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# Experimental, Numerical and Analytical Characterization of Slosh Dynamics Applied to In-Space Propellant Storage, Management and Transfer

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## **Motivation**

Advancements in long term, in-space, cryogenic propellant storage and transfer science and technologies are key to increasing safety, decreasing cost, and increasing payload mass of NASA's space missions.

## **Overall Goal**

Perform slosh experiments with water and LN2 to generate data relevant to benchmarking and expanding CFD simulation tools to characterize slosh dynamics of cryogenic propellants in 1g and microgravity storage, management, and transfer applications.



# Progress Towards Goal/Agenda

- Analytical models implemented
- Ground-based test platforms
- Damping tests
- Forced sinusoidal excitation tests
- CFD simulations
- Next year plans and future work



# Analytical Models

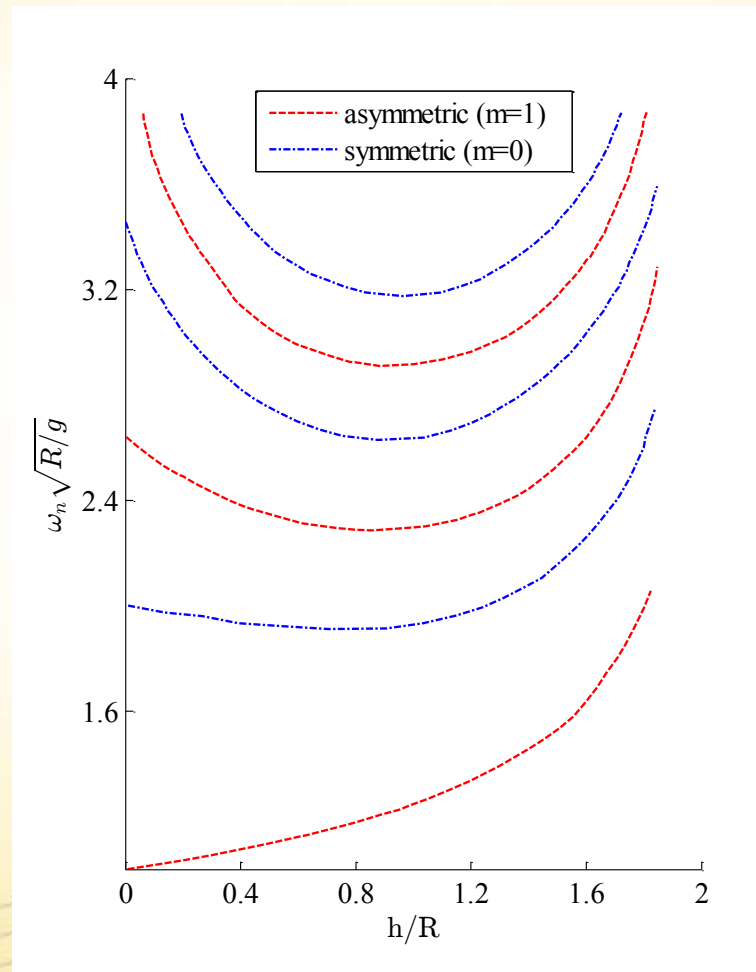
- Modes
- Wall height and forces

$$\frac{d^2\eta_n}{dt^2} + \omega_n^2\eta_n = -\lambda_n^2\alpha\frac{D_n}{E_n}\frac{d^2x}{dt^2} \quad F_s = -m_l\frac{d^2x}{dt^2} - \pi\rho_l(\alpha R)^2\sum_{n=1}^{\infty}D_n\frac{d^2\eta_n}{dt^2}$$

- Assumptions: rigid sphere, inviscid, first three asymmetric (m=1 azimuthal wave number) modes
- Implemented in MATLAB

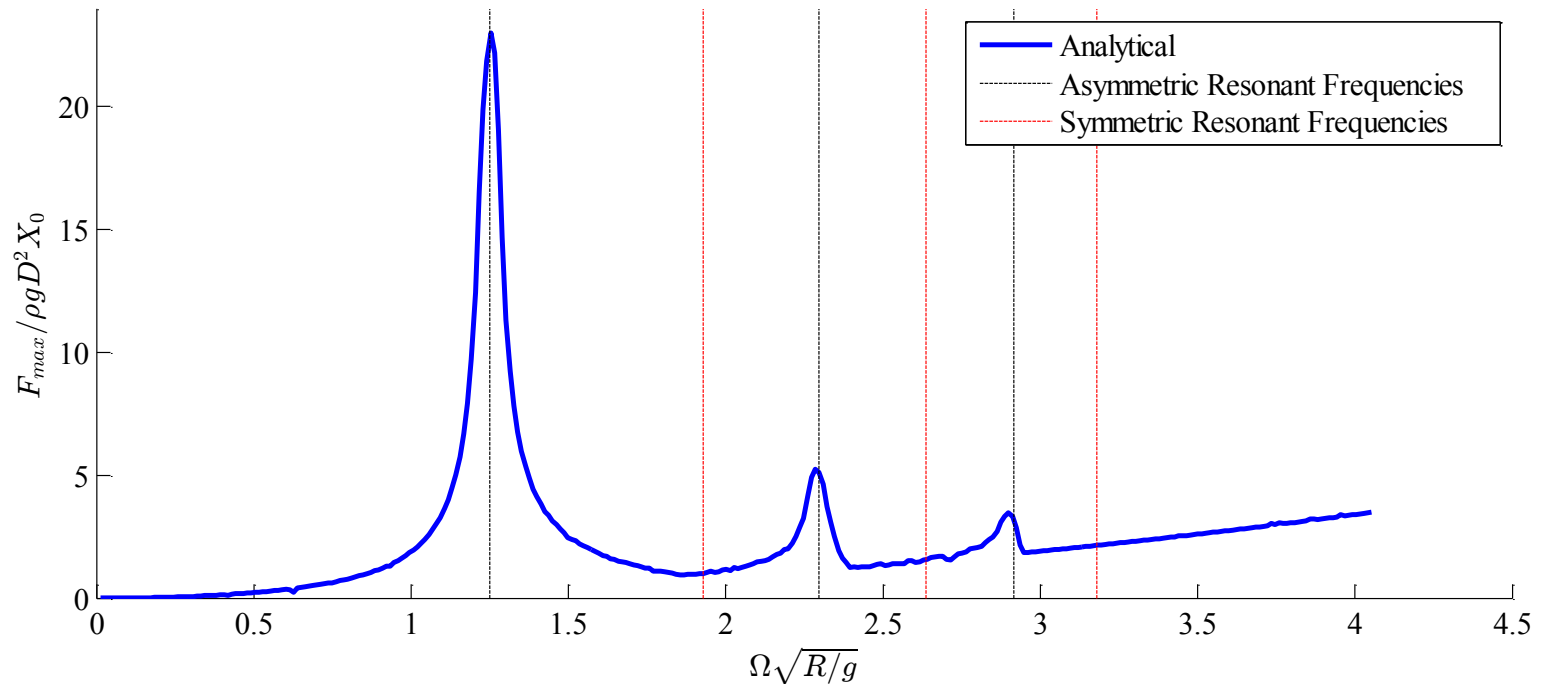


# Analytical Modes





# Force Parameter vs. Excitation Frequency Parameter





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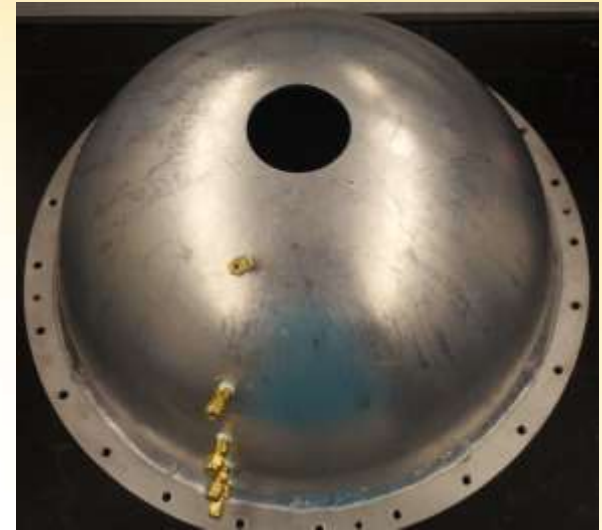
# **TANK AND INSTRUMENTATION**



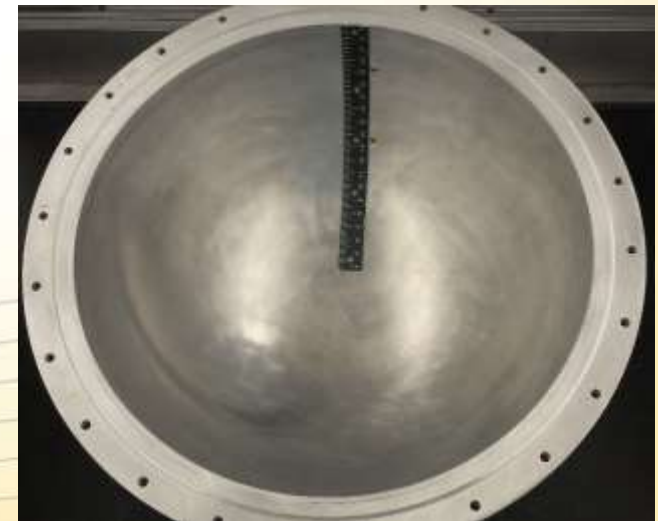


# Tank

- ~30cm inner diameter
- Aluminum
- O-ring seals
  - Rubber for water
  - Lead wire for LN2
- Aluminum ruler screwed to inside
- Brass thermoprobe pass-thrus
- Hole for camera



Outside of upper half



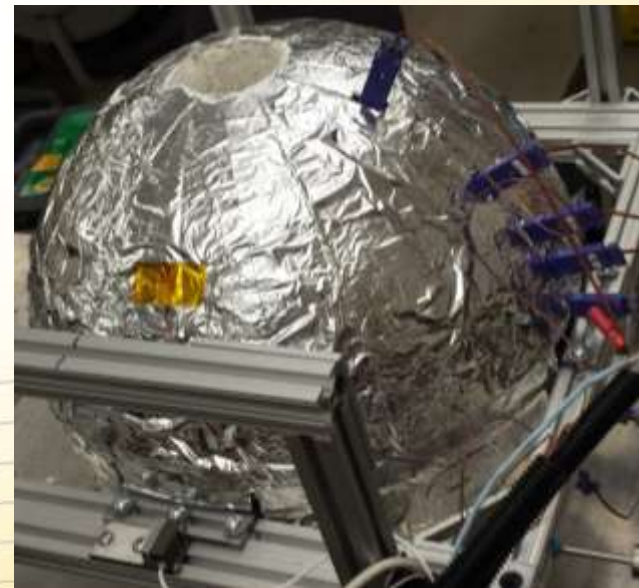
Inside of lower half





# Tank

- Low density polyurethane foam insulation
- Aluminized nylon radiation barrier
- Polycarbonate mounting brackets
- Aluminum extrusion frame



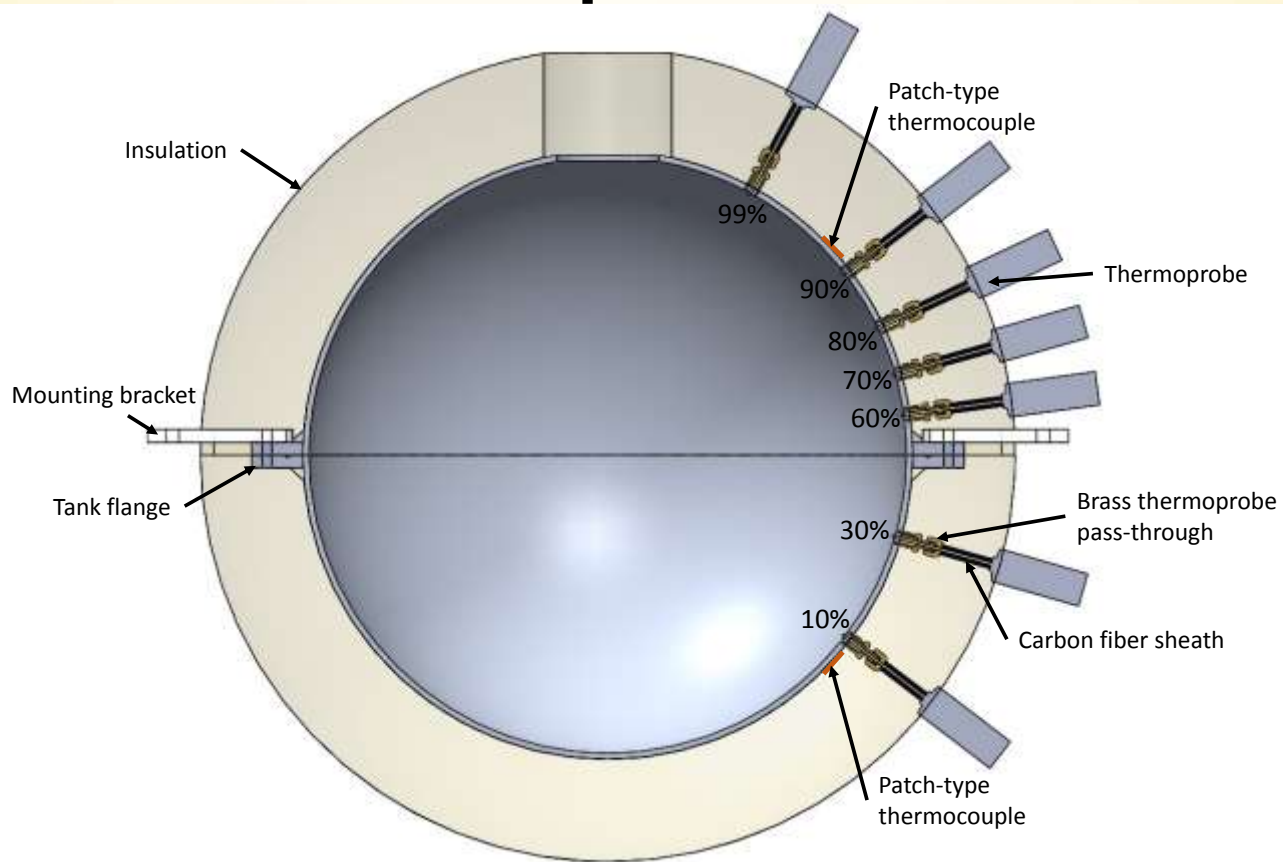


# Instrumentation

- PCB piezoelectric force sensor in forcing axis
- Accelerometer in forcing axis
- LVDT for position measurement
- 7 Thermoprobes and 4 patch-type thermocouples
- National Instruments data acquisition system
  - Synchronized
  - Capable of 6kHz sampling, 1-2kHz used



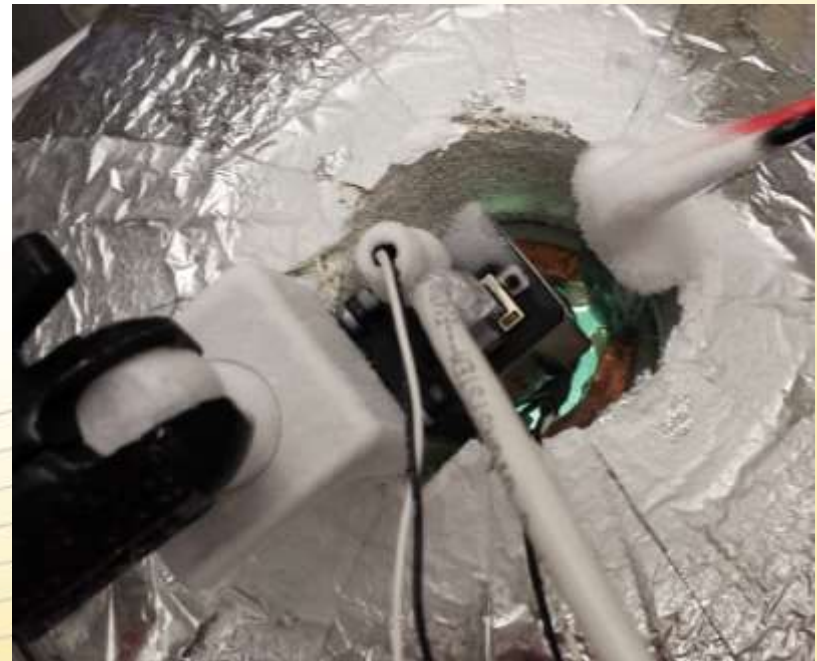
# Tank cross-section and thermocouple locations





# Imaging

- IDS Machine vision camera
  - 1MP at 34fps
  - Fisheye lens
  - C frame grabber
- Lighting challenging
- Anti-distortion software did not help much





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**CFD**





# CFD Approach

- STAR-CCM+
- Tank modeled as perfect sphere with a ring-shaped pressure outlet
- Hexahedral dominant mesh, wall prism layer
- Implicit unsteady, 2<sup>nd</sup> order time and space
- VOF formulation
- Laminar
- Incompressible, isothermal
- Position-commanded motion





# CFD Approach

- 3-axis forces, 3-axis moments, and wall height recorded vs. time
- Wall height recorded via a field function that emulates the ruler inside the tank
- Tabularized position input from filtered LVDT data attempted
  - Ultimately used a pure sinusoidal excitation
- Computational resources primary limiter



# Mesh size and Time step Dependence Study

- Meshes
  - Hexahedral: 115k, 340k, 580k, 1.3M cells
  - Polyhedral dominant: 1.2M cells
- Time step
  - 0.001s and 0.0005s
  - 0.0002s for largest meshes
- Test case: 50% fill, 1.5Hz, 3mm amplitude excitation, 10s runtime.
- 580k mesh and 0.001s dt selected despite mesh and time dependence due to computational resource limitations



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# RESULTS



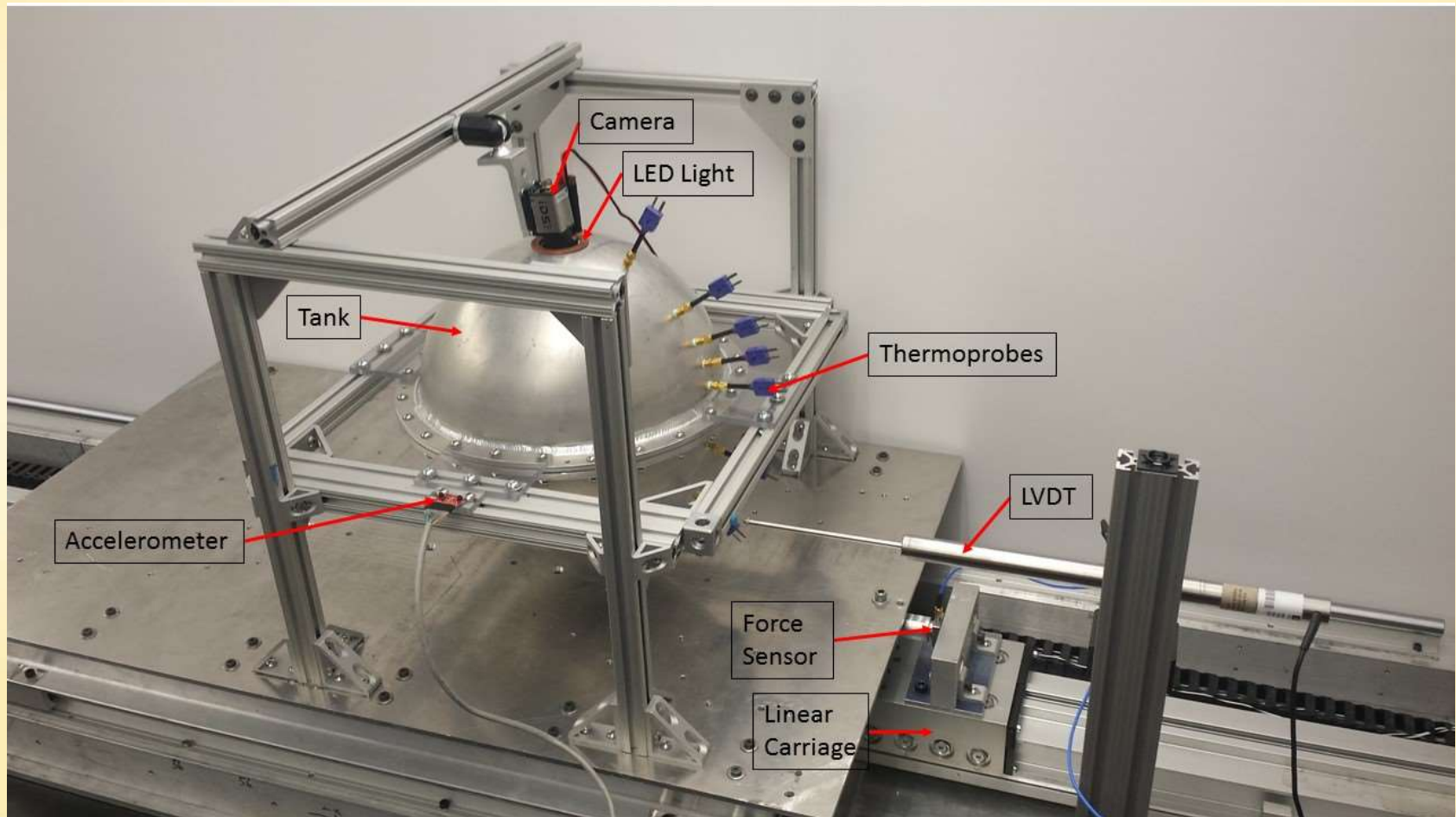
# Static Boil-Off Tests

- Insulated tank, no motion
- Filled to 90% following chill-down process
- Fluid level measured by eye from internal ruler for 4, approximately 20 min periods
- For validating a GFSSP model
- Table starts around 86% and ends around 7%

Arc height start [m]	Arc height end [m]	$\Delta$ Volume [m <sup>3</sup> ]	Boil-off rate [kg/h]
0.315	0.303	0.00054	1.307
0.23	0.224	0.000412	0.997
0.165	0.157	0.000382	0.928
0.132	0.12	0.000352	0.851



# Damping Test Setup







# Damping Tests

- 10 volume fractions
- 2 cycle sinusoidal excitation at 1Hz and 2Hz, various amplitudes
- Data collected for 30-120s
- Data postprocessed in MATLAB





# Damping Calculations

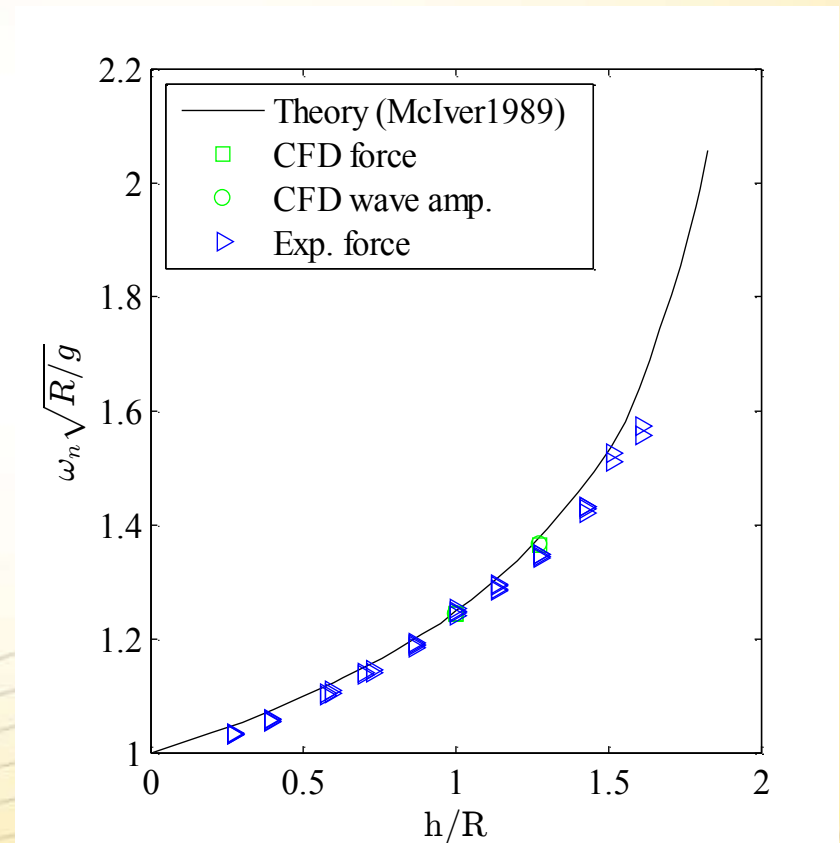
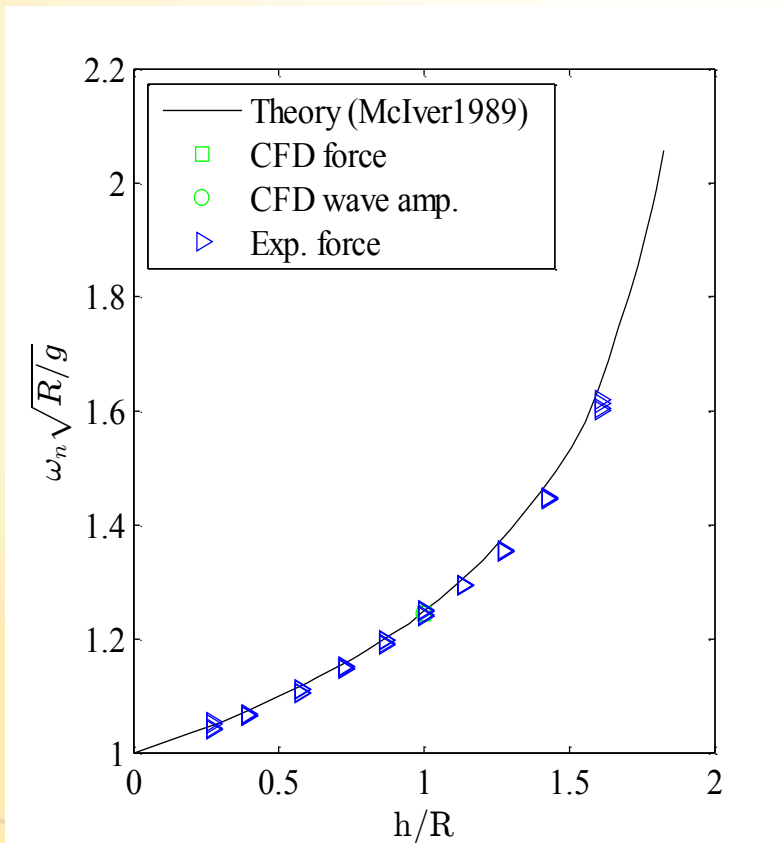
- Force decay:  $\delta_F = \ln\left(\frac{F_n}{F_{n+1}}\right)$
- Wave amplitude decay:  $\delta_{WA} = \ln\left(\frac{W_n}{W_{n+1}}\right)$
- Damping factor:  $\gamma = \frac{\delta}{2\pi}$
- Peak-to-peak amplitude used
- Smoothed and averaged values presented
- Various correlations based on fill level, tank radius, viscosity, and gravity



# First Mode Frequencies

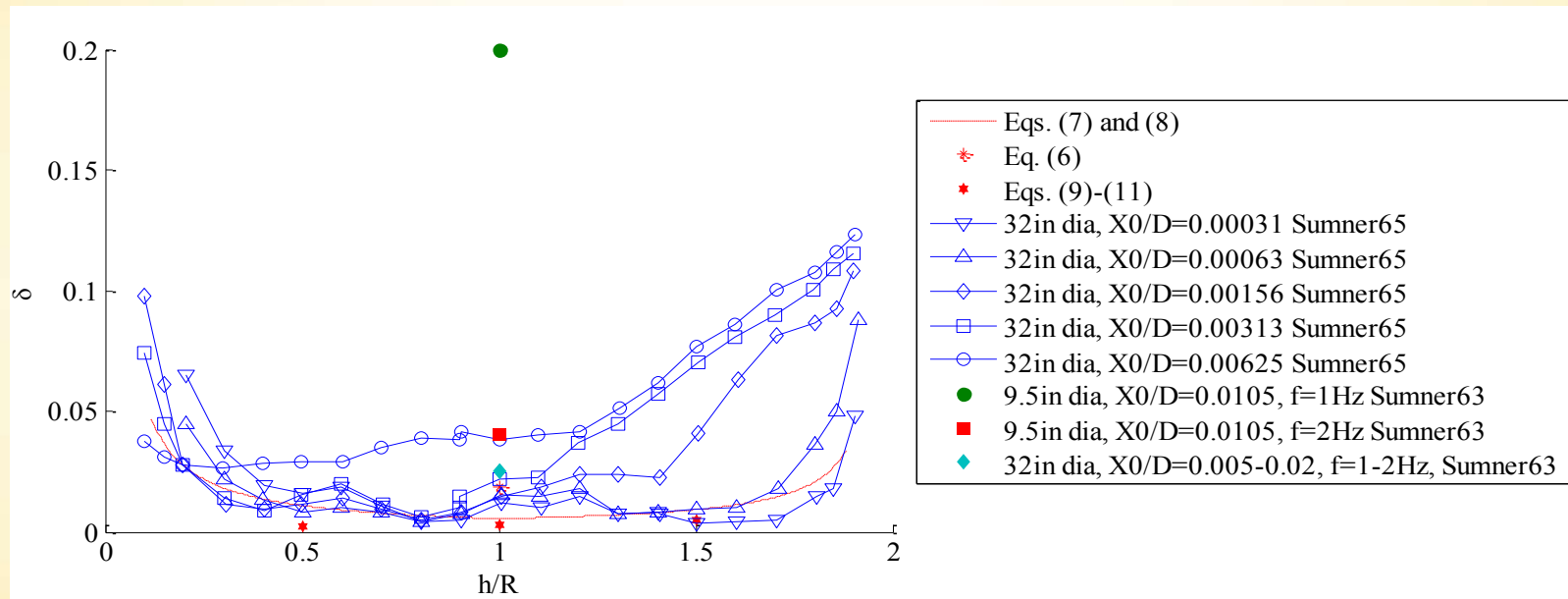
## Water

## LN2





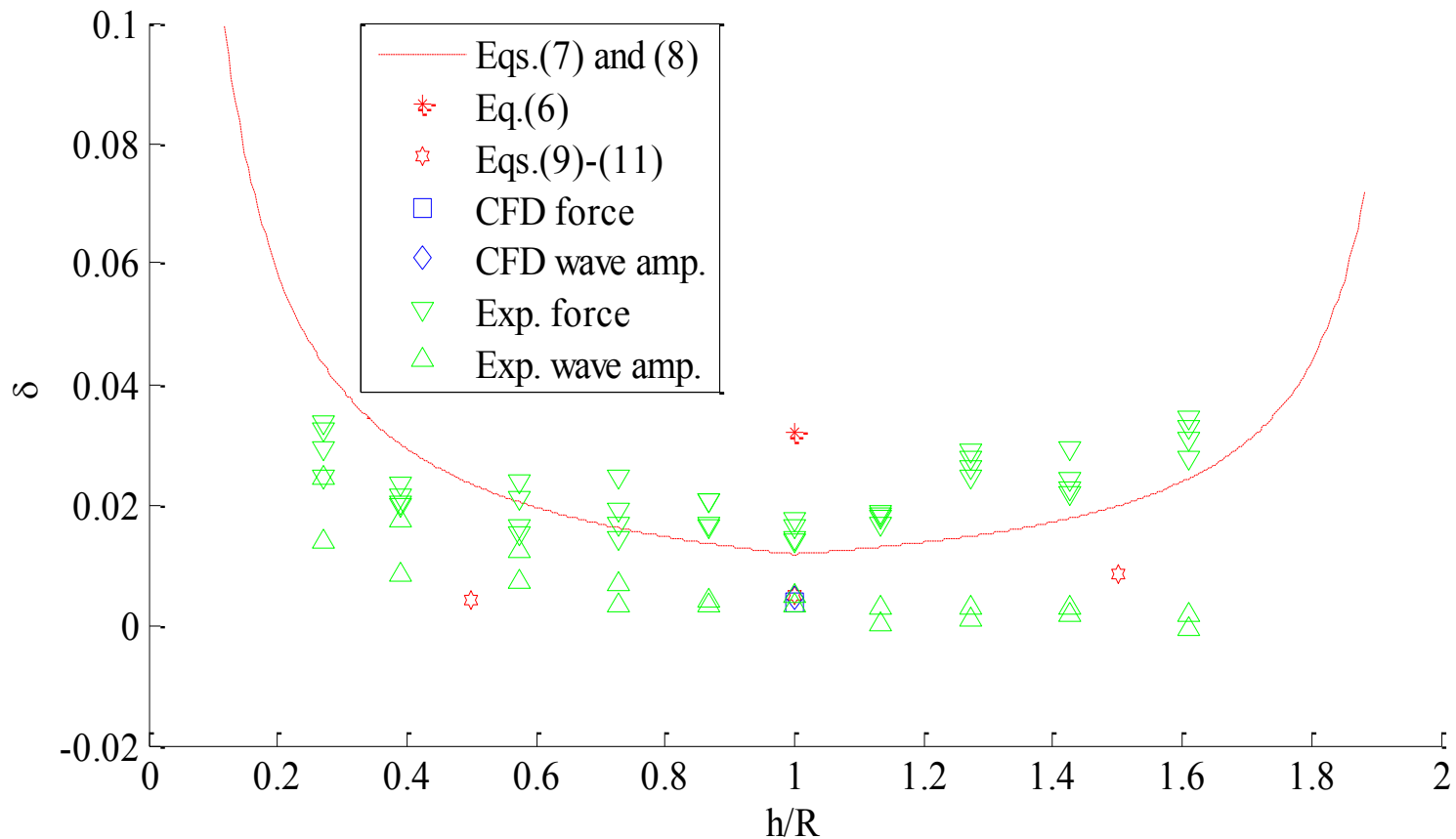
# Correlations vs. Sumner Experimental Data



- 32in diameter tank with water
- Sense of the magnitude and variance expected
  - 400%+ difference from correlations for some points
- X0/D for this project range from 0.0169 to 0.1014
- Dependence on excitation amplitude apparent

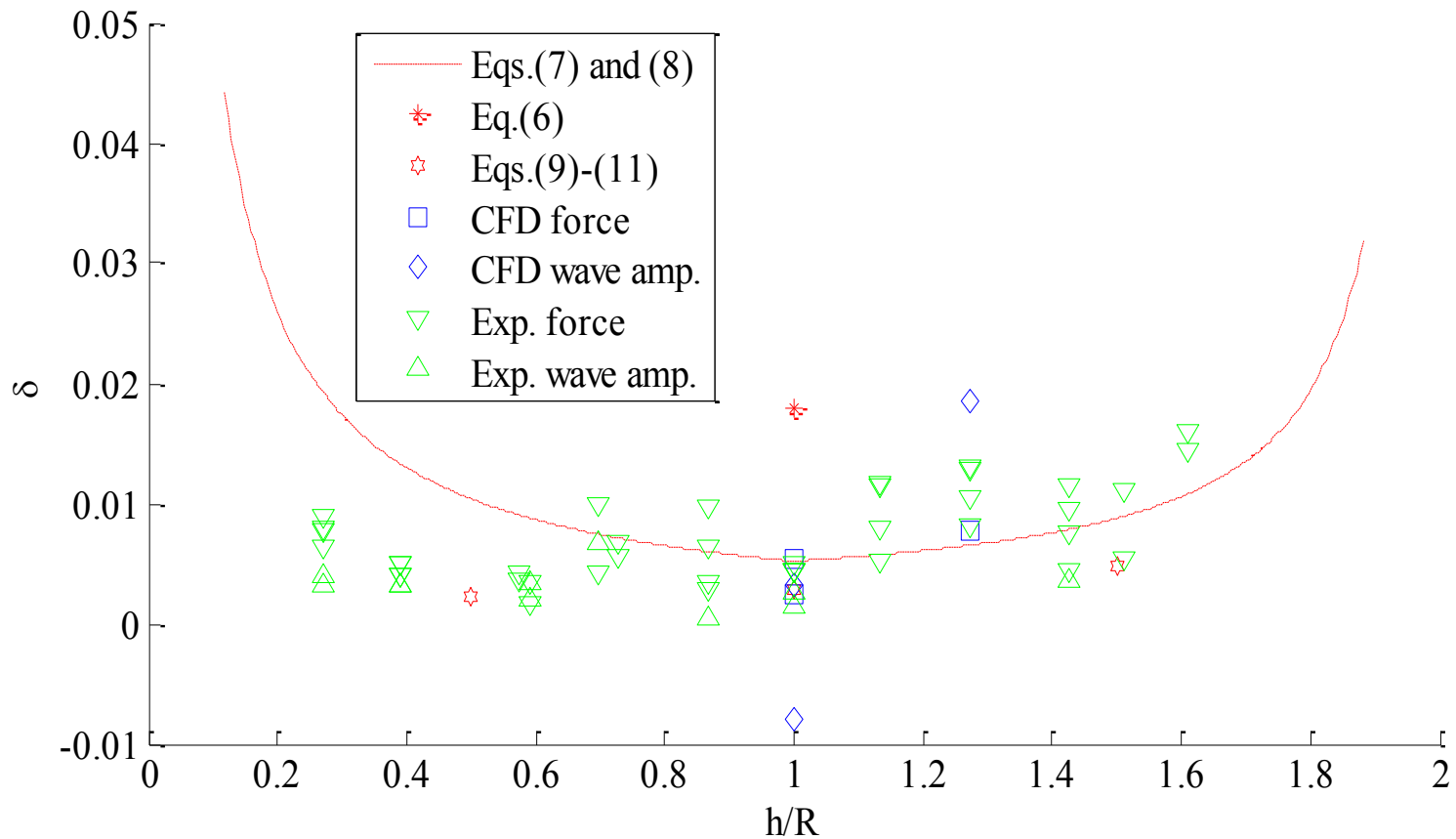


# Logarithmic Decrement - Water





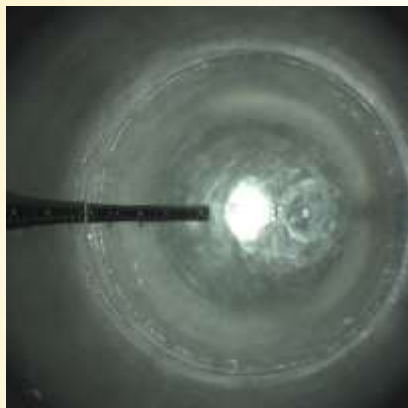
# Logarithmic Decrement - LN2



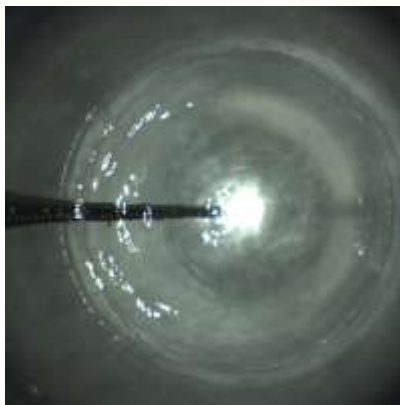


# Fluid surface comparisons -Water

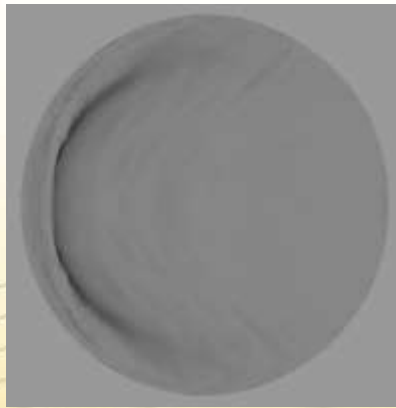
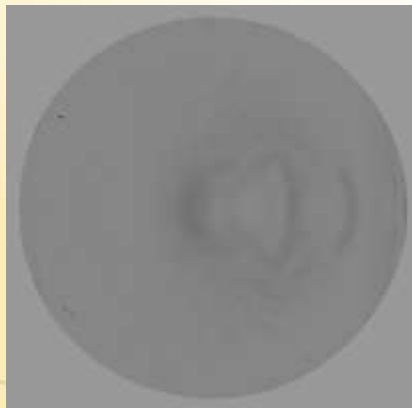
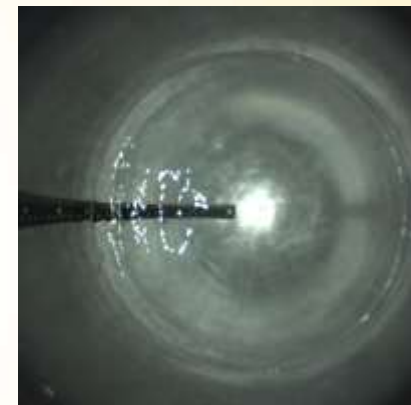
1.4s



2.1s



3.3s



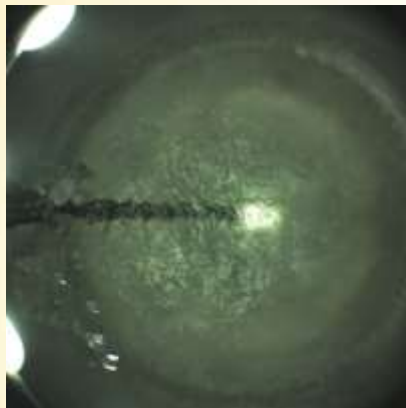




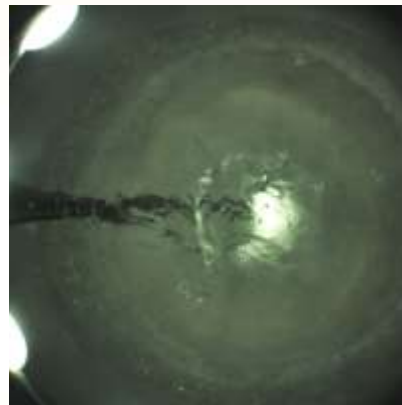
# Fluid surface comparisons

## -LN2

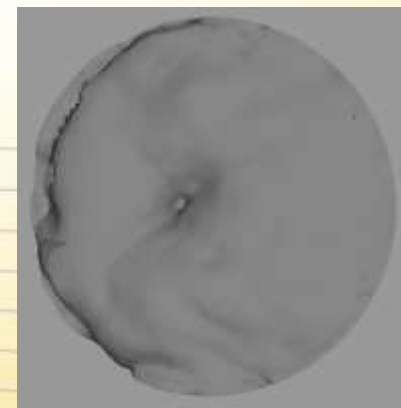
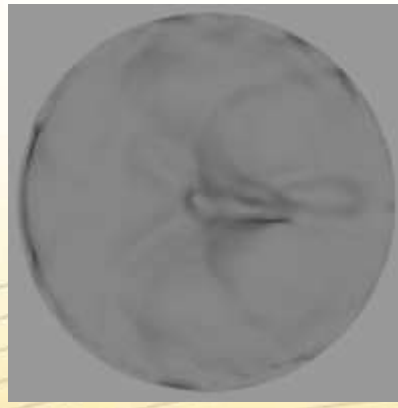
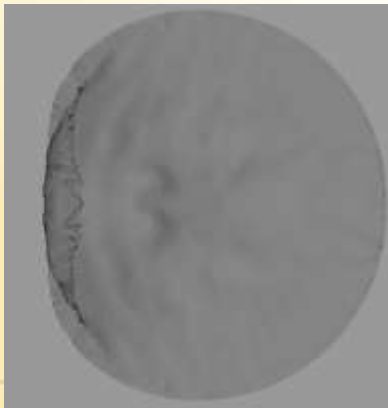
1.2s



2.2s



7.5s





# Videos

- (place holder. Too big to embed)

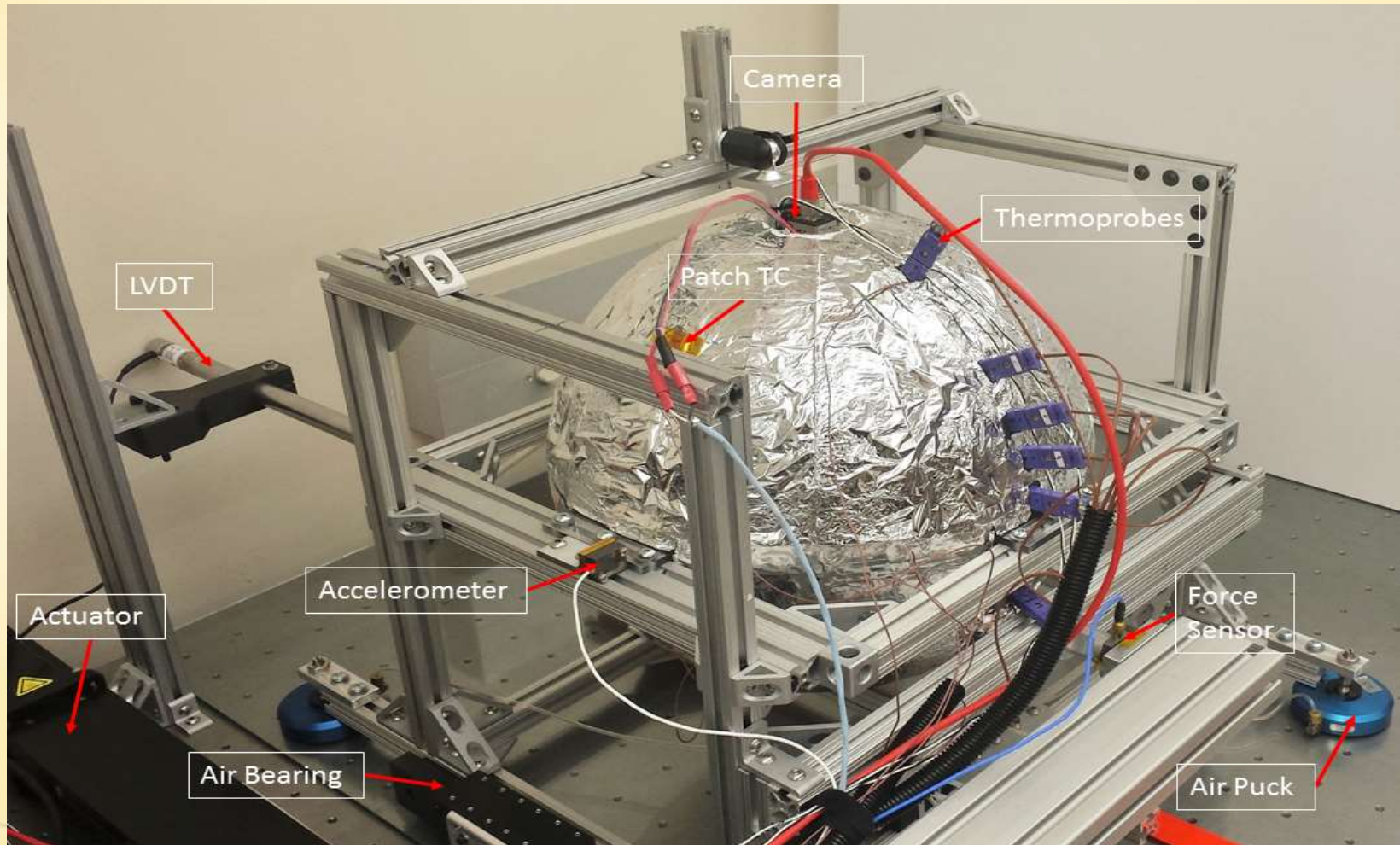


# Damping Conclusions

- Force decay method likely more accurate
- Splashing, high nonlinearity, many other modes excited
- Rotation induced in some cases
- Clear dependence on excitation amplitude and frequency
- Higher error likely a combination of:
  - Experimental error
  - Correlations not applicable
  - Correlations inadequate
- Use better excitation for future tests
- CFD does fair to poor job at predicting damping



# Forced Excitation Test Setup





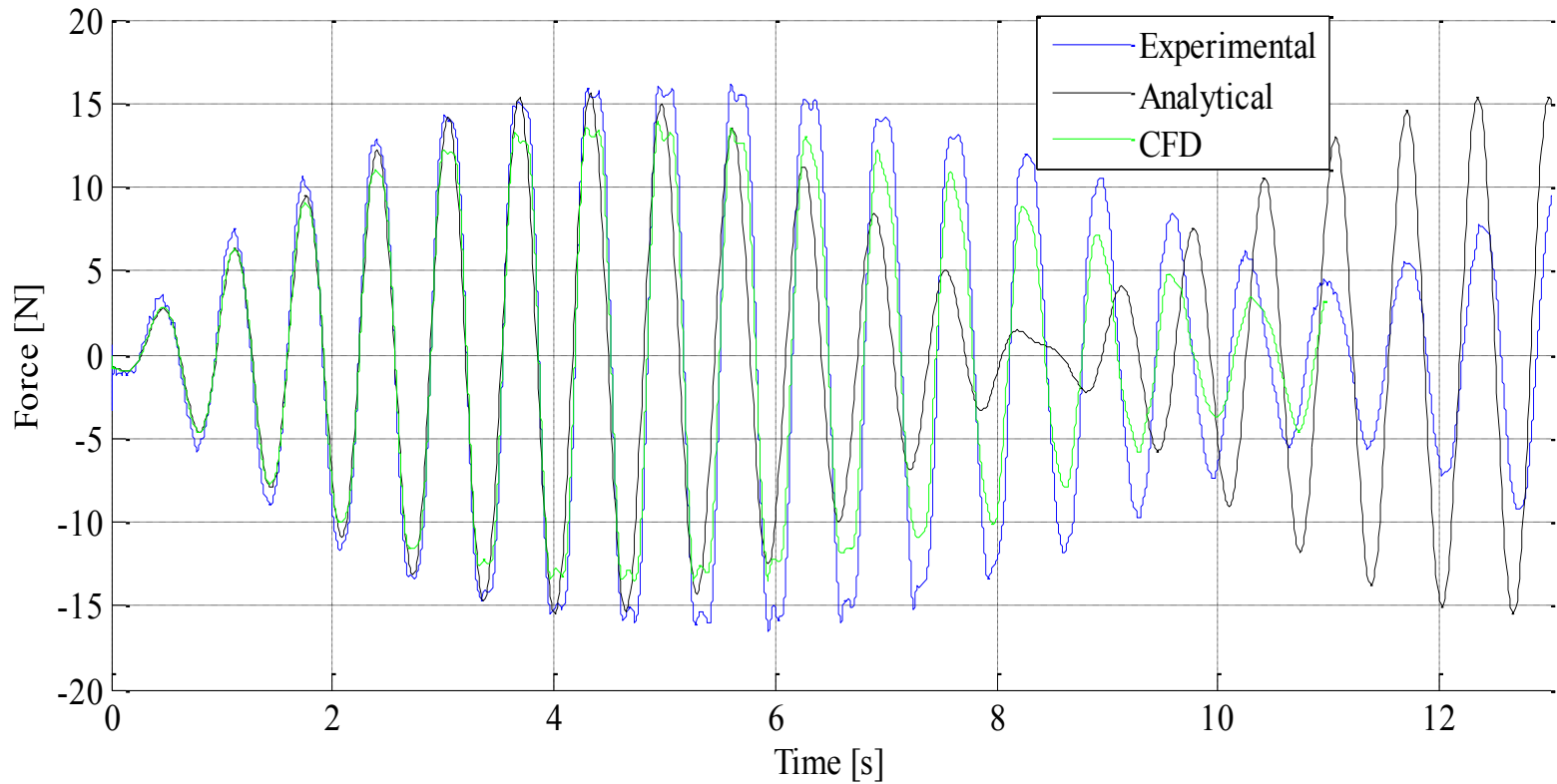


# Forced Excitation Tests

- 20% and 50% for water, 50% for LN2
- Approximately 20 frequency/amplitude combinations
  - 0.5 to 4.5Hz
- Tests repeated 3 times
- Data collected for 30-60s depending on number of cycles
- Data postprocessed in MATLAB



# Slosh Force vs. Time

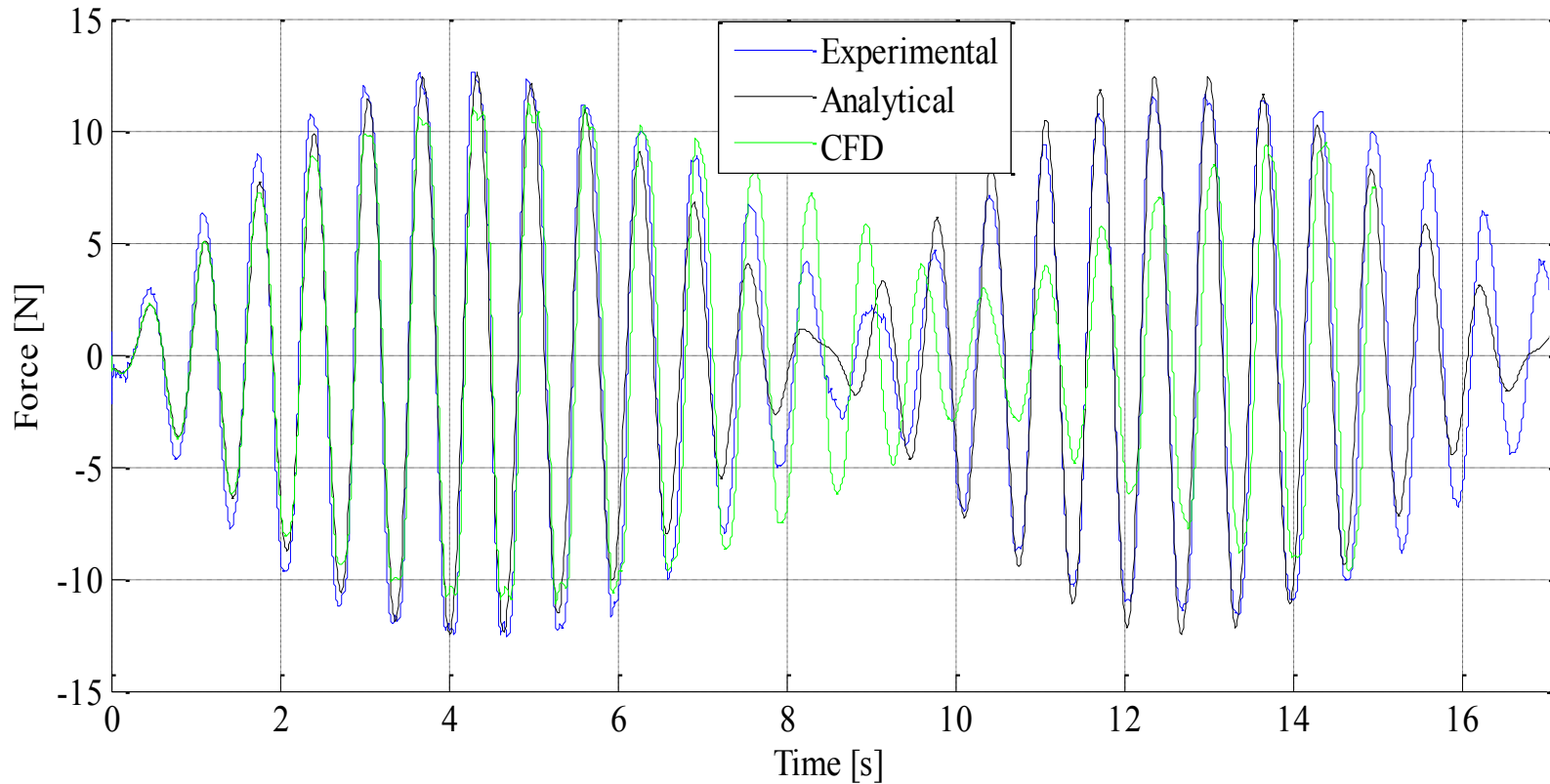


- Water, 1.5Hz, 3.04mm, 50%





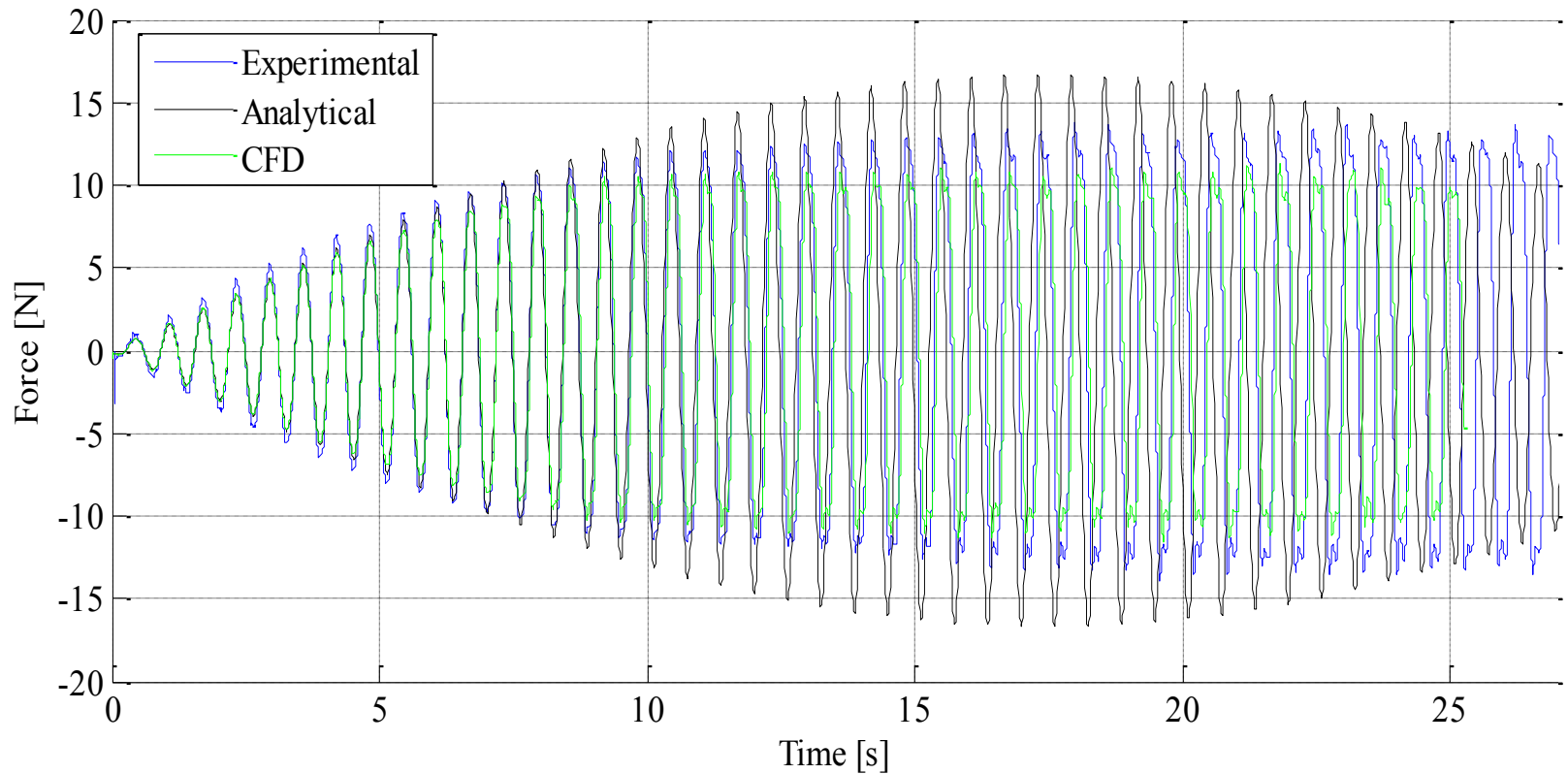
# Slosh Force vs. Time



- LN2, 1.5Hz, 3.04mm, 50%



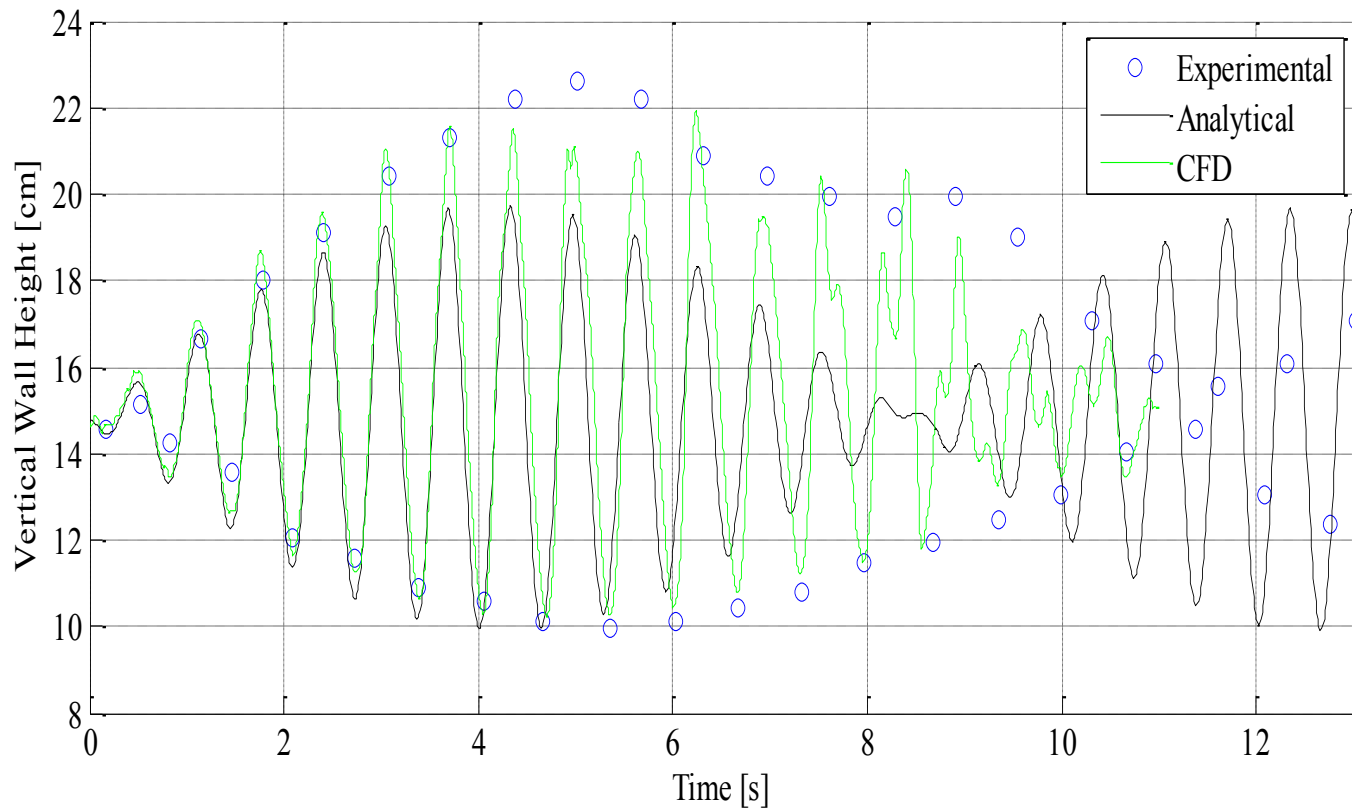
# Slosh Force vs. Time



- LN2, 1.59Hz, 0.93mm, 50%



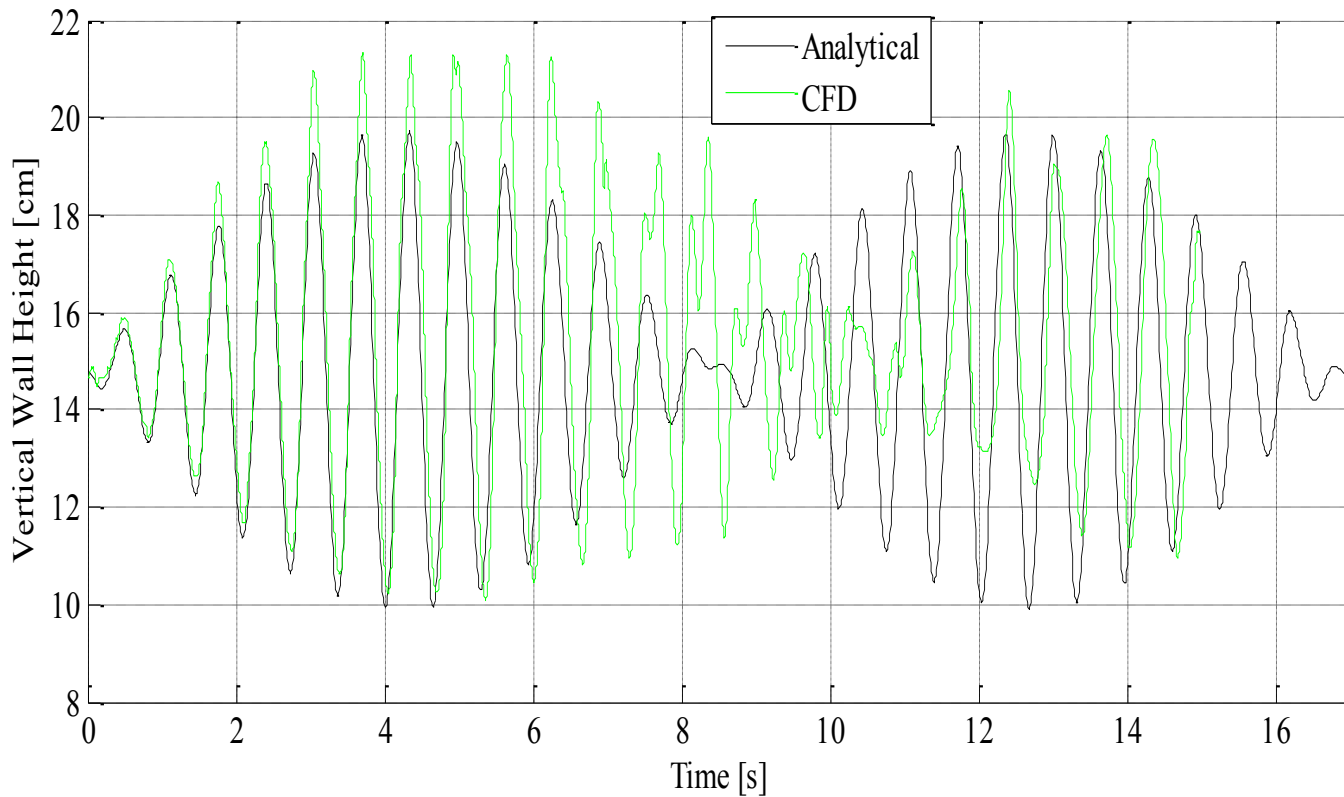
# Wave Height vs. Time



- Water, 1.5Hz, 3.04mm, 50%



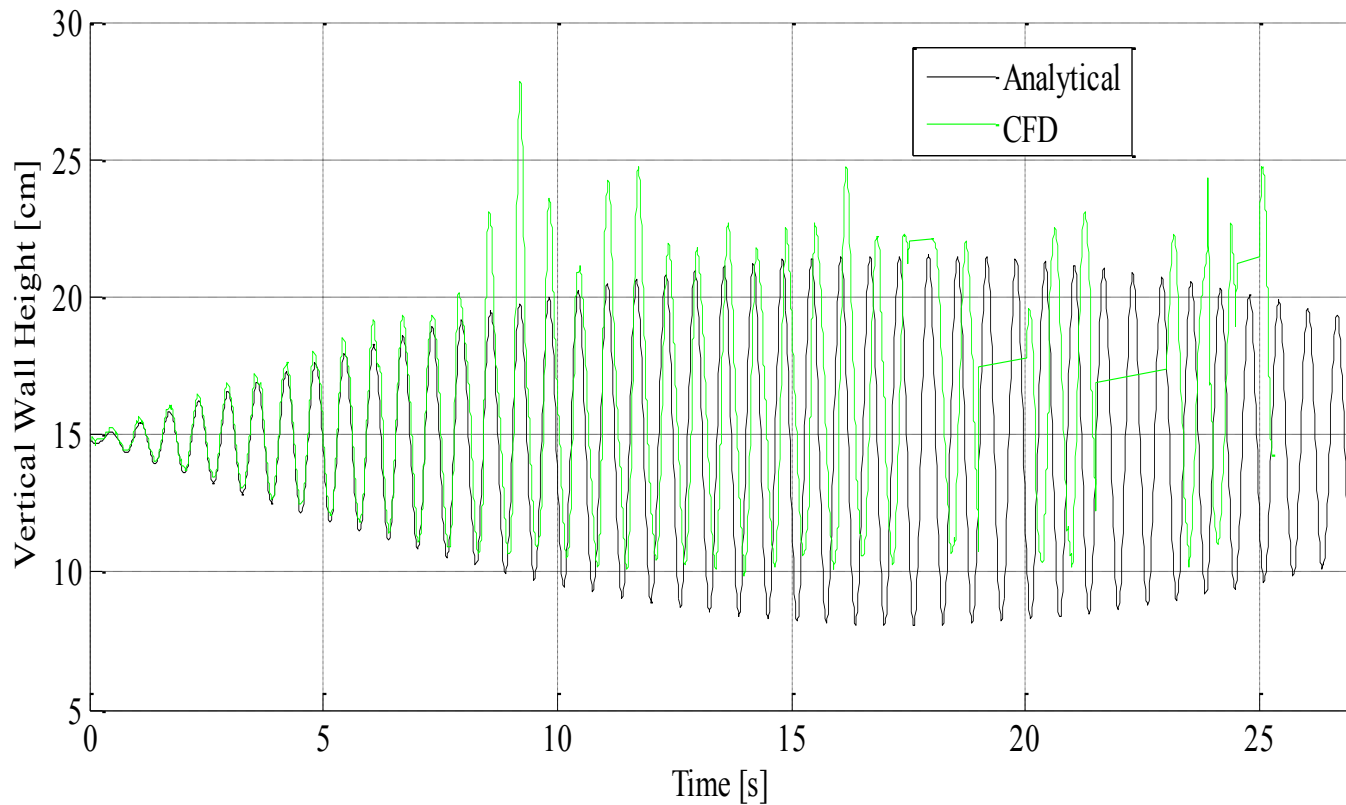
# Wave Height vs. Time



- LN2, 1.5Hz, 3.04mm, 50%



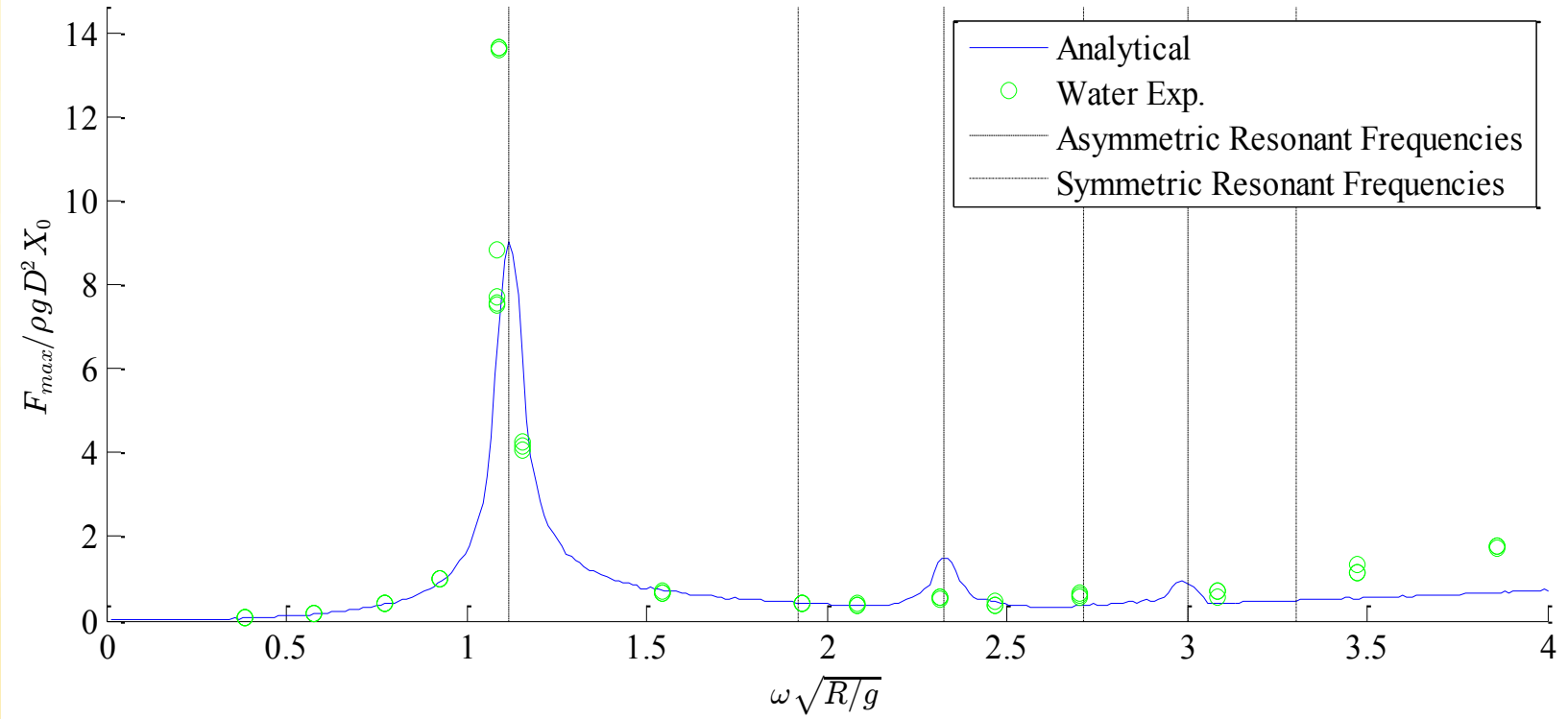
# Wave Height vs. Time



- LN2, 1.59Hz, 0.93mm, 50%



# Force Parameter vs. Frequency Parameter

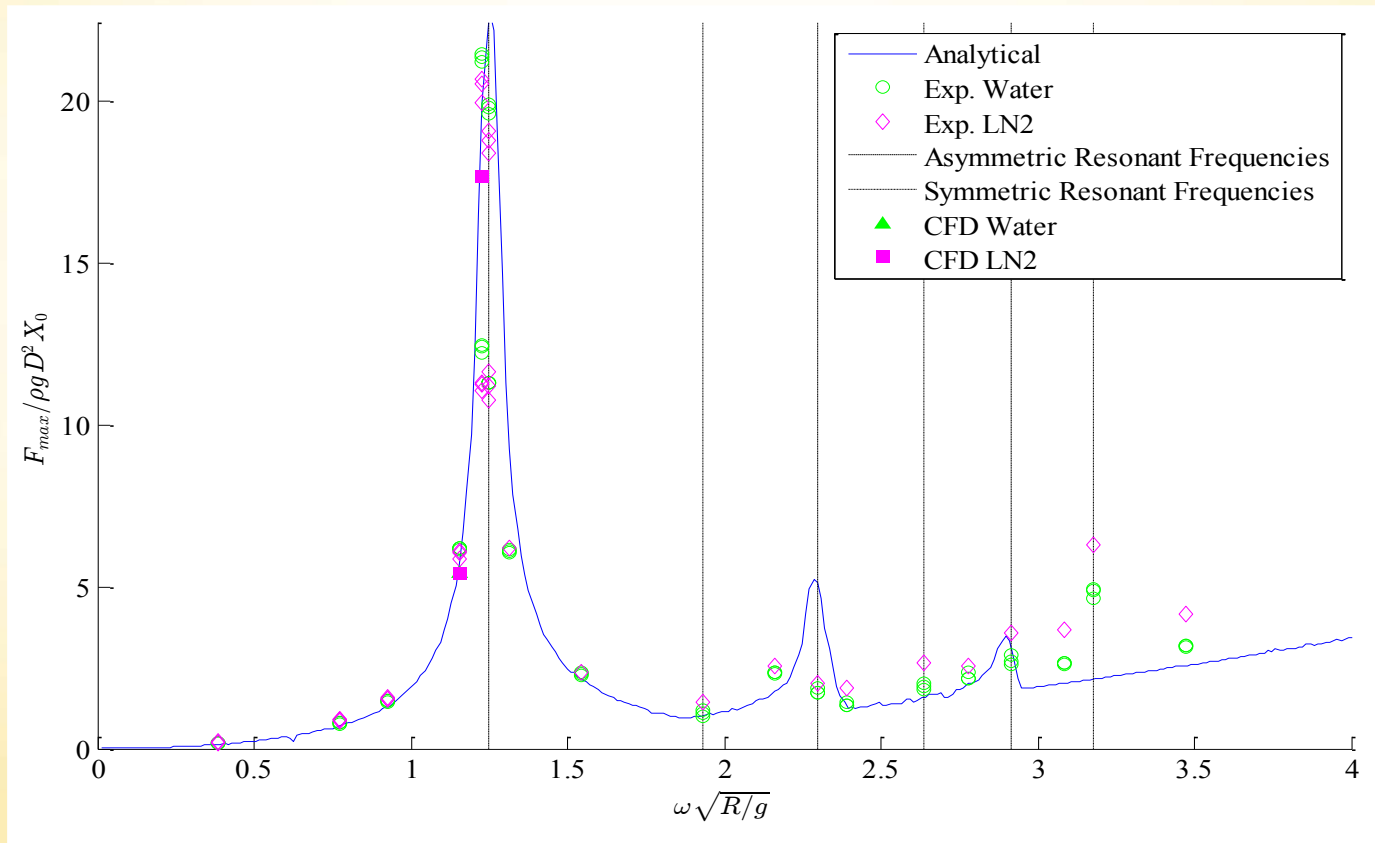


- Water, 20%





# Force Parameter vs. Frequency Parameter



- Water and LN2, 50%





# Videos

- (place holder. Too large to embed)



# Conclusions/Results from forced excitation tests

- First mode resonant frequency slightly lower than theoretical
- Did not successfully excite the 2<sup>nd</sup> and 3<sup>rd</sup> asymmetric frequencies
  - Did seem to excite the 3<sup>rd</sup> symmetric
- CFD does a fair job of predicting forces and wave height
- Rotation/swirl common at excitation frequencies equal to or above the first mode



# Uncertainty/Error

- Volume measurement large source of error
  - Boiling
  - Camera resolution and angle
  - +/- 3mm to 5mm
    - At 50% fill, +/-4mm corresponds to +/- 270mL (+- 2%)
- Tank not a perfect sphere
- Mechanical vibration noise
- No rigorous uncertainty analysis performed, though tests were repeated with that in mind



# Final Conclusions and Future Work

- Some confidence in the CFD models to accurately predict fluid slosh
  - Need to perform many more simulations
  - Larger mesh
- Need to perform an uncertainty analysis
- Hardware improvements necessary
  - Reading fluid heights from 100000's of images is not feasible
  - Lighting
  - Thermocouple instrumentation
- Damping tests need to be rerun with an emphasis on only strongly exciting the first mode
- Rotational modes are high amplitude/low decay
  - Clearly important to understand, but nothing planned





# Final Conclusions and Future Work

- Forced excitation tests: additional volume fractions
- Fluid management devices
  - Baffles
- Free pitching axis
- “Floating tank” approach versatile
  - Free translation tests
- “In-space” part
  - Parabolic aircraft flight experiments
  - CFD modeling of past work
    - Drop tower
    - FIT-MIT SPHERES SLOSH ISS experiment
- Brainstorming possible fluid transfer experiments



# Acknowledgments

- NASA OCT
- NASA KSC LSP
- NASA MSFC ER42
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- Bernard Kutter
- Barry Battista



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**EXTRA**





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# Thermocouple Example Plot





# Interesting Videos

- (too large to embed)



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# Mesh Cross-sections







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# Cool pictures of seal test

