Validation of High-Resolution CFD Method for Slosh Damping Extraction of Baffled Tanks

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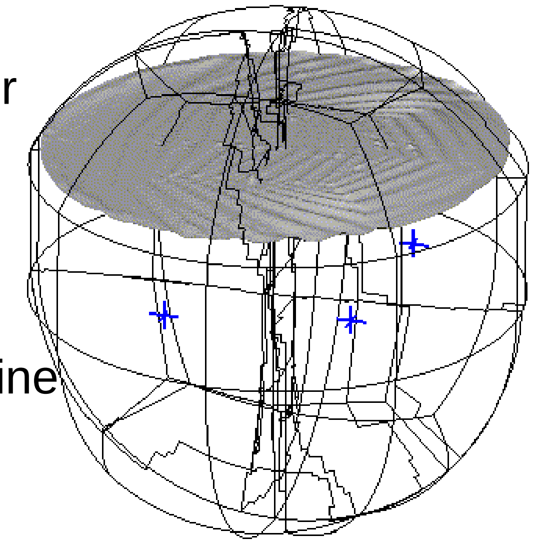
Sloshing of Propellant Tanks

Phenomena

- Oscillations of the free surface of a liquid in a partially filled tank

Significance

- Potential source of disturbance that may affect the stability and structural integrity of space vehicles.
- Can circulate sub-cooled propellant near the liquid vapor interface resulting in increased condensation and corresponding pressure collapse. Conversely: rapid vaporization and pressure rise near heated wall.
- Concern for propellant surface orientation during Upper Stage burn (to ensure sufficient liquid propellant for engine firing).



Driving Mechanisms

- The driving slosh forces: lateral disturbance, oscillatory thrust force (TO), angular rotation during maneuverings.
- It occurs during vehicle taxi, takeoff, engine shut off, and flight maneuvers.

Recent Evolution of CFD-based Propellant Slosh Prediction Capability

1956: Empirical Methods SP-106, etc.

2008: ARES I
Smooth Wall and Ring Baffle Verification Validation

2009: Ares I
- Simultaneous Slosh and Drain
- MECO Simulation

2009: Ares I
LOX Damper

2012: Technical Excellence
Non-Linear Slosh Damping Concept and Prediction
2013: Technical Excellence
Non-Linear Slosh Damping Validation

2014: Launch Services Program
Ullage Effects due to High Amplitude Slosh

2015: NESC
Exploitation of Non-Linear Damping for SLS/EUS Tanks

2014-16: SLS Core Stage
Damping in LOX Tank

2014-16: CATALYST
Spherical Tank Slosh Model including Linear and Non-Linear Regimes

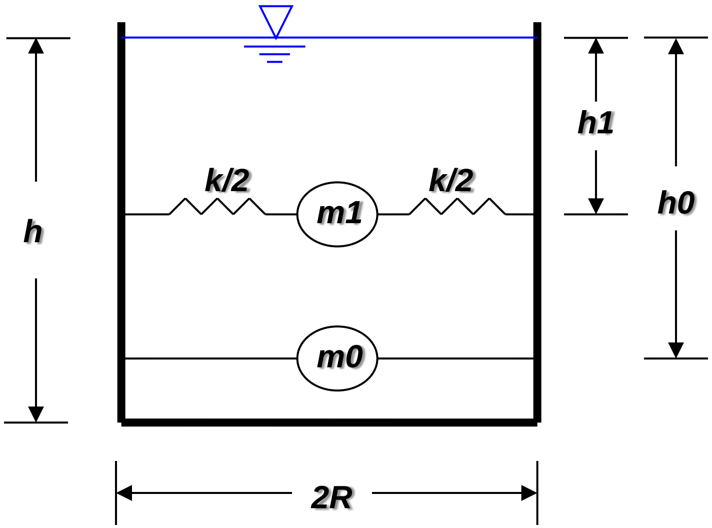
2015: Summer Intern Program
Microgravity "Slosh" Validation
Continuing interest from LSP

2016: Technical Excellence
Integration of Improved Engineering Slosh Models

Increasing Engineering Capability for Propellant Slosh Abilities

Verification of Spring-Mass Analogy for Slosh

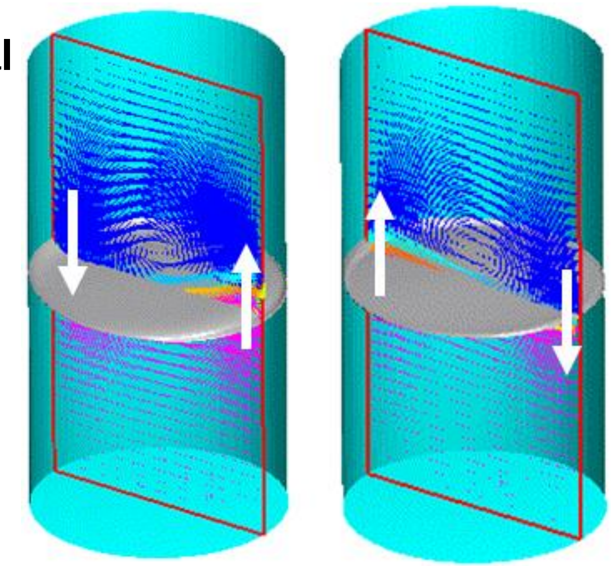
Spring-Mass Analogy of Fluid Slosh in a Circular Cylindrical



Analytical slosh frequency (Abramson, 1966: NASA SP-106):

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{1.841g}{R}\tanh\left(\frac{1.841h}{R}\right)}$$

$$\frac{m_1}{m} = \frac{0.4547R}{h}\tanh\frac{1.841h}{R}$$



Comparison for a Cylindrical Water Tank of R=3"

Slosh Frequency

Liquid Level	h/R=2.0	h/R=1.0	h/R=0.5	h/R=0.25
Analytical	2.4523 Hz	2.3880 Hz	2.0867 Hz	1.6058 Hz
Present CFD	2.4539 Hz	2.3753 Hz	2.0920 Hz	1.6155 Hz
Error	**0.06%**	**0.53%**	**0.256 %**	**0.97%**

Slosh Mass

Liquid Level	h/R=2.0	h/R=1.0	h/R=0.5	h/R=0.25
Analytical	0.22735	0.43236	0.66028	0.78252
Present CFD	0.22858	0.43380	0.66402	0.77950
Error	**0.54%**	**0.33%**	**0.56 %**	**0.39%**

- **Excellent agreements for the simple geometries when an analytical solution exists !!**

Nonlinear Sloshing Damping: How to Determine ?

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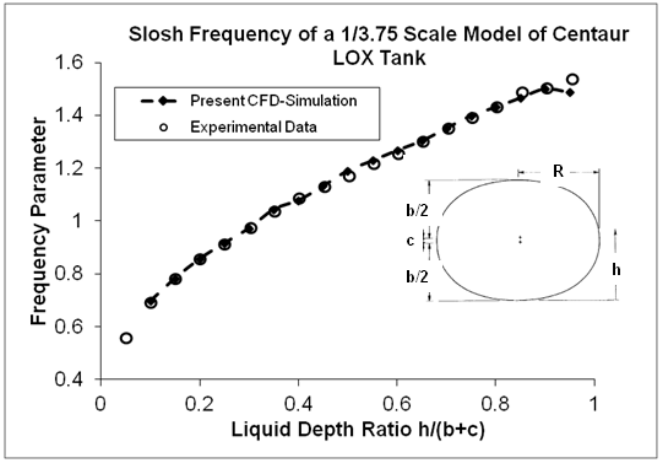
Two Phase CFD Tool at ER42, CFD-ACE+

- **Well verified and validated for slosh frequency, mass, and mass center**
  - Yang and Peugeot, “Propellant Sloshing Parameter Extraction from Computational Fluid Dynamics Analysis”, *J. of Spacecrafts and Rockets, 2014.*

Table 1 Sloshing frequency comparison for water in a cylindrical tank ($R = 3$ in.)

Liquid level	$h/R = 2.0$	$h/R = 1.0$	$h/R = 0.5$	$h/R = 0.25$
Analytical	2.4474 Hz	2.3880 Hz	2.0868 Hz	1.6064 Hz
Present CFD (80,000)	2.4485 Hz	2.3832 Hz	2.0822 Hz	1.61 9Hz
Error (80,000)	−0.1549%	−0.201%	−0.215%	−0.822%



  - Demonstrated and validated for surface break up.
  - Preliminarily validated for damping due to ring baffle (by EV31 Ravi Purandare).

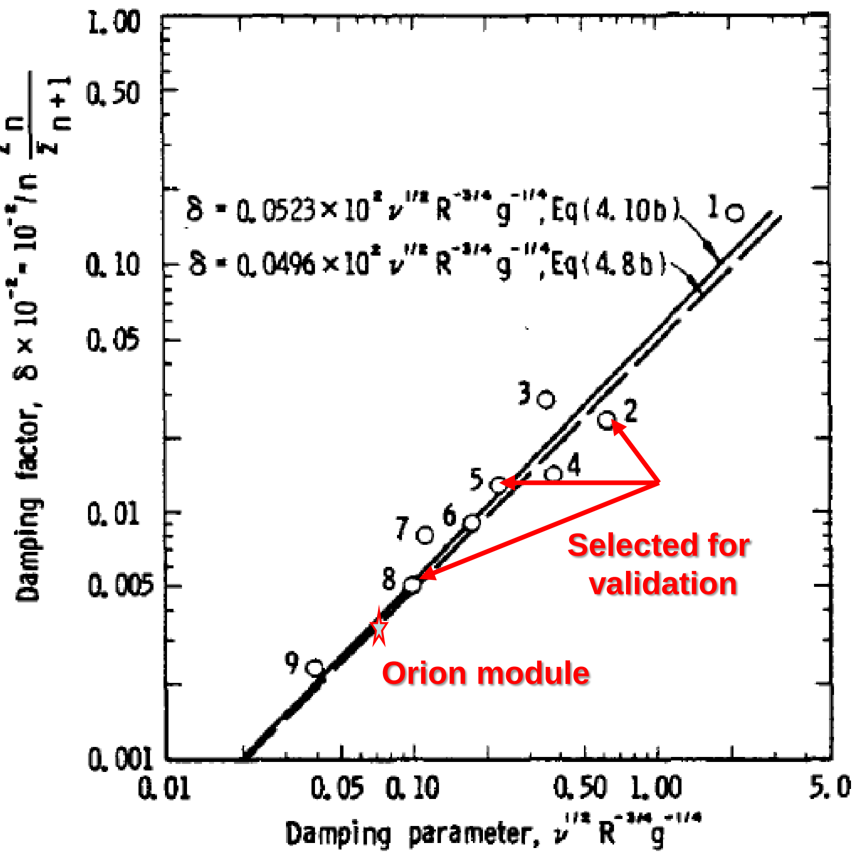
- **Modeling smooth wall damping is a challenge**
  - Numerical damping for the solution stability could be larger than physical damping (from JPL results: 400% higher damping ratio, 0.03% (empirical) vs. 0.13% (Flow-3D).
  - Boundary layer has to be well resolved.
  - Numerical damping has to be estimated, and reduced to minimum.

- **Our approach**
  - . Fundamentally sound validation against experiments using smooth wall cylindrical tank. Estimate numerical damping or find the techniques to remove/reduce numerical damping.

Experimental Data Collections

For partially filled circular cylinder tank with smooth wall

- No analytical solution exists for slosh damping.
- Experimental data correlation only (liquid height/R > 2) based on a set of experiments.



Test Conditions Selected for Validation:

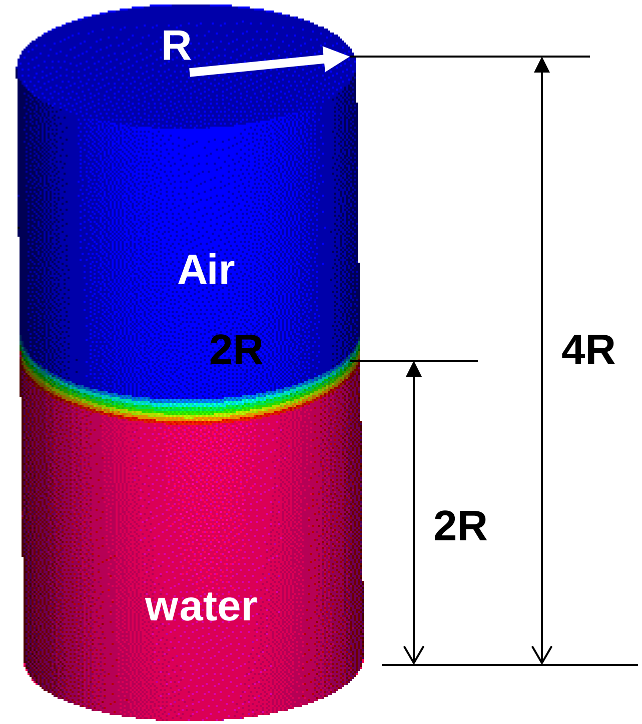
- All in water
- Cylindrical tank with flat bottom surface
- Several radius of the tank to assess grid resolution effect.
- R=3.8 cm = 1.5 inch
- R=15.2cm= 6.0 inch
- R=45.7cm= 18 inch

* Orion Service module: R=25 inch

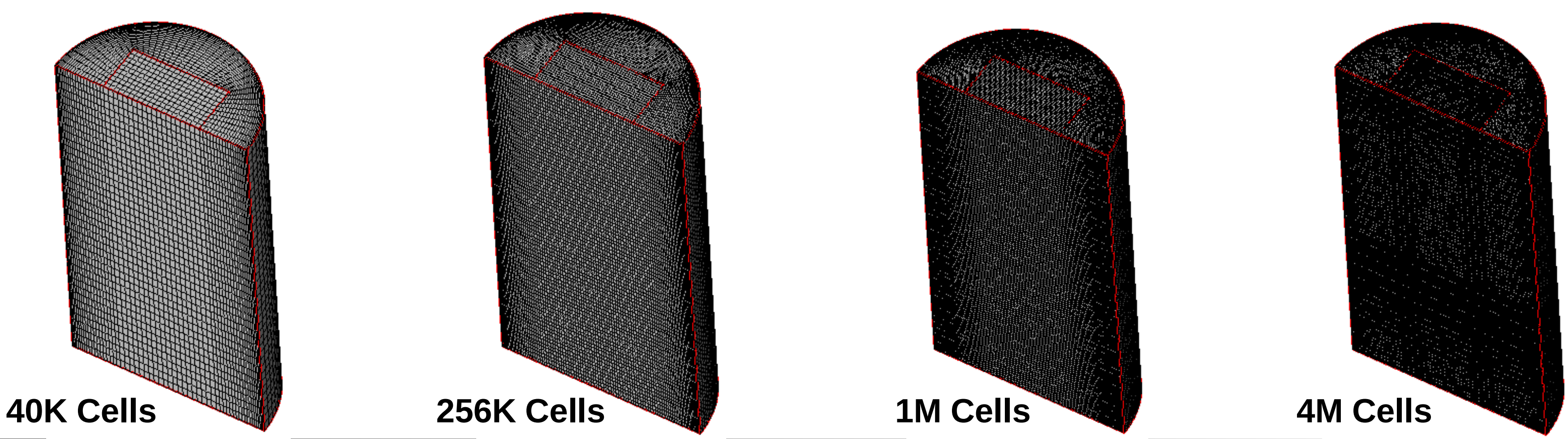
Data point	Tank radius, cm	Kinematic viscosity, stokes	Test liquid, [reference]
1	15.2	0.836	SAE 10 - W oil [4.13]
2	3.8	0.00929	Water [4.4]
3	15.2	0.0223	Kerosene [4.4]
4	7.6	0.00929	Water [4.4]
5	15.2	0.00929	Water [4.13]
6	38.1	0.0223	Kerosene [4.13]
7	38.1	0.00929	Water [4.13]
8	45.7	0.00929	Water [4.13]
9	152.5	0.00929	Unpublished Convair / Astronautics data

CFD Validation

Simulation Model: Half of the cylinder
Radius: 1.5 inch
Liquid Fill Level: **2R**
Initial Slosh Amplitude: 0.05R (in linear regime)
Grid Type: Hexahedral
Grid Cell Numbers: 40K, 256K, 1M and 4M
Liquid Phase: Water; **Gas Phase:** Air
Boundary Conditions: non-slip wall on all sides and bottom; fixed pressure at top
Time Step Size: CFL=0.1; or dt_{max}=0.5ms
Temporal Scheme: 2nd Order Crank-Nicolson:
Spatial Scheme: 2nd order Central + 1% 1st Order



Increasing spatial resolution →



CFD Error Estimation for Slosh Damping

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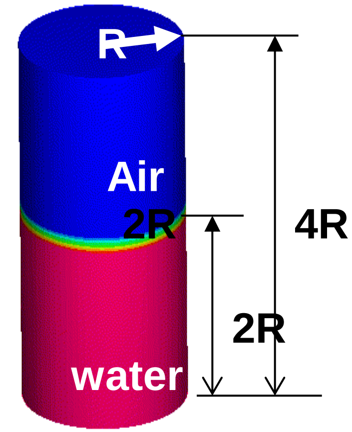
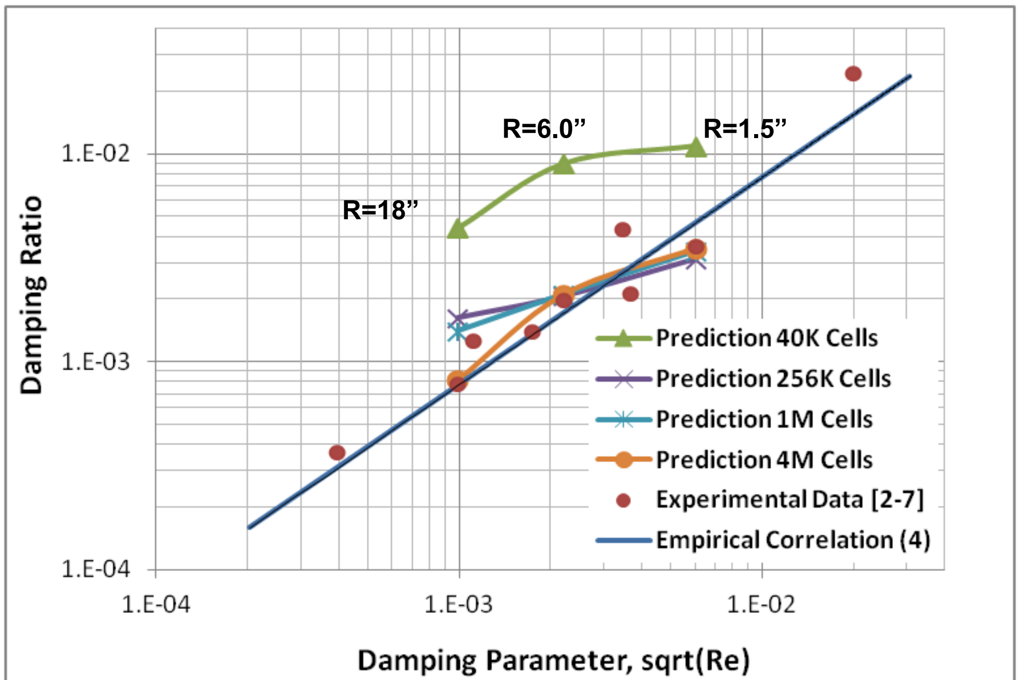
Determination of Slosh Damping: A Very Challenging Task

- No analytical solution exists. The damping physics involve the vorticity dissipation which requires full solution of the nonlinear Navier-Stokes equations.
- Previous investigations and knowledge were mainly carried out by extensive experimental studies.
- For any CFD tool, one must resolve a thin boundary layer near the wall and must minimize numerical damping.



CFD Validation for Smooth Wall Cylindrical Tank of Different Sizes

•Grid refinement study and comparison to experiment.
•Grid resolution requirement



Tank Radius	Required Total Grid Size
1.5"	256K
6.0"	516K
18"	4M

Root-Mean-Square Error: 4.5%
Maximum Error: 5.5%

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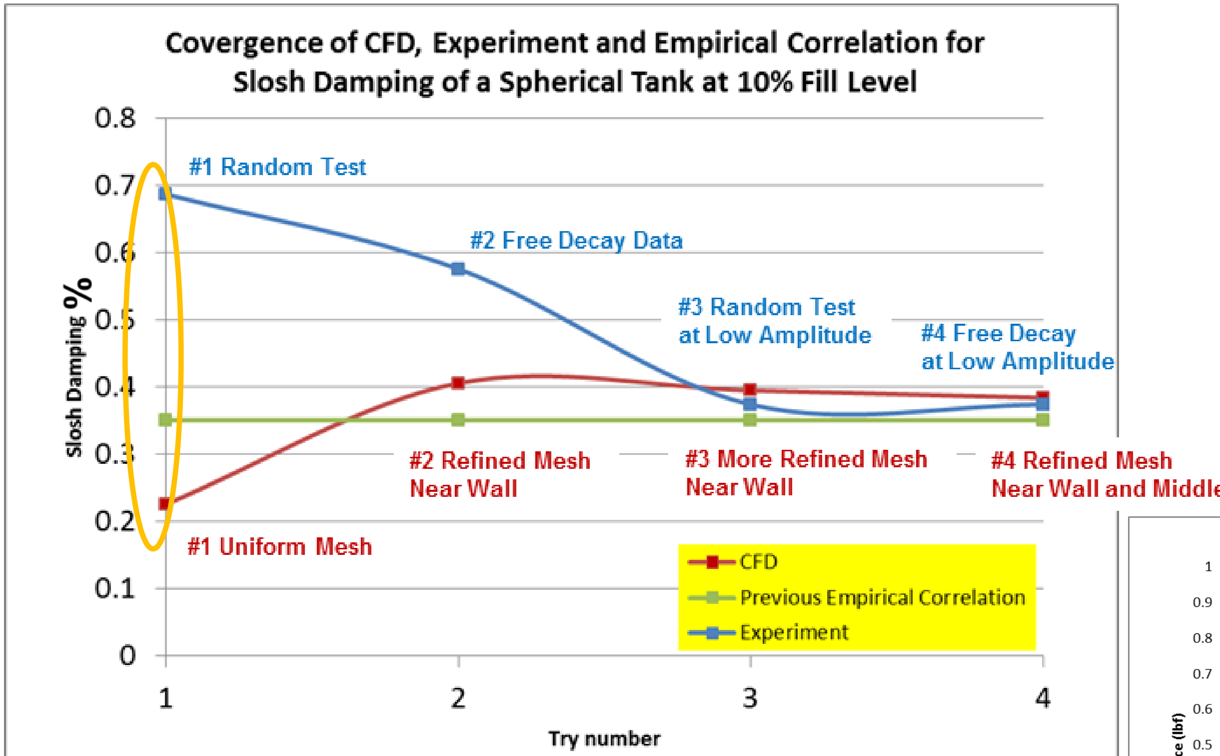
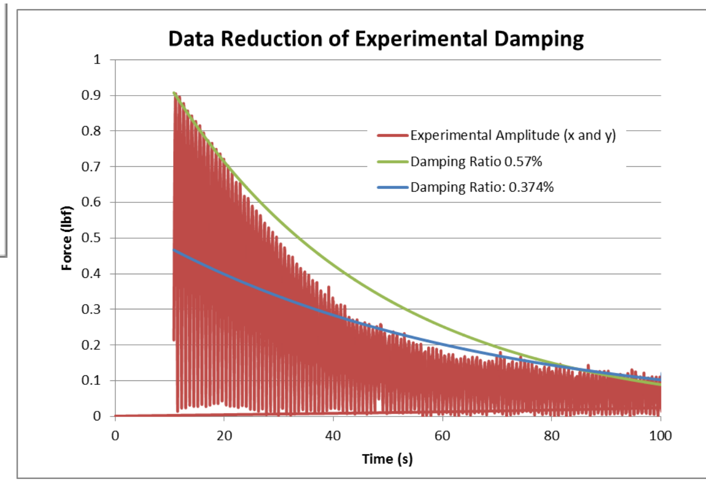
CFD Error Estimation for Slosh Damping

<u>CFD Validation of Slosh Damping for a Smooth Wall Spherical Tank</u>

•Spherical tank with D=43", liquid fill height of 10%.



Test by ET-40 (2015)



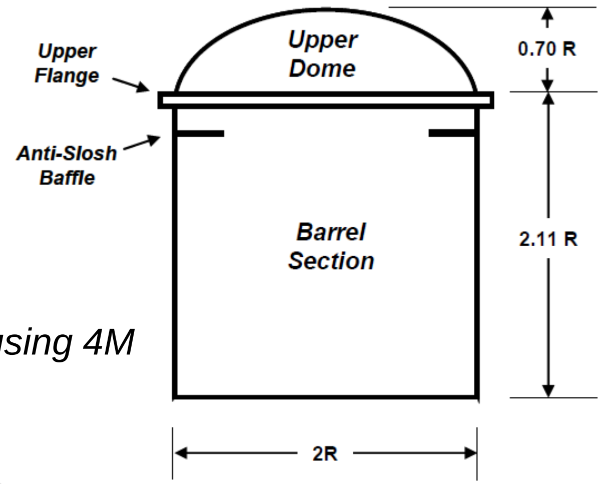
Error: 2.65%

A successful validation requires close collaboration between analysis and experiment

Experiment and Simulation Article with Baffle

Experimental Work of ET40 (June, 2011)

- *The tank model consists of a cylindrical barrel section and a spheroidal upper dome.*
- *1/5 Ares LH2 tank.*
- *Tank radius: 21.56”*
- *Baffle location: 43.91”; width: 4.4”.*
- *Liquid fill levels: 41” to 53”.*
- *Test liquid: water*

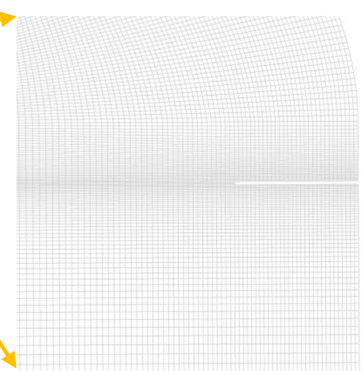


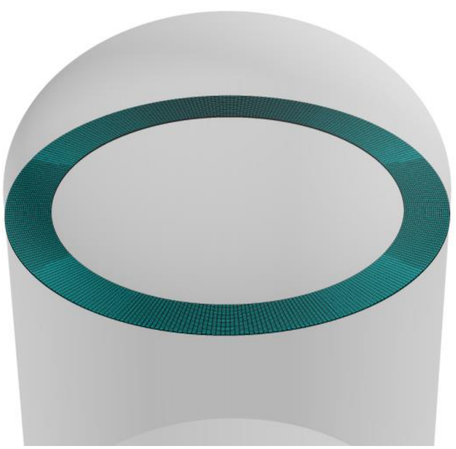
Simulation Model

- *5.7M Cells (based on our previous study using 4M cells for Orion smooth wall tank)*

3D tank model

Cross-section of Grid





Grid around (above) and on (right) the baffle

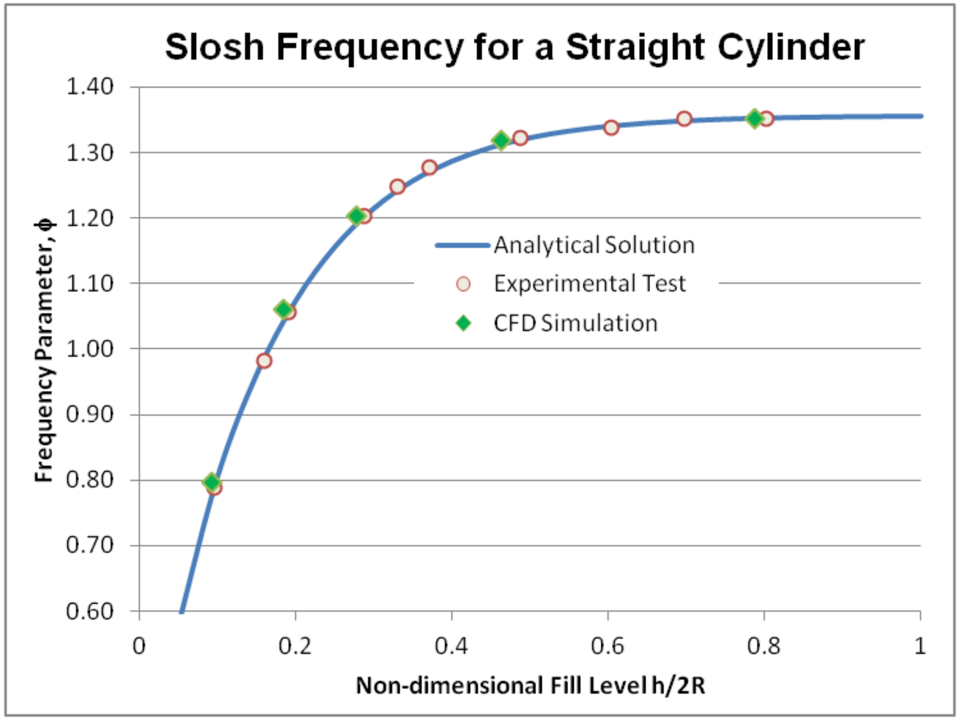
For the Liquid Levels Below the Baffle, It is Slosh In a Cylindrical Tank

- *Analytical solution is available for slosh frequency*

$$f = \frac{1}{2\pi}\left(\frac{1.841g}{R}\tanh\left(\frac{1.841h}{R}\right)\right)^{1/2}$$

Frequency parameter $\phi = 2\pi f / \sqrt{R/g}$

- *Verification can be made against analytical solution;*
- *Validation can be made again experimental data;*
- *The grid has been redistributed to have uniform size;*
- *Baffle is removed. Total cell number: 4M*



Observations:

- **Very good agreement between all three: analytical, CFD, and experiment.**
- **A confidence builder for further investigations.**

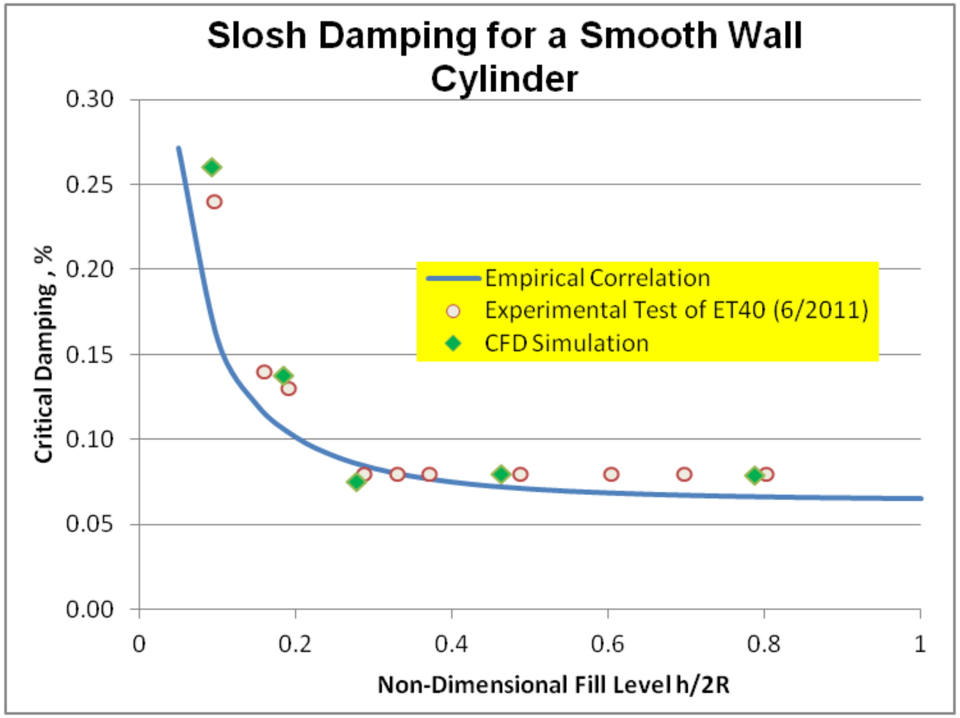
Validation for a Straight Cylindrical Tank: Damping

For the Liquid Levels Below the Baffle, It is Slosh In a Cylindrical Tank

- *For the smooth wall damping: empirical correlation:*

$$\zeta = \frac{4.98}{2\pi} * \frac{\nu^{0.5}}{R^{0.75} g^{0.25}} \left\{ 1 + \frac{0.318}{\sinh(1.84h/R)} \left[1 + \frac{1 - h/R}{\cosh(1.84h/R)} \right] \right\}$$

- *Previous smooth wall damping can be used for validation(again)*
- *This study: fill level effect; Previously: tank size effect.*



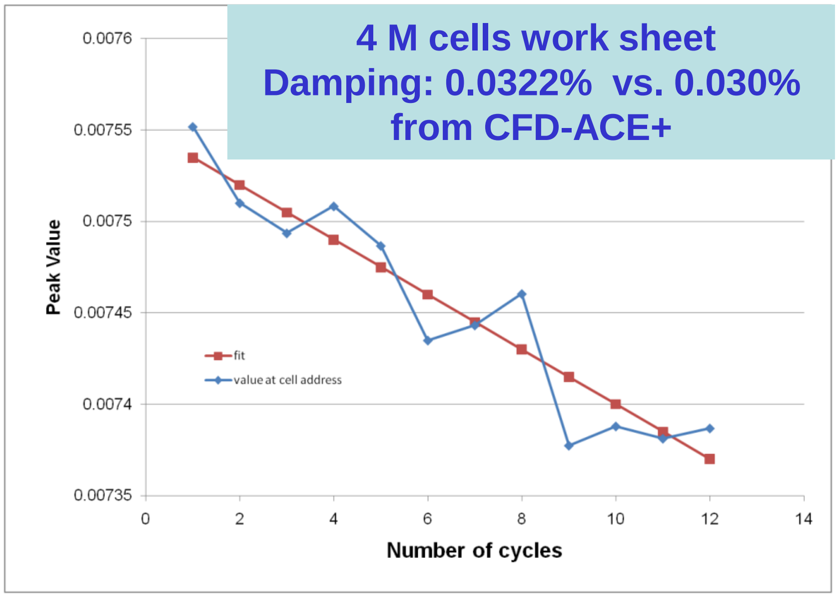
Observations:

- **Very good agreements between all three for fill level above h/2R=0.25. CFD results agree with experimental data, except at the lowest fill level.**
- **For fill level h/2R < 0.25, the empirical correlation under predicts damping.**

Verification and Validation of Loci-Stream-VOF

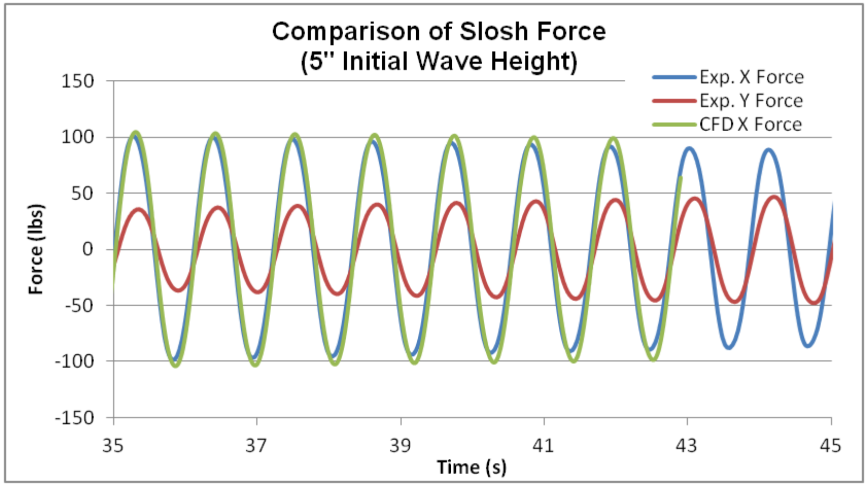
Verification vs. CFD-ACE+

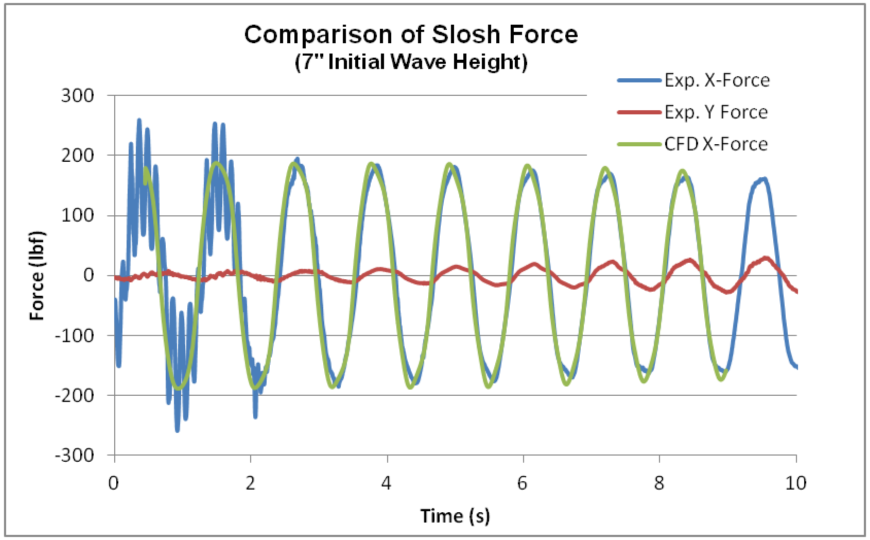
- Grid Cells: 1 Million and 4 Million
- 2” Initial wave height.
- Orion Tank with Smooth Wall



Verification Achieved!

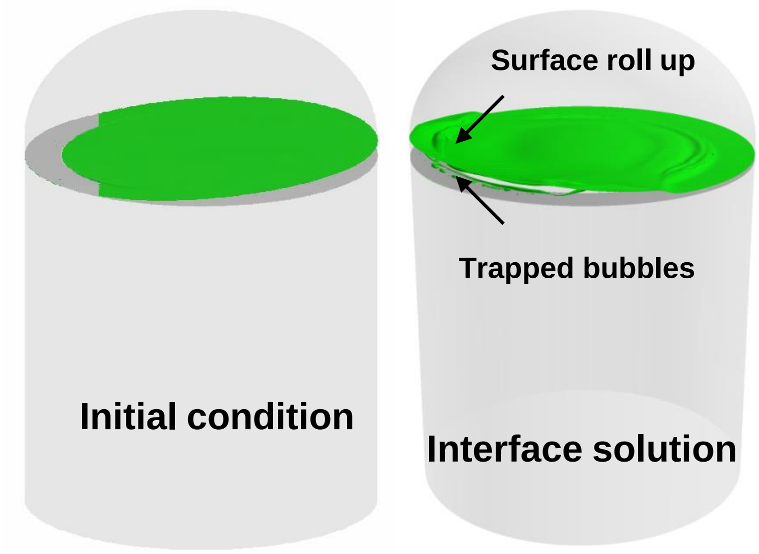
Validation vs. ET40 Using 86% Orion Tank

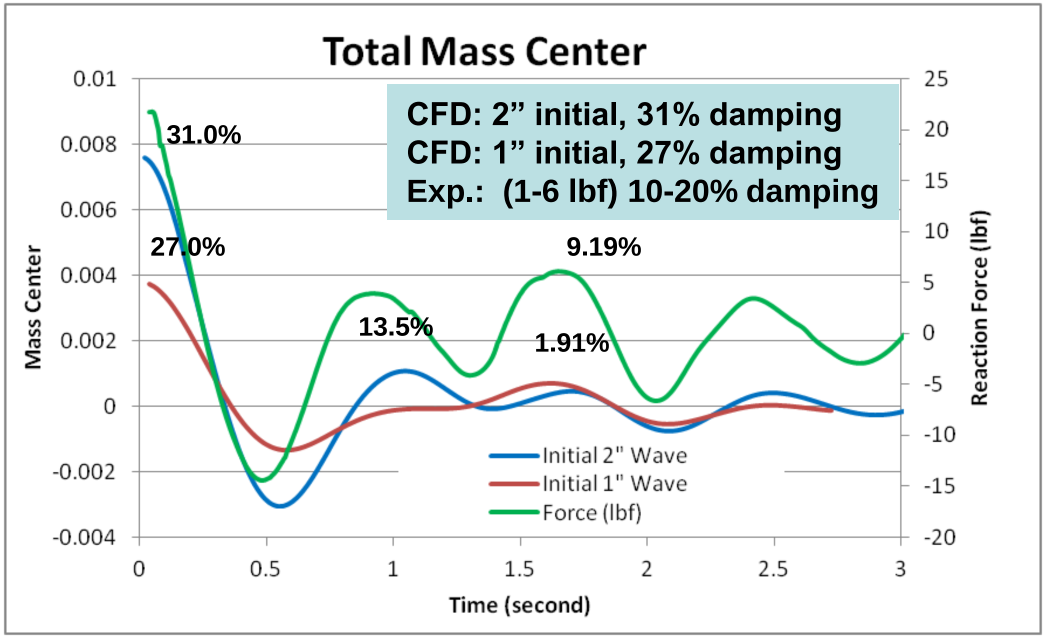


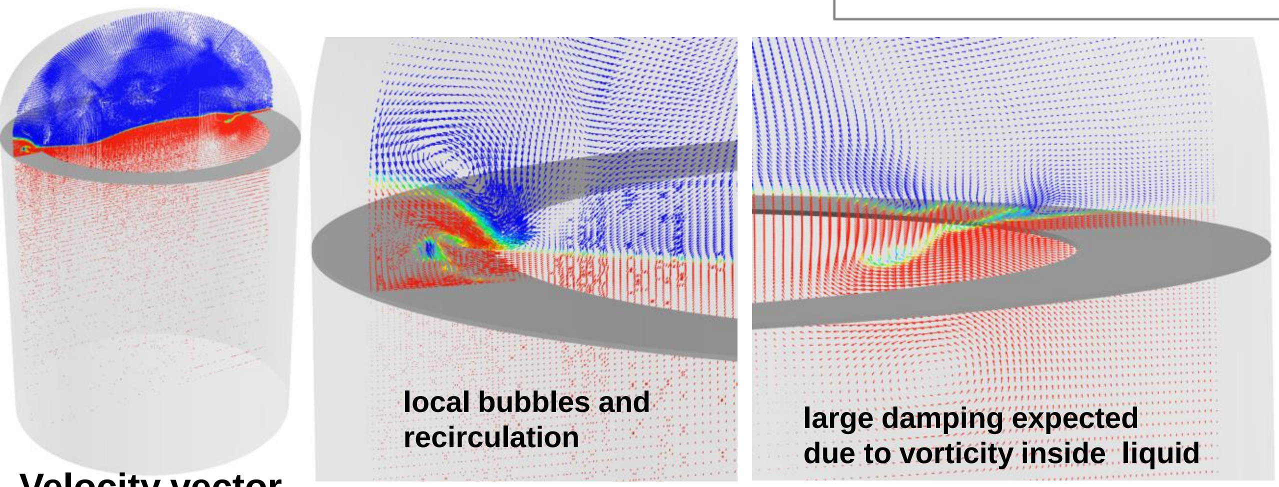


Validation for Baffled Tank Damping: h=44.84”

Fill Level Right above Baffle h=44.84”, h_B=43.91”





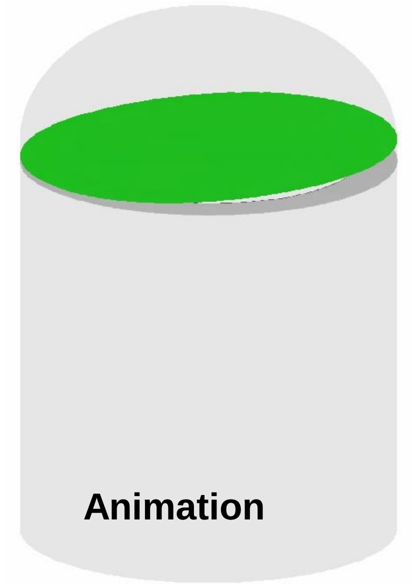


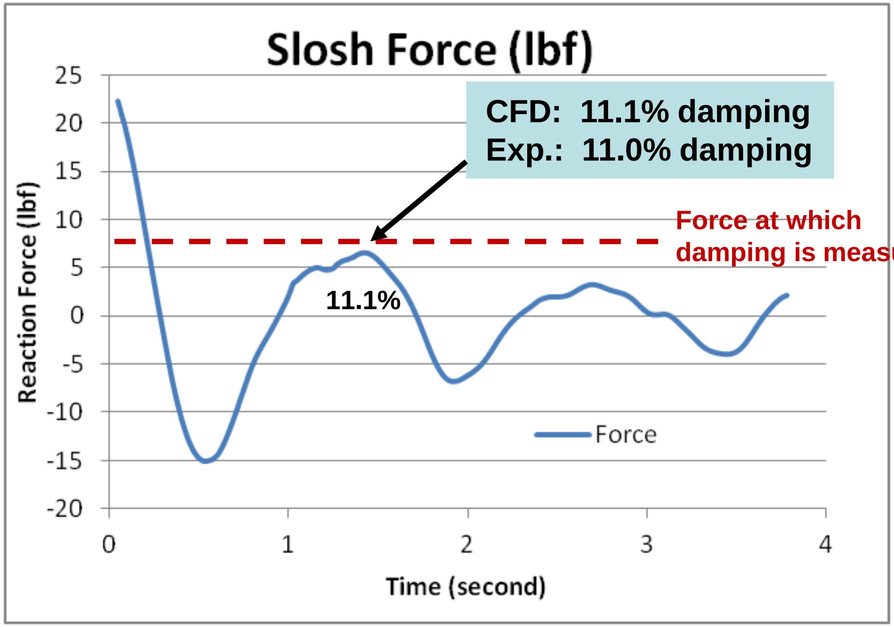
Observations:

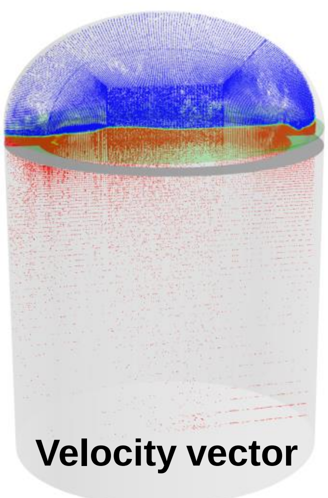
- Damping is very high when the interface is just above the baffle.
- Damping is also a strong function of the initial amplitude, making quantitative comparison difficult.
- CFD reveals the fundamental damping physics.

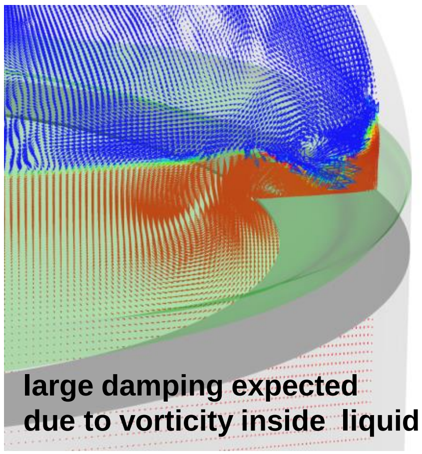
Validation for Baffled Tank Damping: h=45.56”

Fill Level Above Baffle h=45.56”, h_B=43.91”









Observations:

- The initial wave amplitude in CFD was set at 1”.
- Based on the reaction force level, the experimental damping was measured at the second peak.
- CFD agrees well with experimental data.

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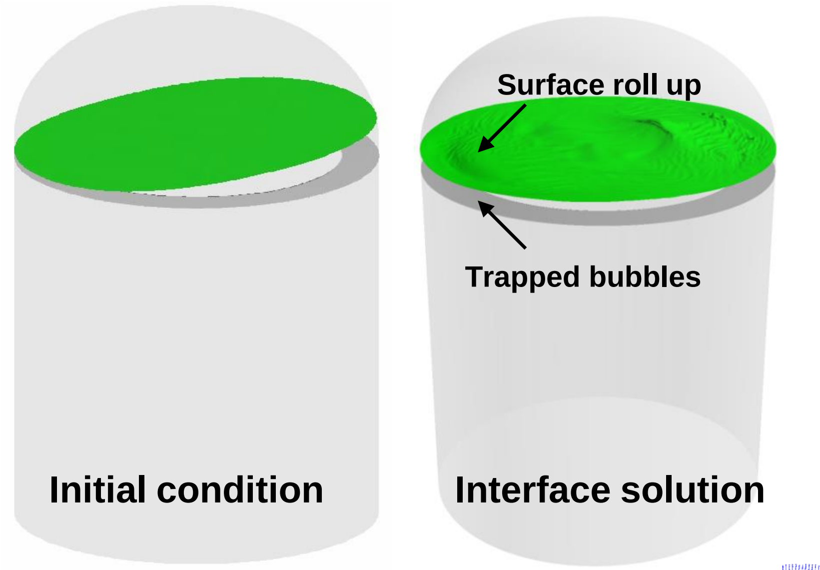
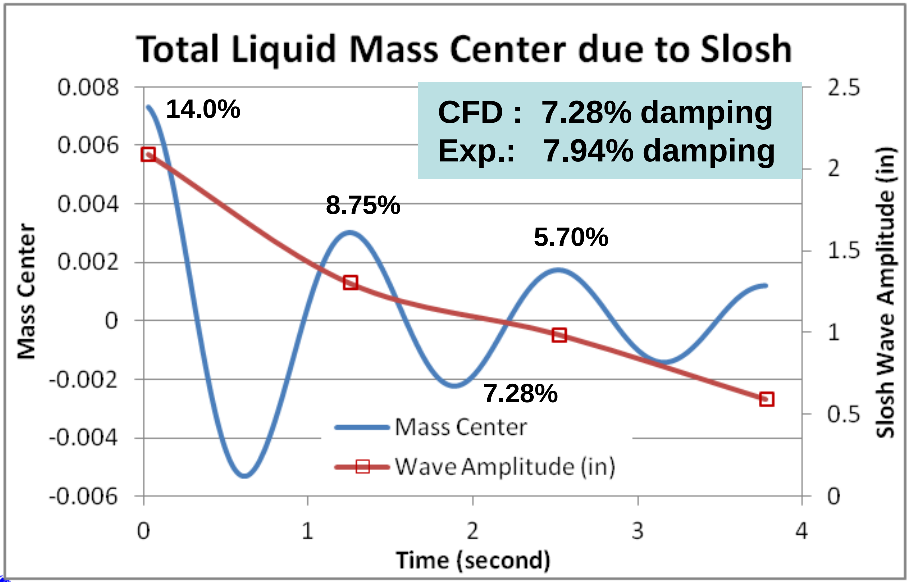
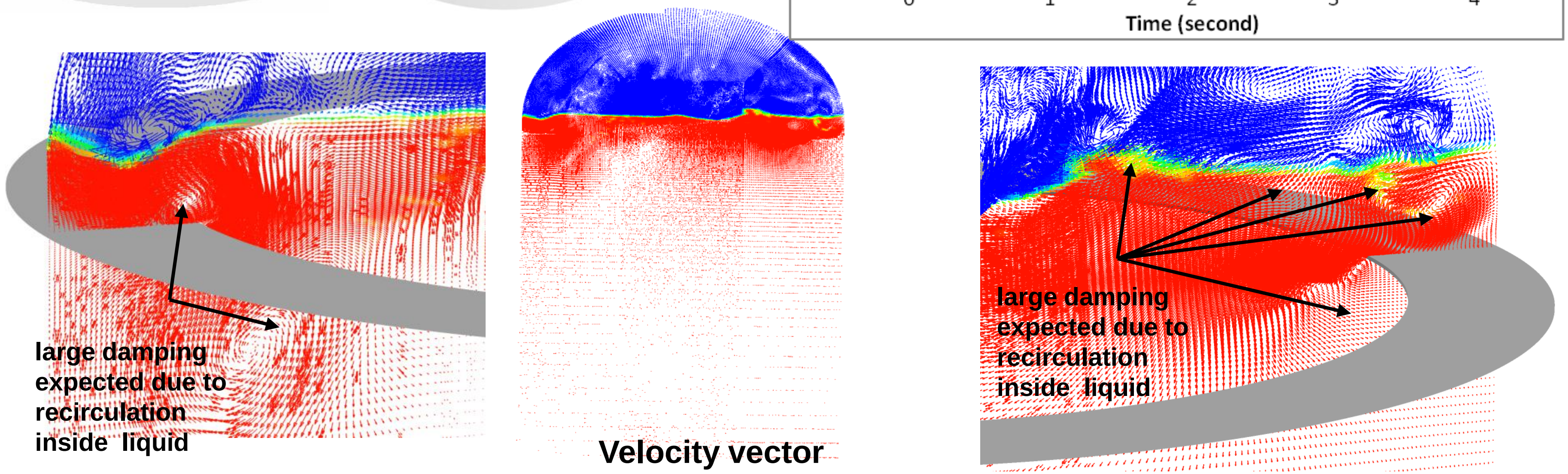
Fill Level Right above Baffle h=46.64”, h_B=43.91”

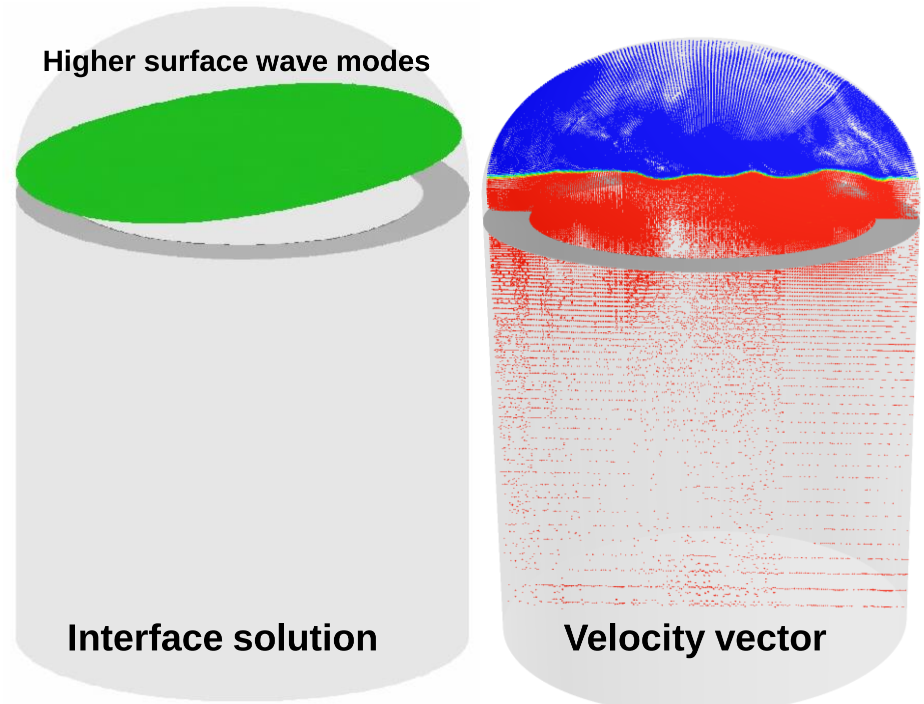


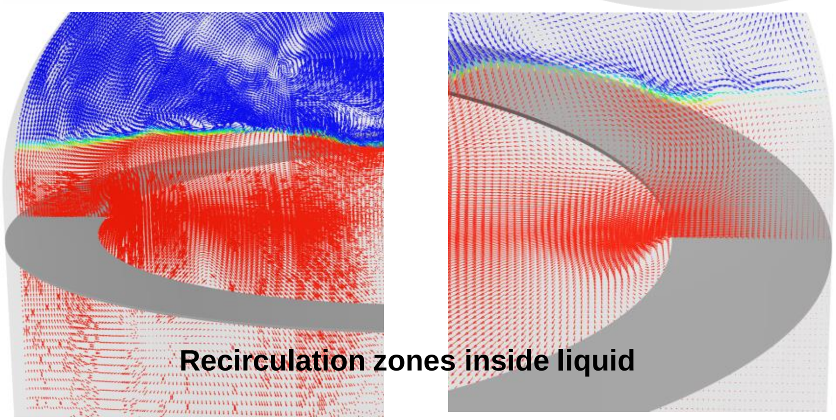


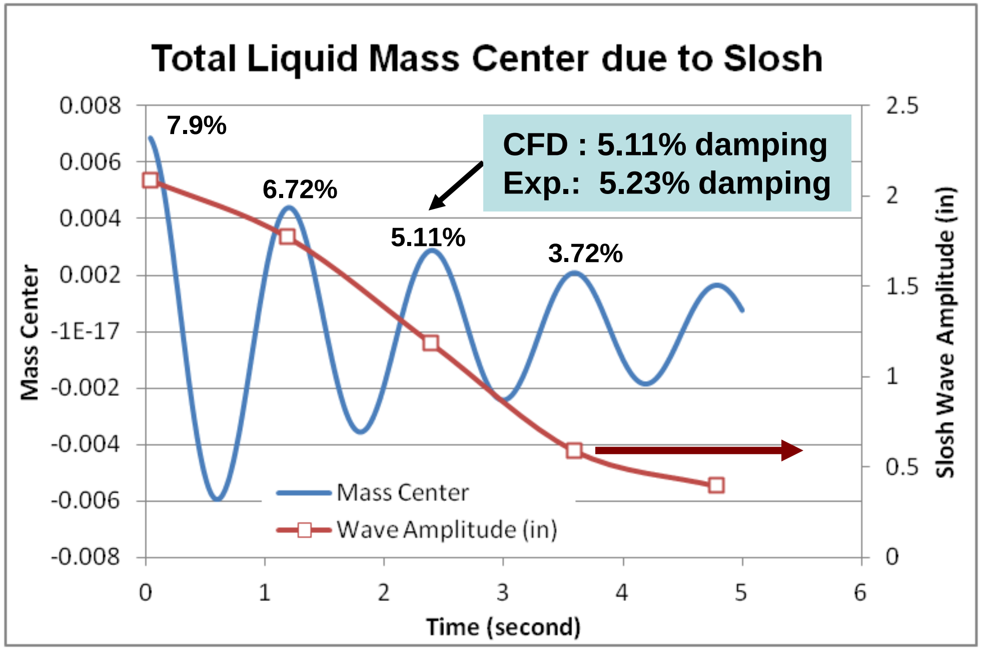


Validation for Baffled Tank Damping: h=48.07”

Fill Level Above Baffle, h=48.07”, h_B=43.91”





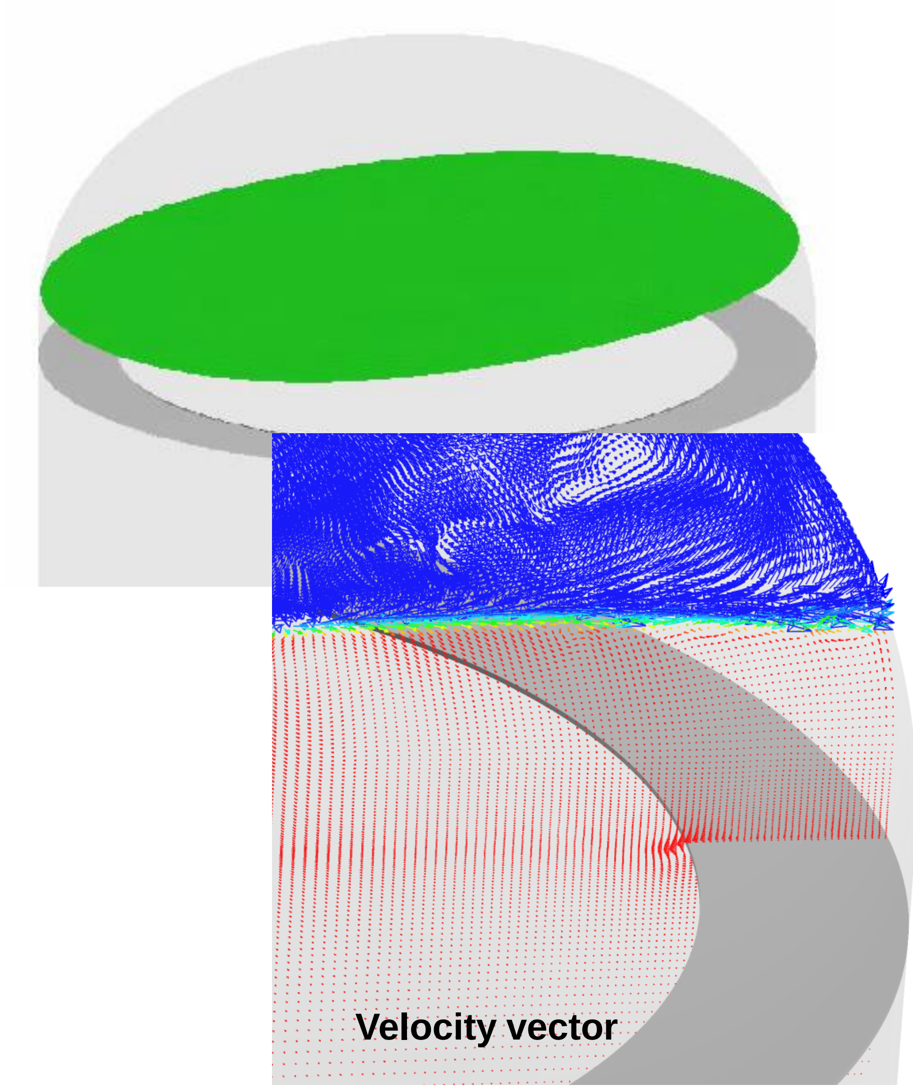


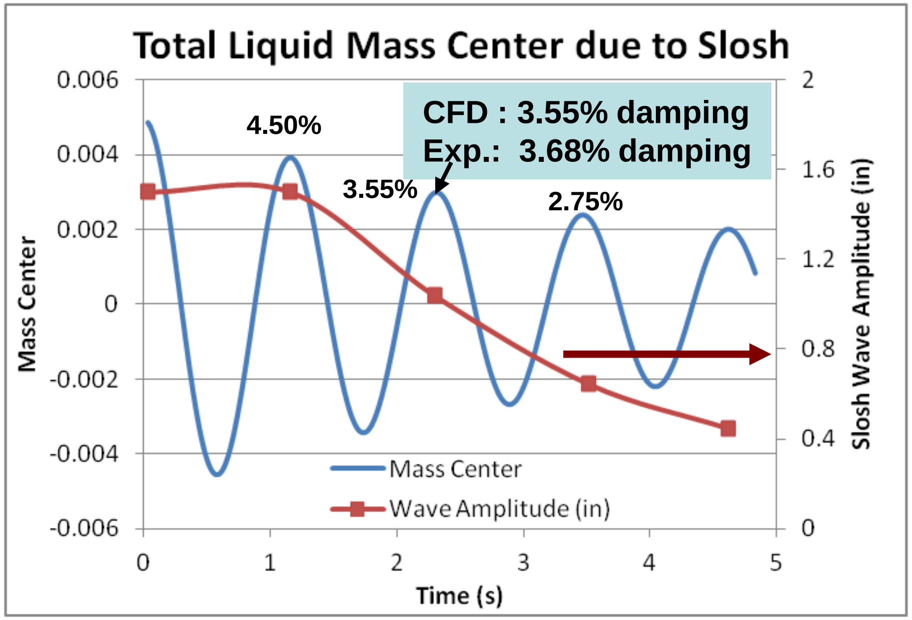
Observations:

- With the existence of baffle, the damping is a function of slosh amplitude.
- Very good agreements with experimental data at the same slosh amplitude of 1”.
- High damping comes from higher modes due to the interaction of surface wave with baffle and local circulations around baffle tip.

Validation for Baffled Tank Damping: h=49.16”

Fill Level Above Baffle, h=49.16”, h_B=43.91”



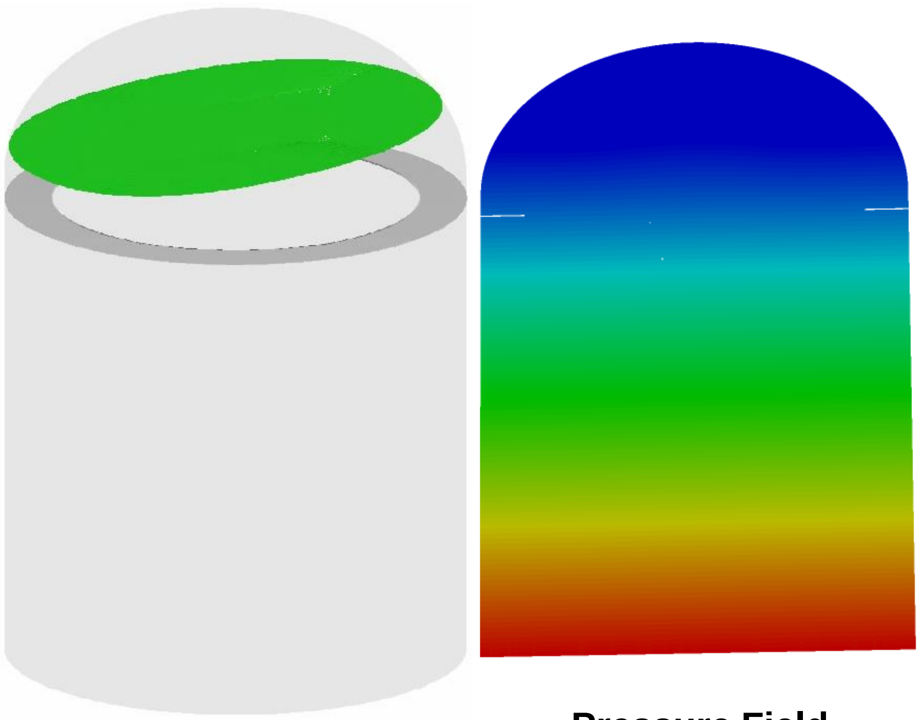


Observations:

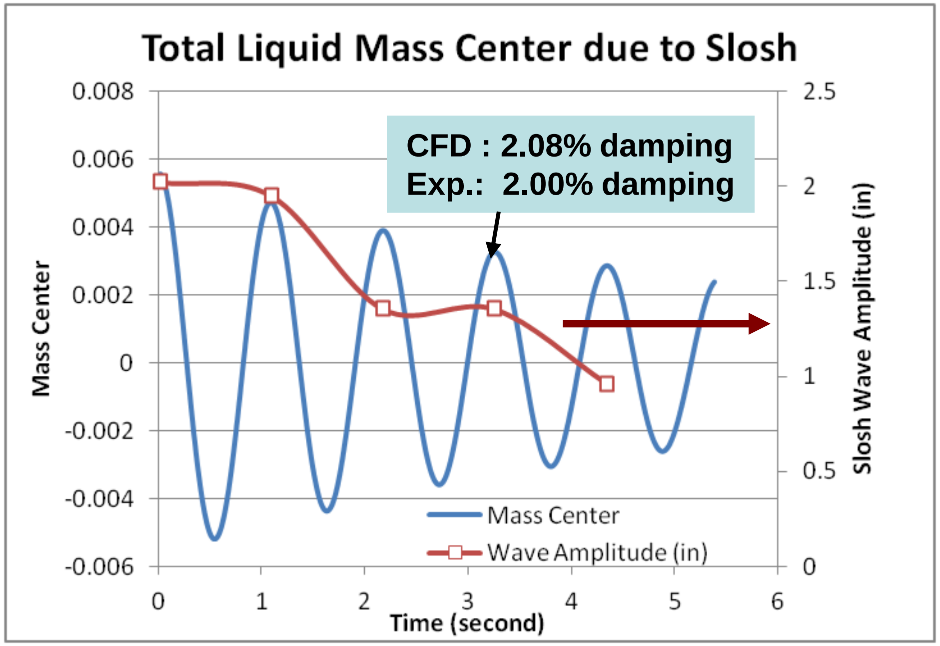
- Damping decreases as fill level is away from the baffle.
- Some viscous shear near the baffle, and small recirculation visible.
- Again, damping is a function of the slosh amplitude. With 1” inch wave amplitude (the same as experiment), CFD prediction agrees very well with experimental measurement.

Validation for Baffled Tank Damping: h=51.19”

Fill Level Above Baffle, h=51.19”, h_B=43.91”



Pressure Field



Observations:

- **Damping decreases as fill level is away from the baffle.**
- **Some viscous shear near the baffle, but small recirculation visible.**
- **Again, damping is a function of the slosh amplitude. With 1” inch wave amplitude (the same as experiment), CFD prediction agrees very well with experimental measurement.**

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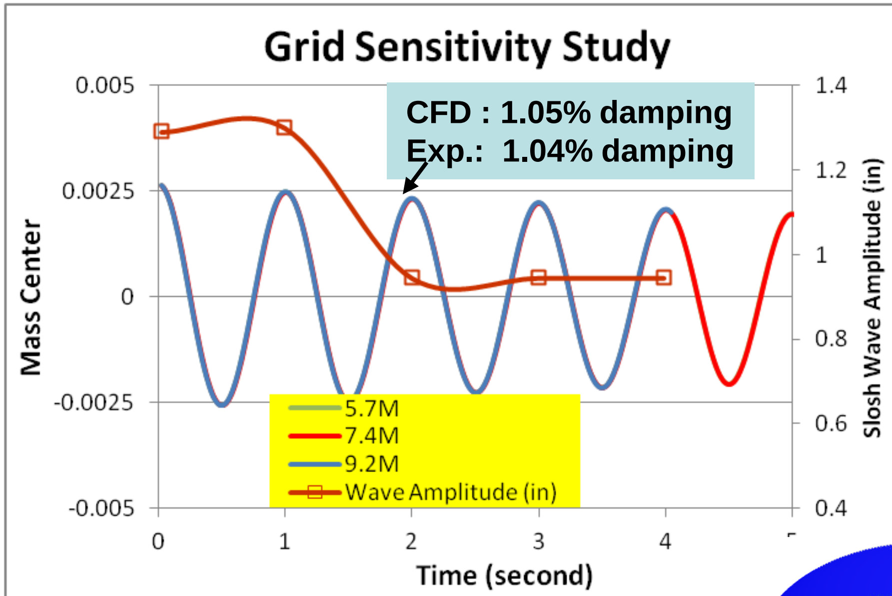
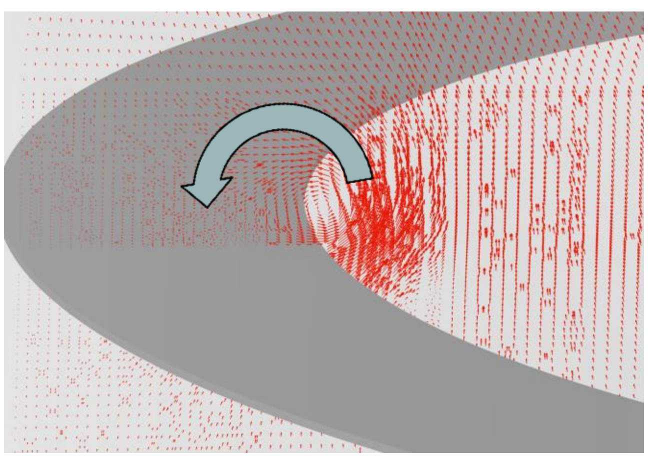
Fill Level in the Dome Section (Grid Refinement Study), h=53.19” h_B=43.91”

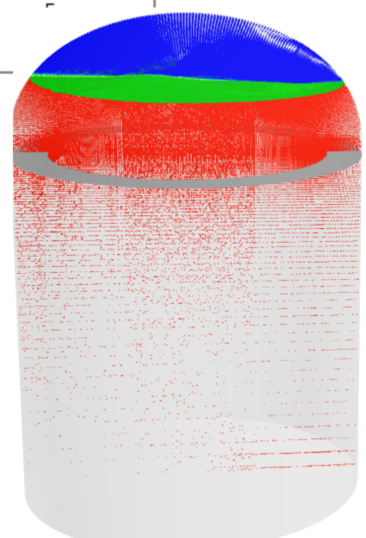
•Grid refinement: 10% increase in each direction; from 5.7M to 7.4M, and to 9.2M.

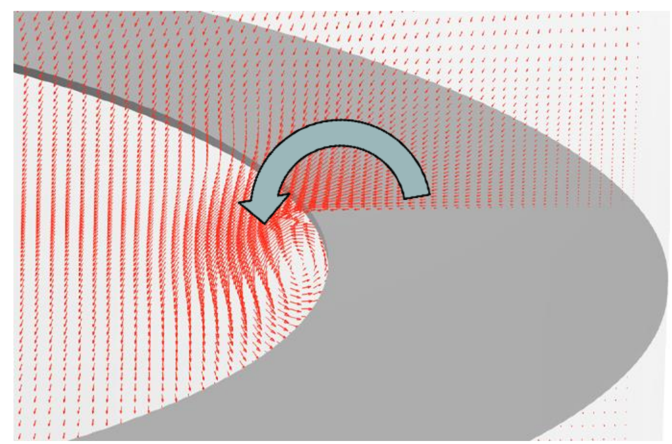


Grid Size	5.7M	7.4M	9.2M	Exp.
Damping	1.05%	1.04%	1.03%	1.04%

- **With 5.7M grid, we have achieved grid independent solution.**
- **Our prediction is in very good agreement with experiment**
- **The enhancement of slosh damping: flow separation around baffle.**







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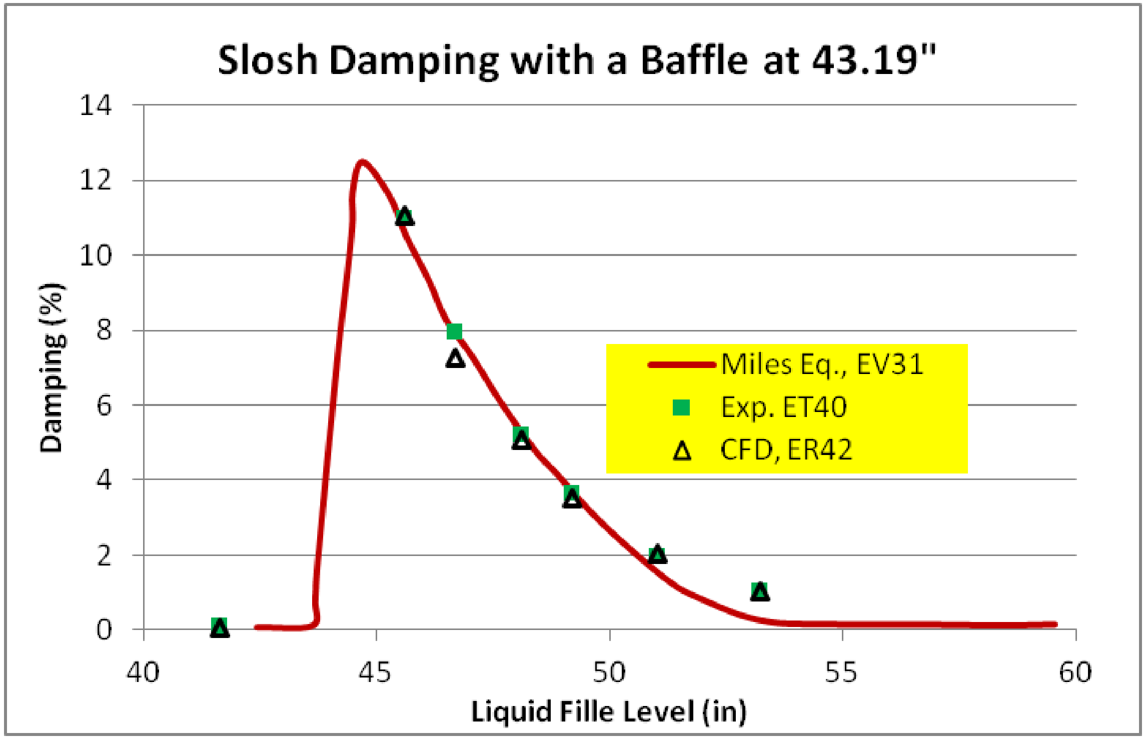
Comparison of Experiment, Analysis (Miles' Equation by EV31) and CFD



Observations:

- **CFD results are in good agreement with experimental data at all fill levels, thus we conclude that using Loci-STREAM-VOF with this procedure for the purpose of predicting Slosh Damping due to a Baffle is validated.**
- **Miles's equation predicts good fit to the experimental data. However, deviations occur in the dome section (high fill levels)**

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Conclusion

Summary

- The predicted slosh damping values from Loci-Stream-VOF agree with experimental data very well for all fill levels in the vicinity of the baffle.
- Grid refinement study is conducted and shows that the current predictions are grid independent.
- The increase of slosh damping due to the baffle is shown to arise from:
  - a) surface breakup;
  - b) cascade of energy from the low order slosh mode to higher modes; and
  - c) recirculation inside liquid phase around baffle.
- The damping is a function of slosh amplitude, consistent with previous observation.
- Miles equation under predicts damping in the upper dome section.