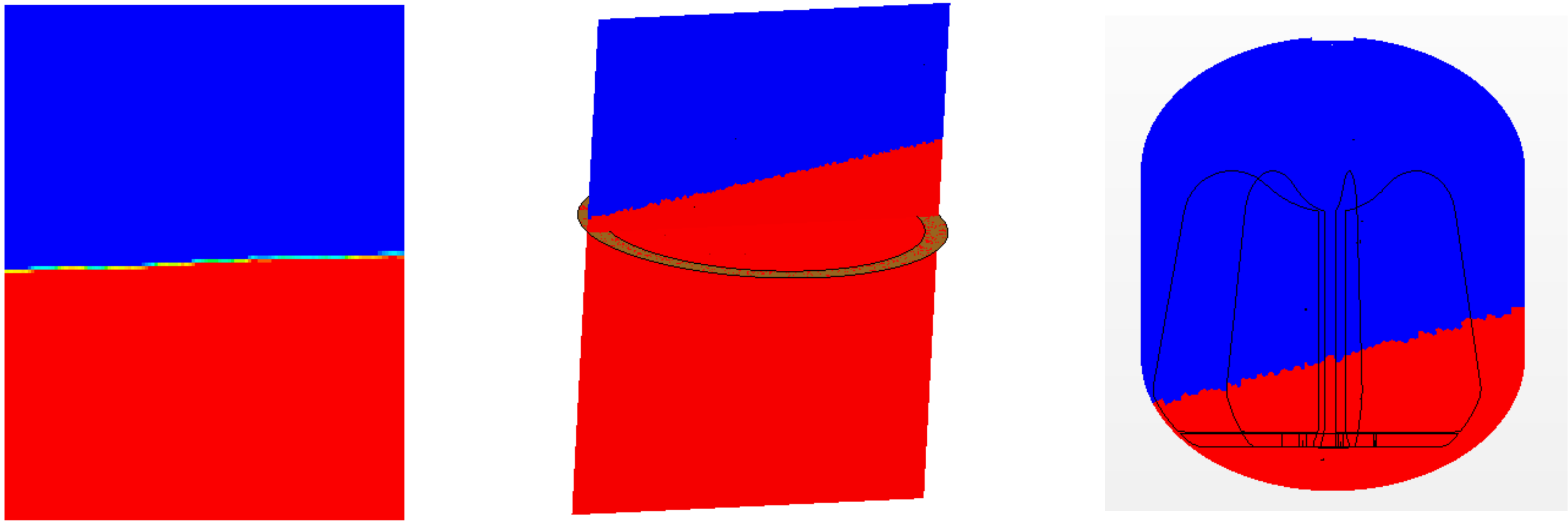
Post-process CFD results to get liquid slosh damping ratios and frequencies

Compare results with experimental, empirical, and analytically derived damping ratios and frequencies

Choose the best CFD model parameters for the required engineering application

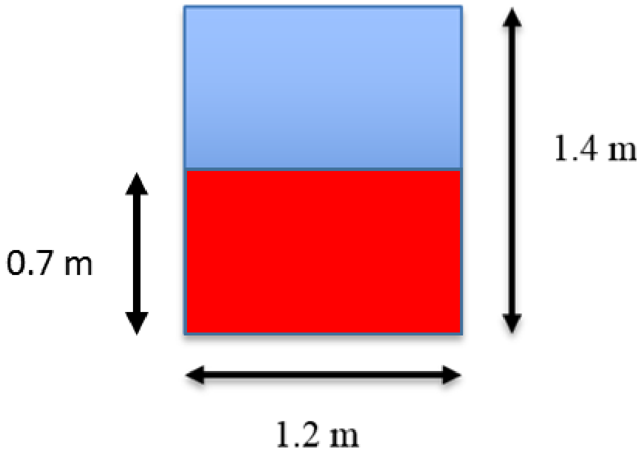
Validation Approach

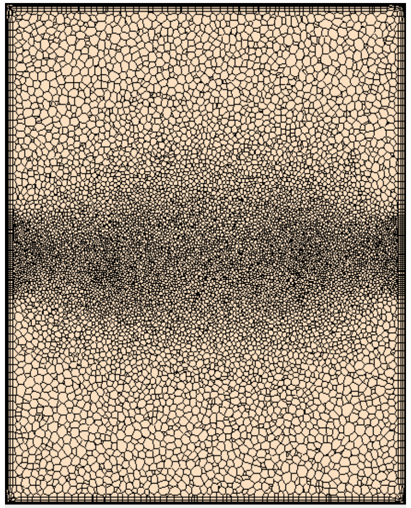
- There is a lack of experimental data for slosh in flight tanks because it is prohibitively expensive to get that data
- By showing that STAR-CCM+ can accurately model slosh in simple geometry tanks where we do have experimental and analytically derived data, we gain confidence in the ability of STAR-CCM+ to model slosh in a flight tank



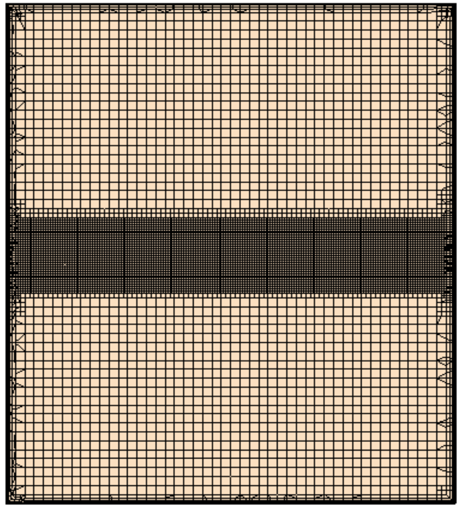
- The same modeling approach is used for the simple tanks as is used for the flight tank

Bare Tank Study Setup



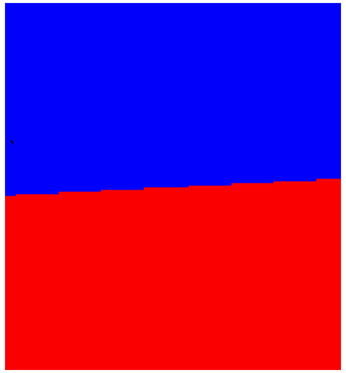


Polyhedral



Trim

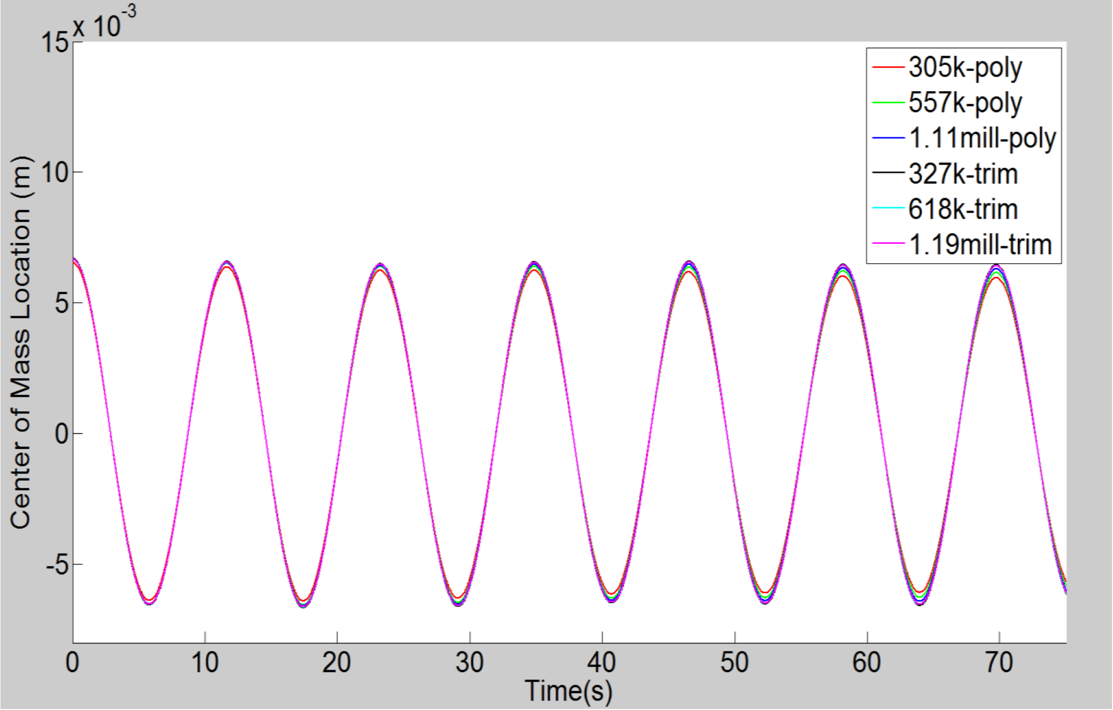
- A right cylindrical tank is studied
  - Empirical relations exist for liquid slosh damping
  - Methods exist for deriving the liquid slosh frequency from the geometry of a bare tank
- CFD Setup:
  - Full 3D Model
  - Varied the mesh type, mesh refinement, and settling acceleration
  - The liquid surface is initialized at an angle so that sloshing will occur when an settling acceleration is applied

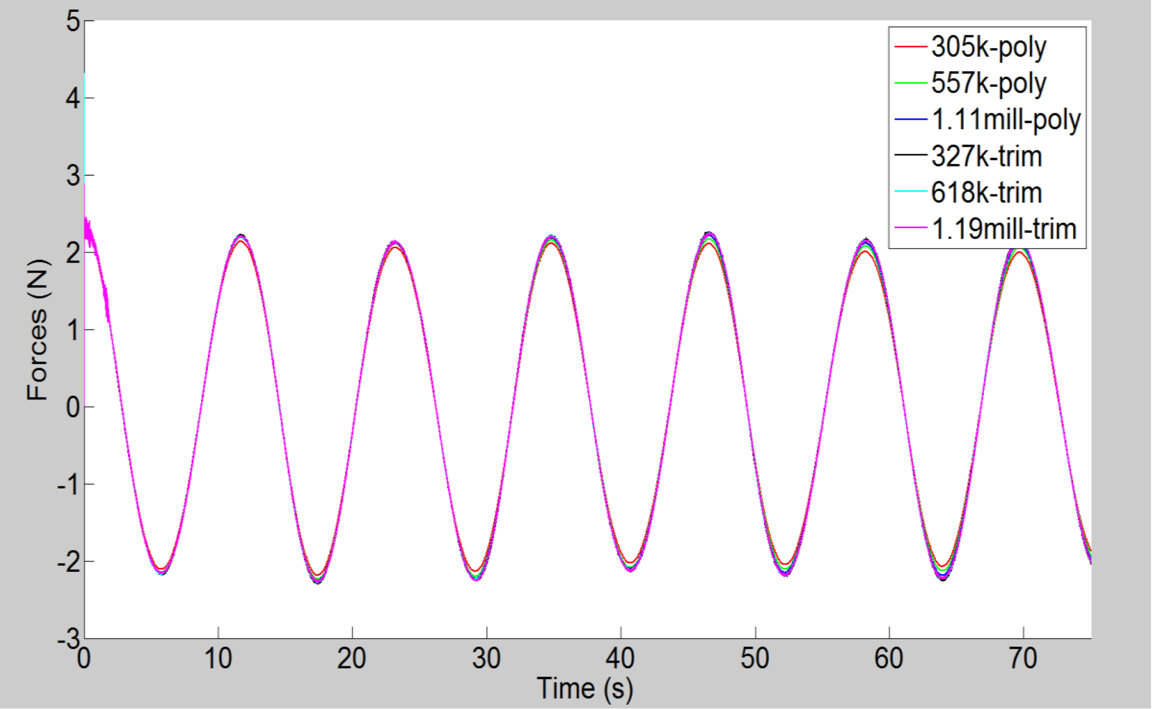


Mesh Type, Cell Count, and Settling Acceleration

Mesh Type	Approximate Cell Count	Settling Acceleration (m/s^2)
Polyhedral	305k	0.0200
Polyhedral	305k	0.0981
Polyhedral	557k	0.0981
Polyhedral (volumetric control)	1110k	0.0981
Trim (volumetric control)	327k	0.0981
Trim (volumetric control)	618k	0.0981
Trim (volumetric control)	1190k	0.0981

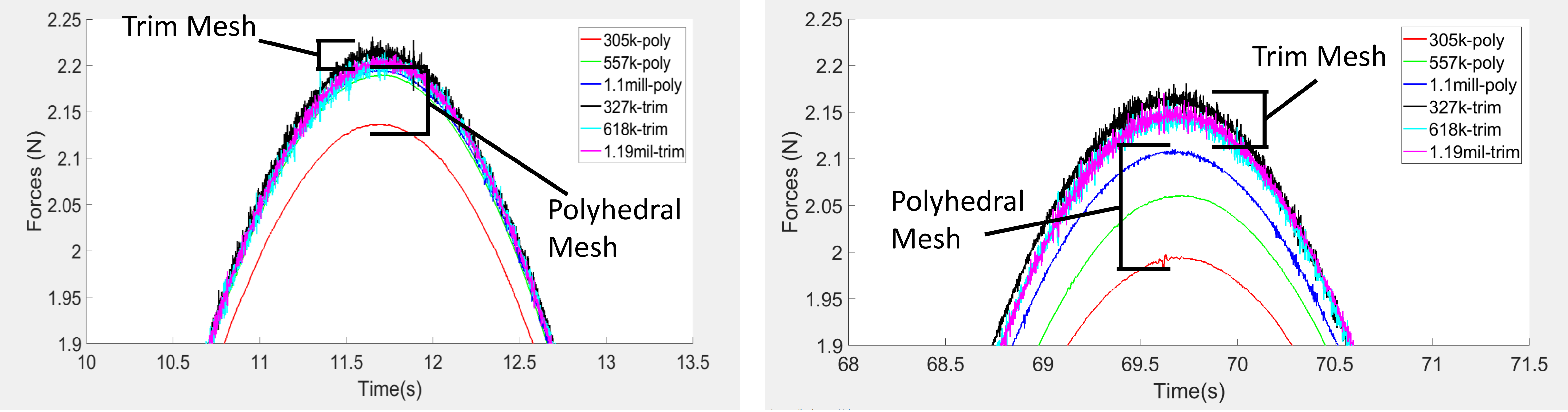
STAR-CCM+ Output





- STAR-CCM+ outputs:
  - Center of mass location
  - Force exerted on the tank
  - Torques exerted on the tank

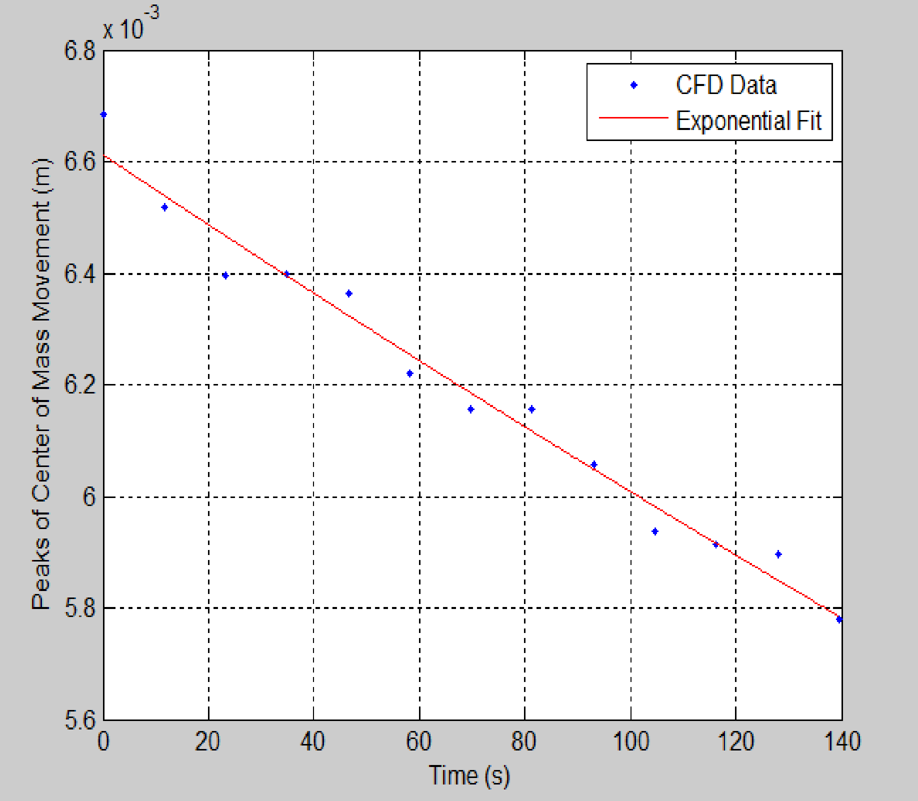
STAR-CCM+ Output

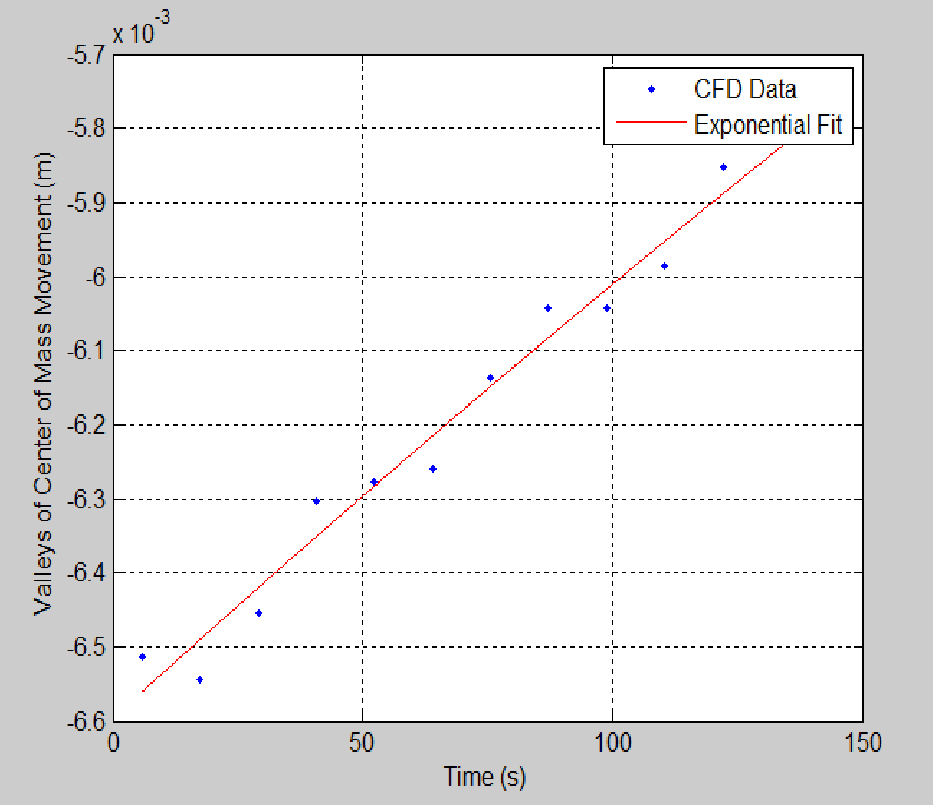


- Polyhedral mesh cases have less noise than trim mesh cases
- Courser polyhedral mesh cases have greater damping than the finer mesh cases
- All cases have similar frequencies
- Center of mass plots do not have noise, so they are used for deriving damping and frequency

Post-Processing of Results

- The damping is derived by fitting an exponential damping envelope to the peaks and valleys of the slosh





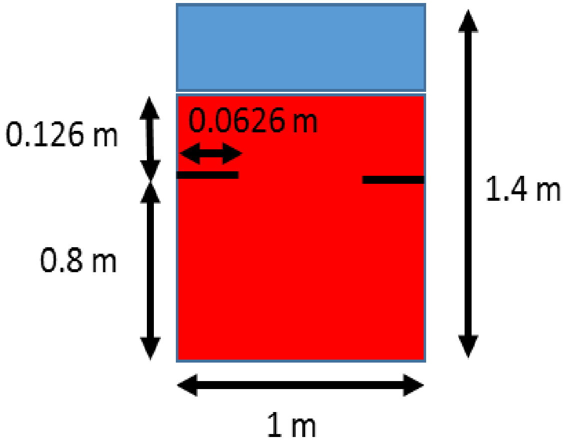
- The frequency of the slosh is calculated from the average period between the peaks

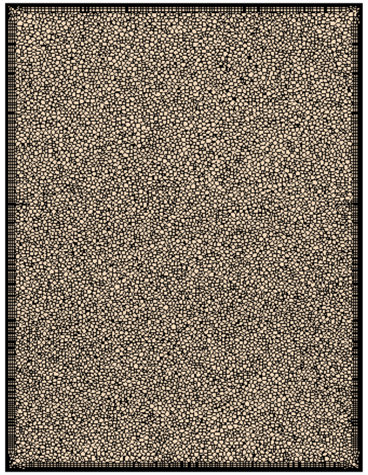
Comparison of Damping and Frequency with Expected Values

Mesh Type	Cell Count	CFD Damping Peaks (%)	CFD Damping Valley (%)	Damping – Mikeshev[1] (%)	Damping – Stephens[1] (%)	CFD Frequency (Hz)	Predicted Frequency[1] (Hz)
Poly	305k	0.2689	0.2295	0.1817	0.1599	0.0388	0.0389
Poly	305k	0.2087	0.2042	0.1221	0.1074	0.0860	0.0861
Poly	557k	0.1773	0.1722	0.1221	0.1074	0.0860	0.0861
Poly	1110k	0.1052	0.1058	0.1221	0.1074	0.0860	0.0861
Trim	327k	0.0513	0.0484	0.1221	0.1074	0.0860	0.0861
Trim	618k	0.0568	0.0573	0.1221	0.1074	0.0860	0.0861
Trim	1190k	0.059	0.0521	0.1221	0.1074	0.0860	0.0861

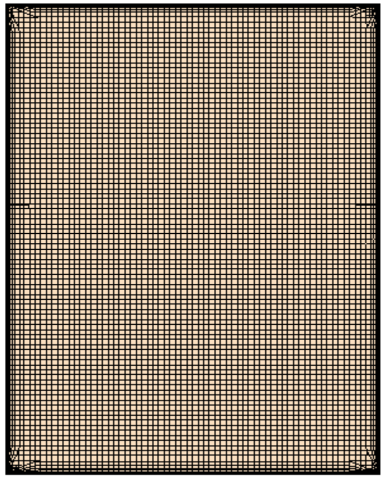
- A polyhedral mesh with sufficient mesh refinement predicts damping well
- All model mesh types and mesh refinements predict the frequency well

Baffle Tank Study Setup





Polyhedral

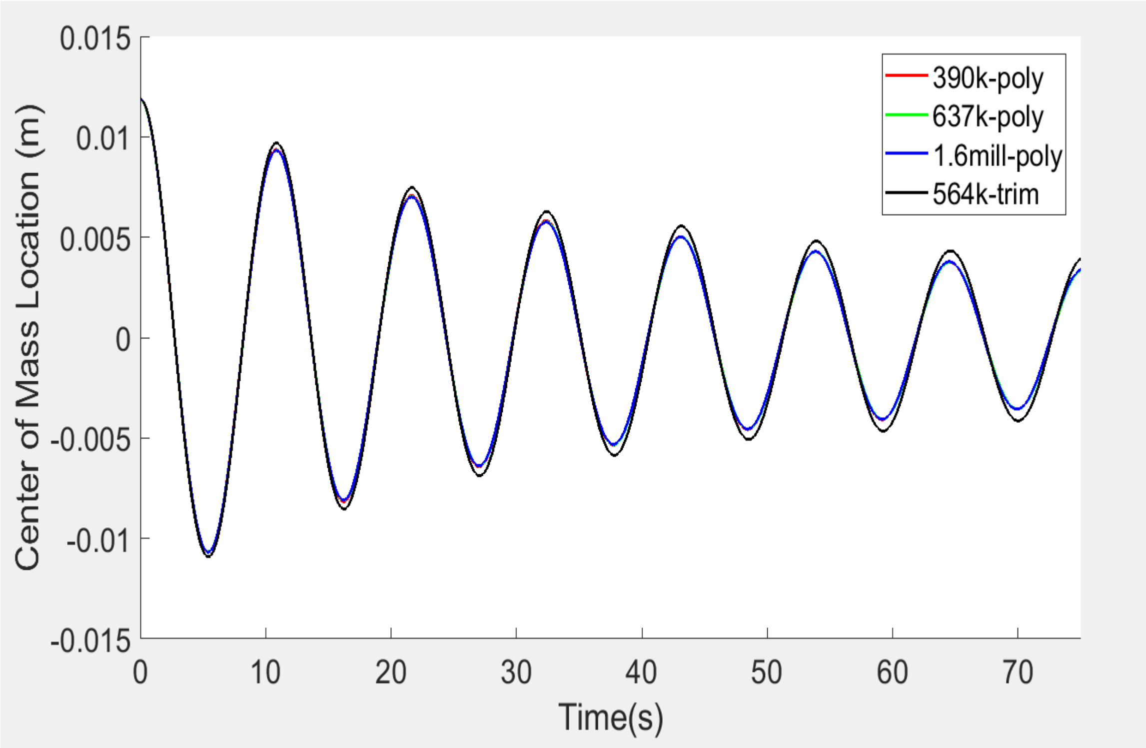


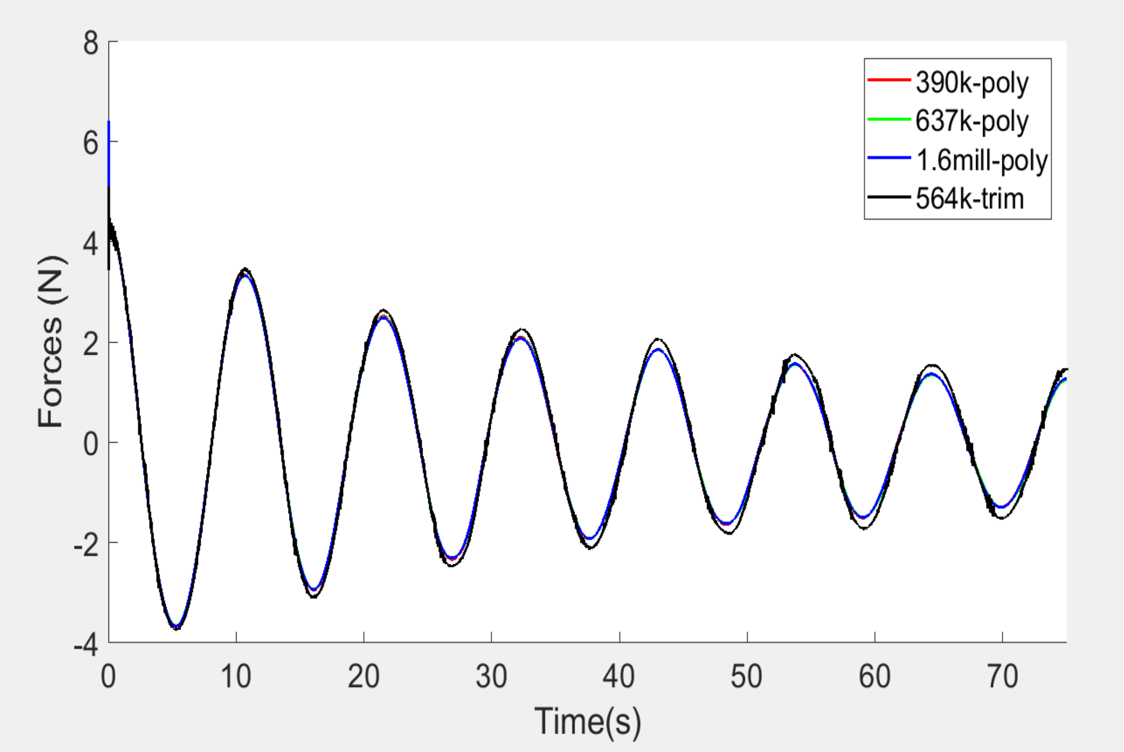
Trim

- A right cylindrical tank is studied with a single ring baffle
  - Experimental data exists for fluid slosh damping
  - Methods exist for deriving the fluid slosh frequency for bare tank geometry, including the effects of damping
- CFD Setup
  - Full 3D model
  - Varied the mesh type and mesh refinement
  - The liquid surface is initialized at an angle

Mesh Type	Approximate Cell Count	Settling Acceleration (m/s^2)
Polyhedral	390k	0.1
Polyhedral	637k	0.1
Polyhedral	1600k	0.1
Trim	564k	0.1

STAR-CCM+ Output





- STAR-CCM+ outputs:
  - Center of mass location
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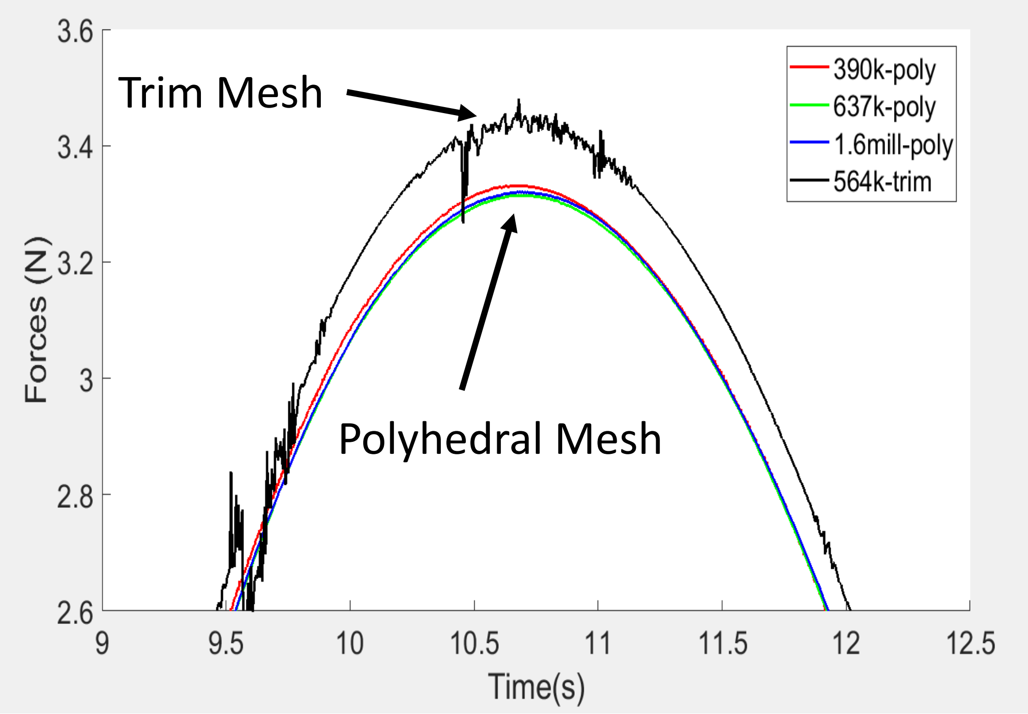
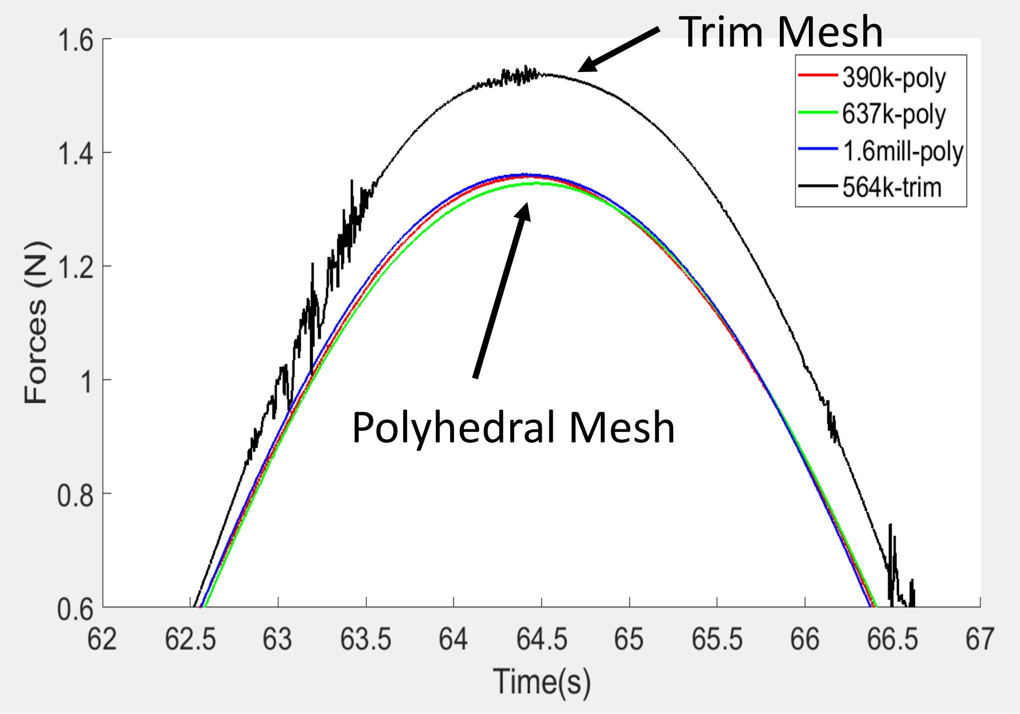
  - Torques exerted on the tank

STAR-CCM+ Output

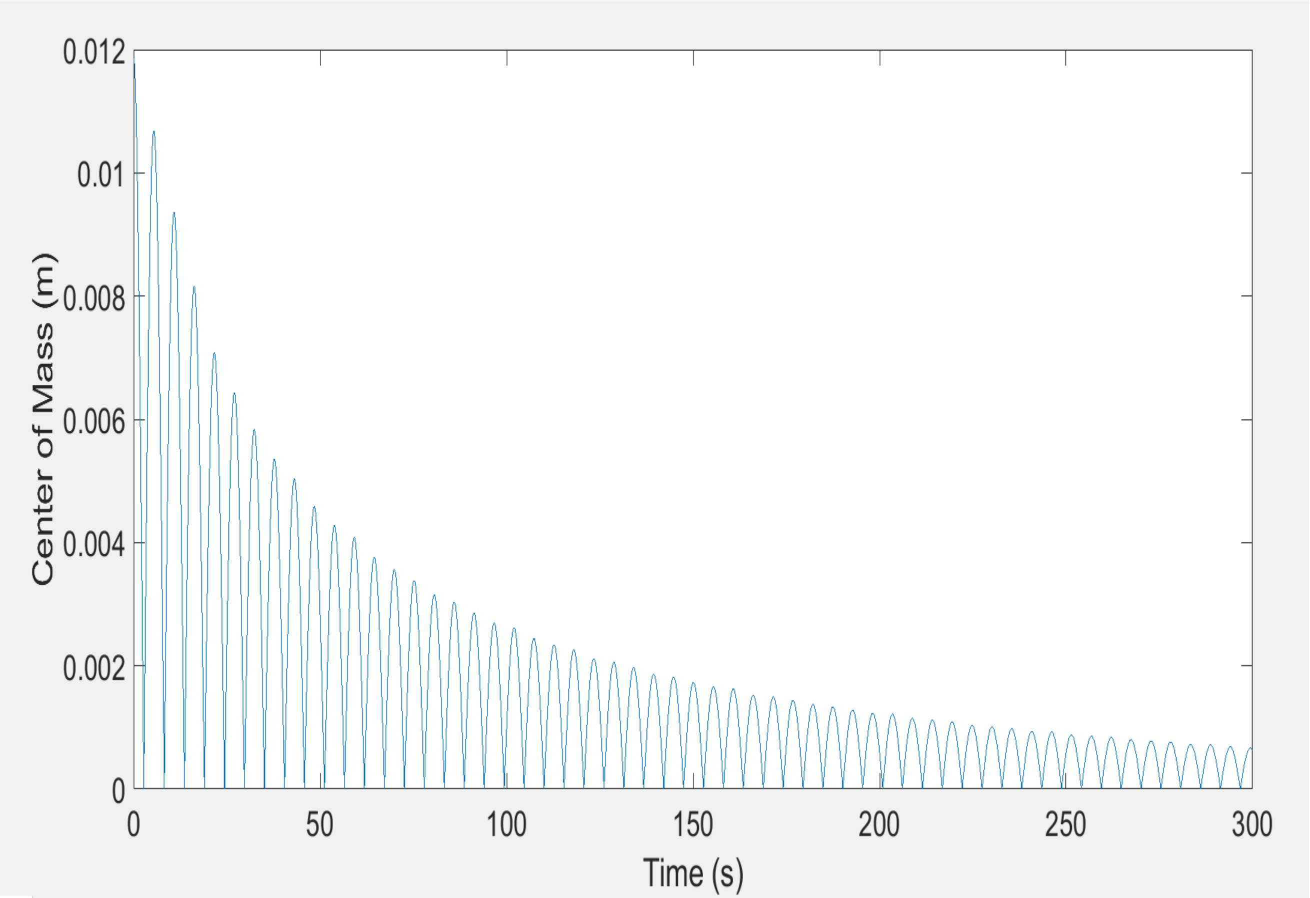




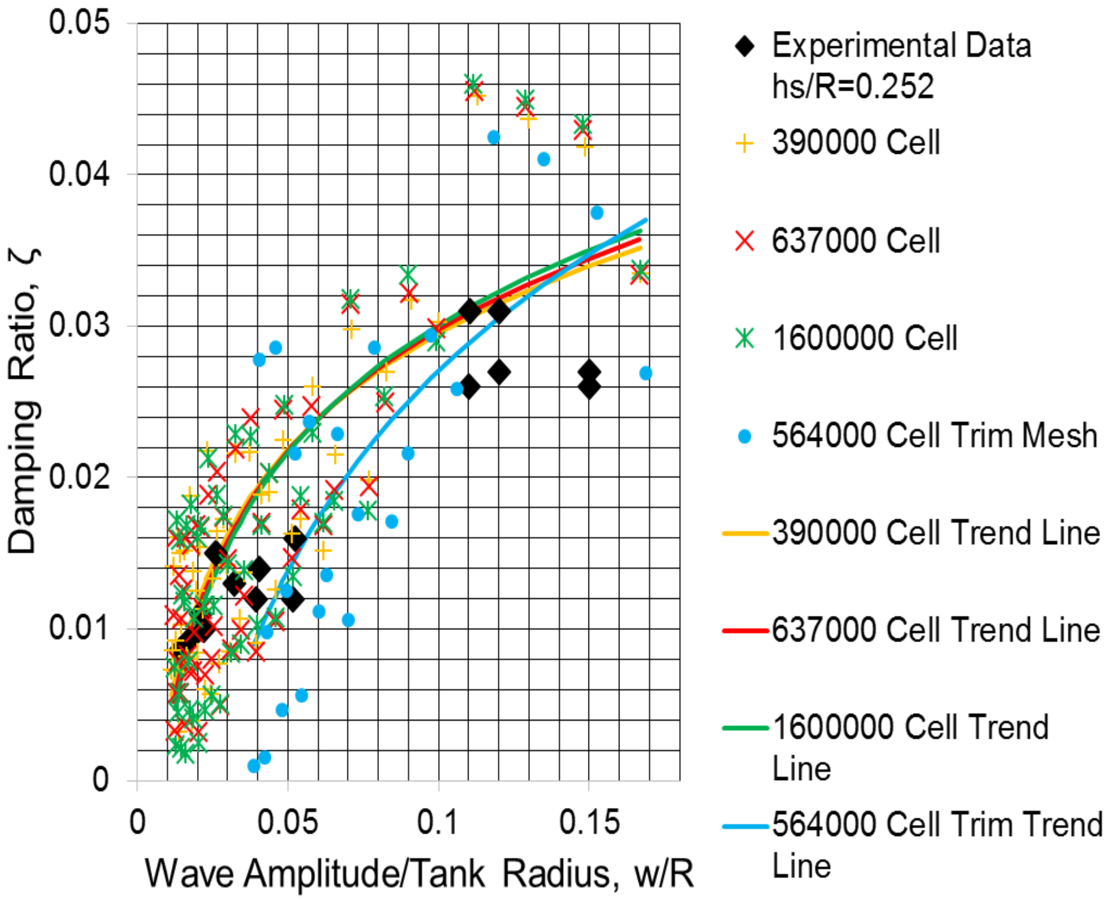
- Trim mesh case results have a lot of noise
- Polyhedral mesh case results are similar regardless of mesh refinement
- Center of mass plots do not have noise, so they are used to derive damping and frequency

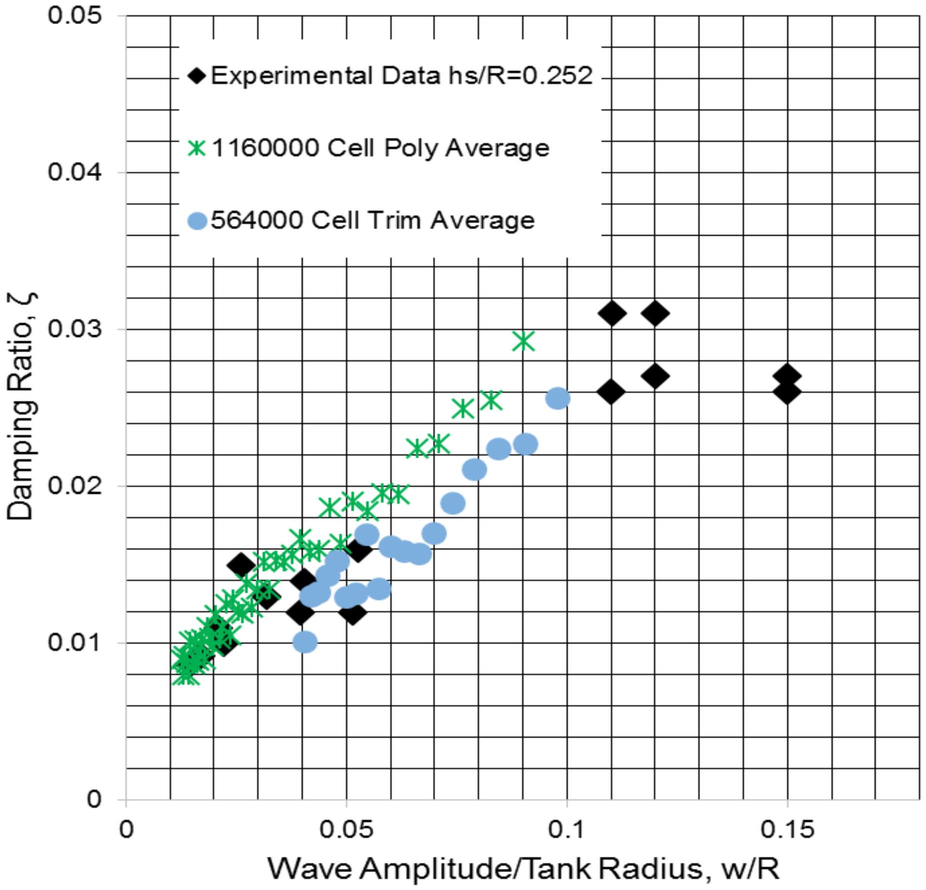
Post-Processing of Results

- Damping is a function of wave height for tanks with a baffle
- The absolute value of the center of mass data is taken to better calculate the damping at a specific wave height
- Damping is calculated from adjacent peaks using the logarithmic decrement method
- The damping data is further processed by taking a 3 point moving average and ignoring the first few peaks of the slosh
    - Reduces the scatter of the data
    - Ignores the transition of the wave shape from a flat surface to a typical wave shape[2]



Comparison of Results with Experimental Data





- Damping trends match the experimental data^1 for a baffle tank with same baffle area blockage and liquid height above the baffle as the tank in the CFD model (experimental data shown in both figures)

Comparison of Frequency with Expected Values

- Frequency is derived from CFD data by averaging the period between each peak

Mesh Type	Cell Count	CFD Frequency (Hz)	Predicted Bare Tank Frequency[1] (Hz)	Damped Natural Frequency from Bare Tank[3] (Hz)
Polyhedral	390k	0.0935	0.09647	0.09645
Polyhedral	637k	0.0934	0.09647	0.09645
Polyhedral	1600k	0.0934	0.09647	0.09645
Trim	564k	0.0931	0.09647	0.09645

- To try and understand why the frequencies are so different, the damped natural frequency was calculated using the equation below[3]

$$f_d = f_n\sqrt{1-\zeta^2}$$

- The damped natural frequency does not match the CFD frequency

Conclusions

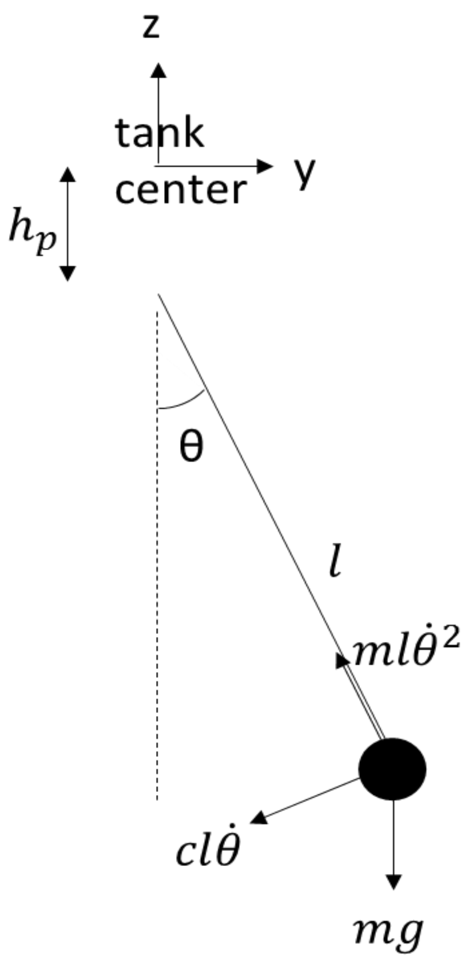
- STAR-CCM+ can accurately model bare tank slosh with the appropriate mesh
  - 1.7% CFD model difference from Mikishev[1] predicted damping
  - 0.2% model difference from Stephens[1] predicted damping
  - 0.1% model difference from analytic model[1] predicted frequency
- STAR-CCM+ can accurately model baffle tank slosh with the appropriate mesh
  - Damping values fall within the scatter of the experimental data[1] when 3 point moving average is used and the first few sloshing peaks are ignored
  - 3.2% model difference from expected damped natural frequency[3]
- The results give us high confidence in the ability of STAR-CCM+ to model slosh in a flight tank
- Depending on the accuracy required by the spacecraft requirements
  - A rougher polyhedral mesh may give results of sufficient fidelity and save computation resources
  - A more refined polyhedral mesh may be required to increase the fidelity and so justifies the extra computation resources
  - A trim mesh may be desired to under-predict the damping and give a more conservative damping solution

Backup

Pendulum Model

- Pendulum models are equivalent mechanical models of slosh
- The propellant slosh mass participation, frequency, and damping can be derived from CFD using the equation below[4]

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



Predicted Damping and Frequency

- For damping the following two equations
  - Stevens et al[1]

$$\zeta=0.83\sqrt{Re_1}\left[tanh(1.84\frac{h}{R})\left(1+2\frac{1-\frac{h}{R}}{cosh\left(3.68\frac{h}{R}\right)}\right)\right]$$

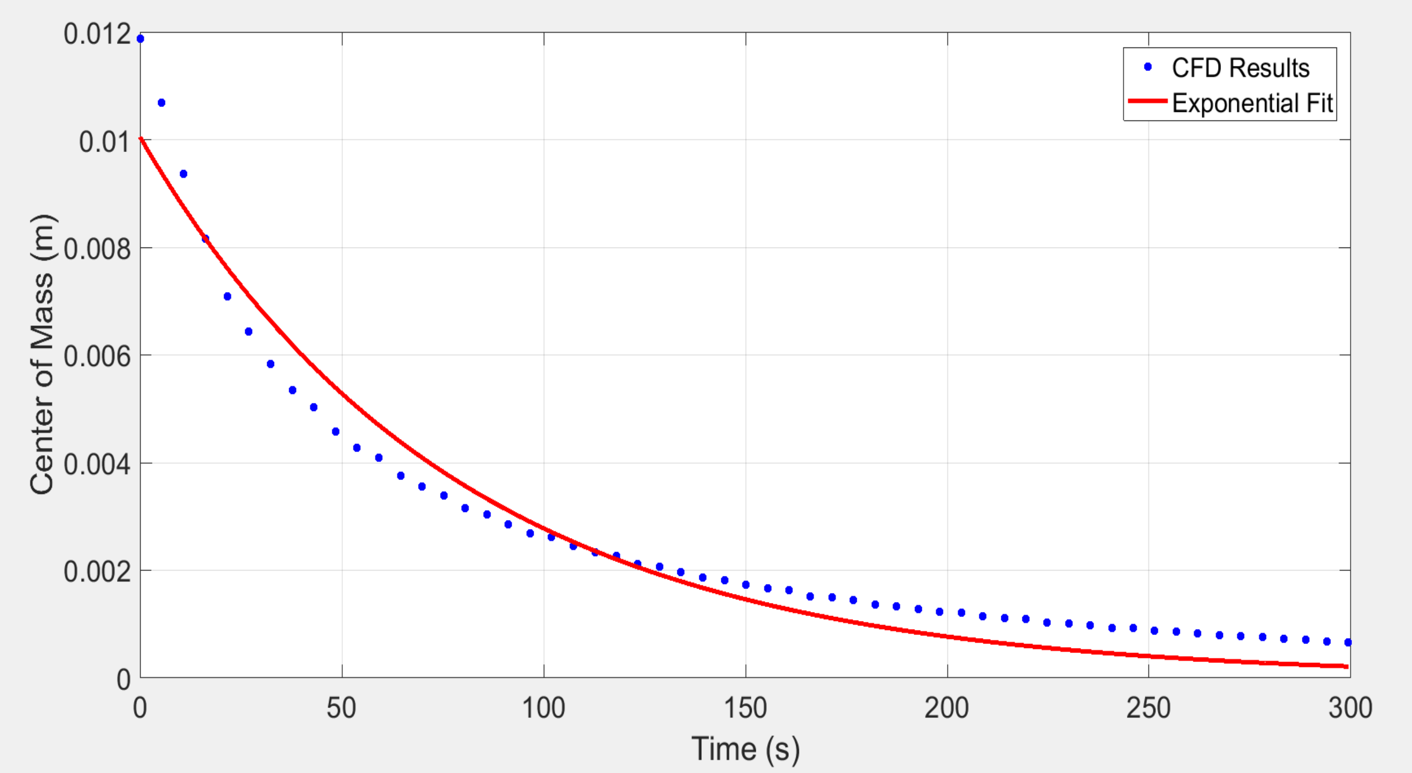
  - Mikishev and Dorozhkin[1]

$$\zeta=0.79\sqrt{Re_1}\left[1+\frac{0.318}{sinh\left(1.84\frac{h}{R}\right)}\left(1+\frac{1-\frac{h}{R}}{cosh\left(1.84\frac{h}{R}\right)}\right)\right]$$

- Frequency is calculated using predictions of the pendulum length from Dodge and then calculating the frequency of the slosh from the pendulum length and settling acceleration[1]

$$L=\frac{R}{1.841tanh(1.841\,h/R)} \qquad f=\frac{1}{2\pi}\sqrt{\frac{g}{L}}$$

Comparison of Results with Experimental Data



- When the pendulum model is used, the damping is constant
- Constant damping may over-predict or under-predict the damping, depending on the wave height

References

1. Dodge, F. T. (2000). *The New "Dynamic Behavior of Liquids In Moving Containers".* San Antonio, TX: Southwest Research Institute.
2. Yang, H., Purandare, R., Peugot, J., & West, J. (2012). Prediction of Liquid Slosh Damping Using a High Resolution CFD Tool. *48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference.* Atlanta, GA: AIAA.
3. *Harmonic oscillator*. (2018, January 13). Retrieved from Wikipedia: https://en.wikipedia.org/wiki/Harmonic_oscillator
4. Ng, W., & Benson, D. (2017). Two-Pendulum Model of Propellant Slosh in Europa Clipper PMD Tank. *Thermal and Analysis Workshop 2017.* Huntsville, AL: NASA.