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

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Determination of slosh damping is a very challenging task as there is no analytical solution. The damping physics involve the vorticity dissipation which requires the full solution of the nonlinear Navier-Stokes equations. As a result, previous investigations and knowledge were mainly carried out by extensive experimental studies. A Volume-Of-Fluid (VOF) based CFD program developed at NASA MSFC was applied to extract slosh damping in a baffled tank from the first principle. First, experimental data using water with subscale smooth wall tank were used as the baseline validation. CFD simulation was demonstrated to be capable of accurately predicting natural frequency and very low damping value from the smooth wall tank at different fill levels. The damping due to a ring baffle at different liquid fill levels from barrel section and into the upper dome was then investigated to understand the slosh damping physics due to the presence of a ring baffle. Based on this study, the Root-Mean-Square error of our CFD simulation in estimating slosh damping was less than 4.8%, and the maximum error was less than 8.5%. Scalability of subscale baffled tank test using water was investigated using the validated CFD tool, and it was found that unlike the smooth wall case, slosh damping with baffle is almost independent of the working fluid and it is reasonable to apply water test data to the full scale LOX tank when the damping from baffle is dominant. On the other hand, for the smooth wall, the damping value must be scaled according to the Reynolds number. Comparison of experimental data, CFD, with the classical and modified Miles equations for upper dome was made, and the limitations of these semi-empirical equations were identified.

I. Introduction

Propellant slosh is a potential source of disturbance critical to the stability of space vehicles. The slosh dynamics are typically represented by a mechanical model of a spring-mass-damper. This mechanical model is then included in the equation of motion of the entire vehicle for Guidance, Navigation and Control analysis. The typical parameters required by the mechanical model include natural frequency of the slosh, slosh mass, slosh mass center location, and the critical damping ratio. During the 1960's US space program, these parameters were either computed from an analytical solution for a simple geometry or by experimental testing of subscale configurations. Since the liquid oscillatory frequency may nearly coincide with either the fundamental elastic body bending frequency or the dynamic control frequency of the vehicle at some time during the powered phase of the flight, the slosh forces could interact with the structure or control system. This can cause a failure of structural components within the vehicle or excessive deviation from its planned flight path [1,2]. It is, therefore, necessary to consider means of providing adequate damping of the liquid motions and slosh forces and to develop methods for accounting for such damping in the vehicle performance analyses.

In order to meet the damping requirement by flight control, baffles of various configurations have been devised to increase the natural viscous damping and decrease the magnitude of the slosh forces and torques [1,2]. In the design of slosh baffle, the most widely used damping equation is the one obtained by Miles [3], which is based on experiments of Keulegan and Carpenter [4]. This equation has been used in predicting damping of the baffled tanks in different diameters ranging from 12 to 112 inches [5-12]. The analytical expression of Miles equation is

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easy to use, especially in the design of complex baffle system. An insightful investigation by Cole [9] revealed that some experiments [1,6,and 7] have shown good agreements with the prediction method of Miles [3], whereas other experiments [10-12] have shown significant deviations. For example, damping from Miles equation differs from experimental measurements by as much as 100 percent over a range of tank diameters from 12 to 112 inches, oscillation amplitudes from 0.1 to 1.5 baffle widths, and baffle depths of 0.3 to 0.5 tank radius. Previously, the much of this difference has been attributed to experimental scatter [9]. A systematical study is needed to understand the damping physics of baffled tank, to identify the difference between Miles equation and experimental measurement, and to develop new semi-empirical relations to better represent the real damping physics. The objective of this study is to use CFD technology to shed light on the damping mechanisms of a baffled tank. First, a CFD solver developed at NASA MSCF, Loci-STREAM-VOF, is validated on a baffled tank. The velocity field is then used to shed light on the damping physics at different fill levels. The scalability and applicability of subscale data using water to full scale tank with cryogenic fluid are investigated. Finally, the limitations on the use of Miles equation are discussed.

II. Computational Fluid Dynamics Solver

Fluid Dynamics Branch (ER42) at MSFC has been active in applying CFD technology to extract slosh damping parameters. An early work [13], using commercial CFD code, CFD-ACE+, has demonstrated the soundness of a CFD approach in modeling the detailed fluid dynamics of tank slosh and has shown excellent accuracy in extracting the mechanical properties for different tank configurations as a function of the liquid fill level. The verification and validation studies included a straight cylinder against an analytical solution, and subscale Centaur LOX and LH2 tanks with and without baffles against experimental results for the slosh frequency, slosh mass, and mass center. The study shows that CFD technology can provide accurate mechanical parameters for any tank configuration and is especially valuable for the future design of propellant tanks, as there is no previous experimental data available for the same size and configuration as the current flight designs.

For a practical partially-filled smooth wall propellant tank with a diameter of 1 meter, the damping ratio is as low as 0.0005 (or 0.05%). To accurately predict this very low damping value is a challenge for any CFD tool, as one must resolve a thin boundary layer near the wall and must minimize numerical damping inside the liquid region. To improve the understanding of the physics behind slosh damping, the authors have taken a fundamentally sound approach [14] first with validations against experiments for the smooth wall cylindrical tank. High-order numerical schemes in CFD-ACE+ were applied using a technique developed to estimate and reduce/remove the numerical damping from the solution. It is demonstrated that with proper grid resolution, CFD can indeed accurately predict low damping values from smooth walls for different tank sizes. With the validated CFD model, a study was made with the damping in the presence of a flat ring baffle that is a commonly used as means of slosh suppression. The damping due to ring baffles at different depths from the free surface and for various sizes of the tank was then simulated, and fairly good agreement with experimental correlation was observed.

During the study of the slosh damping, it was found that commercially available CFD programs simulating gas/liquid interfaces using the Volume of Fluid (VOF) approach were limited to approximately 16 to 32 CPU cores in their parallel scalability. In contrast, non-interface CFD applications were demonstrating useful parallel scalability up to 4,096 processors or more. In response to this finding, NASA/MSFC established a path [15] to fulfill its needs by developing a VOF module to augment the general purpose CFD program Loci-STREAM. Loci [16] is a novel software framework that has been applied to the simulations of non-equilibrium flows. The Loci system uses a rule-based approach to automatically assemble the numerical simulation components into a working solver. This technique enhances the flexibility of simulation tools, reducing the complexity of CFD software induced by various boundary conditions, complex geometries, and different physical models. Loci plays a central role in building flexible goal-adaptive algorithms that can quickly match numerical techniques with various physical modeling requirements. Loci-STREAM [17-18] is a pressure-based, all-speed CFD code for generalized grids in the rule-based programming framework Loci. The coupled simulations between flow solver and VOF transport are carried out using the Loci-STREAM flow solver and a VOF Module developed by CFDRC [19]. The final product, Loci-STREAM-VOF, has been applied to practical rocket propulsion-related VOF applications and has shown significant parallel scalability, up to thousands of CPU cores [15].

III. Results and Discussions

Experimental Setup and Data Collection

During the Ares I development, lateral slosh testing of a subscale Ares I Upper Stage (US) Liquid Oxygen (LOX) and Liquid Hydrogen (LH2) tank was conducted at NASA MSFC [8]. The purpose of these tests was to validate the analytical models and to identify possible limitations in the analysis tools [20]. The parameters of interest were slosh mode shapes, slosh frequencies, slosh mass, pendulum hinge point, and damping.

The main elements of the test bed, fixture and instrumentation at NASA MSFC are shown in Figure 1. A rigid aluminum plate was grouted to the concrete floor. Linear rails were bolted to this rigid aluminum plate. A mounting slip plate was attached to these rails with linear bearings. This mounting slip plate provided a "free-sliding" slip table. A fixture consisting of a base plate, support legs, and a tank support ring was bolted to this slip table. The tank support ring was attached to the support legs through three tri-axial ring type force sensors to measure forces due to fluid sloshing and fixture mass. DC capacitive accelerometers in a tri-axial configuration were placed on each support leg to measure the inputs to the tank. An LVDT was attached to the slip table to measure table displacements. Excitation was applied to the slip table by a hydraulic shaker [8]. A dynamic load cell was used to measure the force inputs to the slip table. The test bed and fixture installed, and the test coordinate system are shown in Figure 2.Water fill levels in the tank were measured using two methods. The first method was a real-time measurement using an ultrasonic distance sensor. This sensor was screwed into a hole manufactured in the top of the tank lid. The second method to measure the water fill levels was by using a rod. For this approach, an initial measurement was made from the very top of the tank.

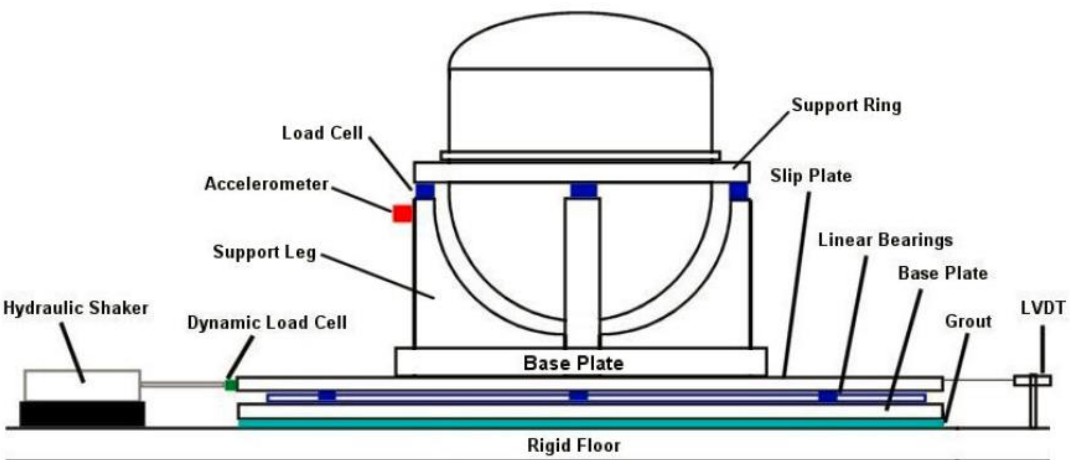


Figure 1. Test bed layout at NSAS MSFC

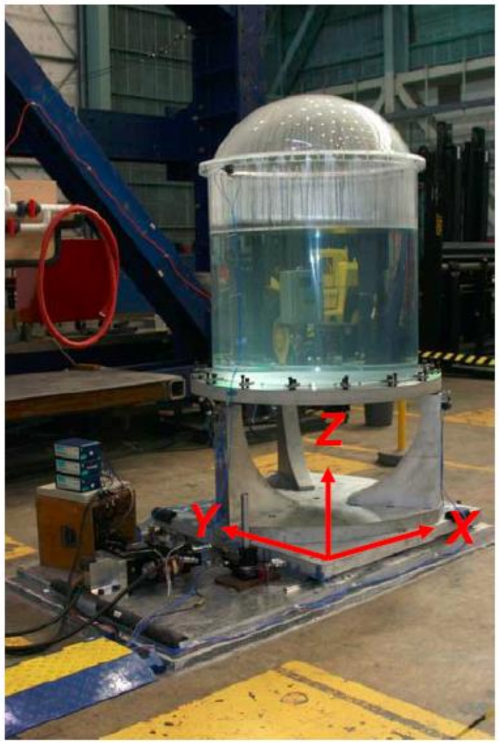


Figure 2. LH2 tank model test setup and coordinate system

In to order measure slosh damping, free decay testing was used to evaluate nonlinear behavior and damping dependency on slosh wave height. In general, excitation was applied as close as possible to the frequency of the first slosh mode. Any significant divergence from the natural frequency caused a "beating" effect on the slosh wave and made it difficult to achieve a steady-state slosh wave. Excitation was increased slowly until a steady state slosh wave height was achieved (typically 1, 2, or 4 inches peak-to-peak). The table was then hard-stopped at a point as close to zero velocity as possible to minimize transient inputs. The hydraulic shaker used to apply the excitation was then used to hold the fixture rigid. Since the shaker armature displacement is controlled in a closed-loop, the shaker controller attempted to maintain the armature at a zero point. This typically caused a small input to the fixture due to the sloshing of the fluid. A small additional amount of damping was observed in lightly damped situations due to this interaction. For this reason, a mechanical stop was implemented to assure that the fixture was held as rigid as possible. Throughput data was acquired at a 100 Hz sample rate during excitation and free decay. This data was post-processed to determine slosh frequency, damping, and pendulum hinge point location.

CFD Model

The simulation under this study is shown in Figure 3. The tank consists of a cylindrical barrel section and a spheroidal upper dome. The tank model diameter and upper dome height were scaled approximately 1/5 of the prototype dimensions, but the barrel section height was scaled a lot shorter than the prototype. The tank model has 43 inches in diameter. The baffle location is at h/R=2.04, and the ratio of baffle width to tank radius, w/R, is 0.204. The liquid tested is water. The CFD model and grid are given in Figure 4. There is a total of 5.7M cells; this number is based on our previous investigation where for a similar sized tank 4 Million cells are needed to resolve smooth wall damping [14]. Grid is packed near the wall and around the baffle as in Figure 4. For grid refinement study, two more grids of 7.4 Million cells and 9.2 Million cells were generated, which represent an increase of 10% and 20%, respectively, in cells account in each direction. The non-slip boundary condition is applied to all the tank walls and baffles.

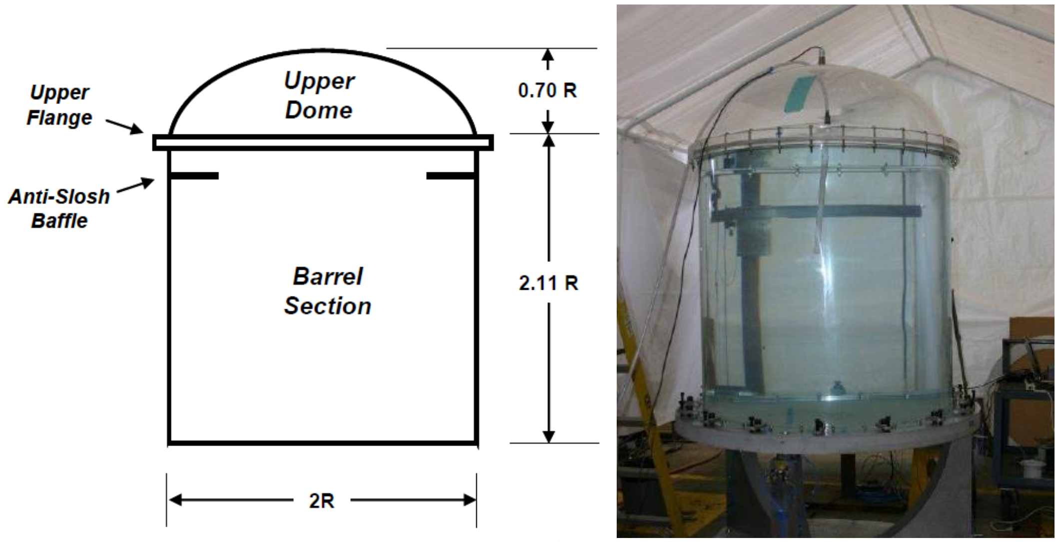


Figure 3. Baffled tank geometry (w/R=2.04)

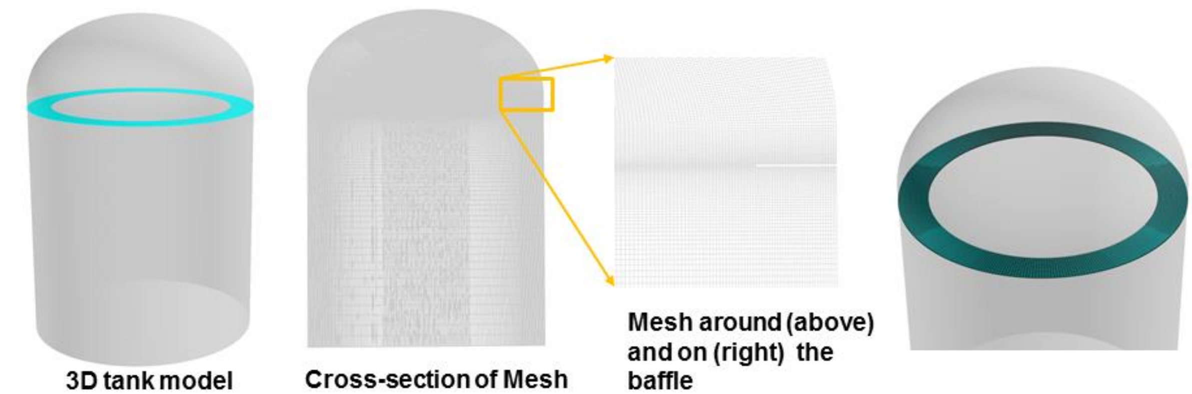


Figure 4 Details of structured mesh constructed to simulate slosh in the baffled tank configuration. Mesh size is 5.7 million cells.

CFD Validation of Slosh Frequency for Smooth Wall Cylinder

Southwest Research Institute has been involved in "sloshing" research since before the start of the US space program. Dr. Norm Abramson, then the leader of the sloshing group has organized and published a monograph [1] which contained very comprehensive knowledge on both experimental and analytical results of sloshing and related subjects. The analytical solutions were derived for simple geometries such as rectangular boxes or the cylindrical tank with flat bottom face. These analytical solutions have been widely used to get mechanical parameters (mass, frequency, damping, mass center) for the preliminary design and for sloshing model input into space vehicles. In reality, the analytical results are applicable only to the simple geometries such as cylindrical and spherical tanks. CFD can become a powerful tool in predicting these parameters for realistic propellant tanks after systematic validation. It is noted that for the model in Figure 4 when the liquid fill level is below the baffle which is located at h/R=2.04, the problems becomes a slosh dynamics in a straight cylinder where the analytical solution of Abramson [1] can be used for verification for CFD and for the calibration of experimental measurement.

The analytical solution for slosh frequency f in a straight cylinder can be written as a function of tank radius R, acceleration level g, and fill level h[1]:

$$f = \frac{1}{2\pi}\left(\frac{1.841g}{R}\tanh\left(\frac{1.841h}{R}\right)\right)^{1/2}; \text{frequency parameter}: \phi = \frac{2\pi f}{\sqrt{R/g}} \tag{1}$$

In our CFD simulation, the initial gas-liquid surface is prescribed with a sinusoidal functional form, the mass center displacement and net forces on the tank wall are recorded. Given in Figure 5 is the comparison of slosh force in the slosh direction (x) from CFD and that from experimental measurement. It is clear CFD solution follows closely with the experimental measurement in terms of the magnitude, frequency and decay rate of the slosh force.

Based on the free decay response, it is possible to extract the slosh frequency at different fill levels. Given in Figure 6 is the variation of the total mass center at different fill levels computed from Loci-STREAM-VOF. Due to bottom wall effect, one can observe the increase of slosh frequency with fill level. The resulting non-dimensional frequency parameter, as defined in Equation (1), is plotted in Figure 7. The frequency actually becomes constant once the fill level h/2R is approaching 1.0. Here, the simulation results of Loci-STREAM-VOF for frequency are consistent with the analytical solution. On the other hand, the fact that test data agrees with analytical solution further verifies the measurement technique and data processing as evident from Figure 7.

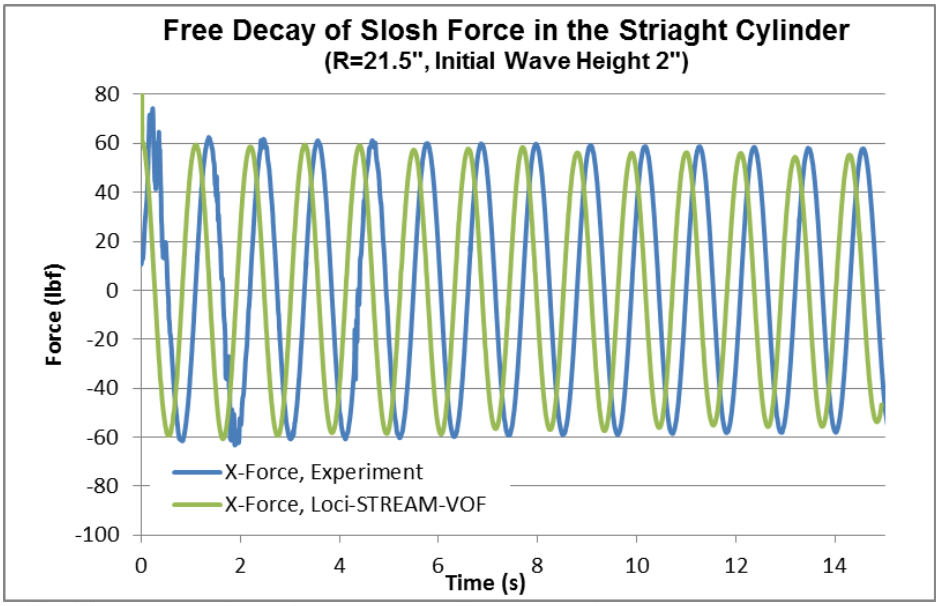


Figure 5. Comparison of slosh force from experiment and from CFD during free decay in the cylindrical section of the tank.

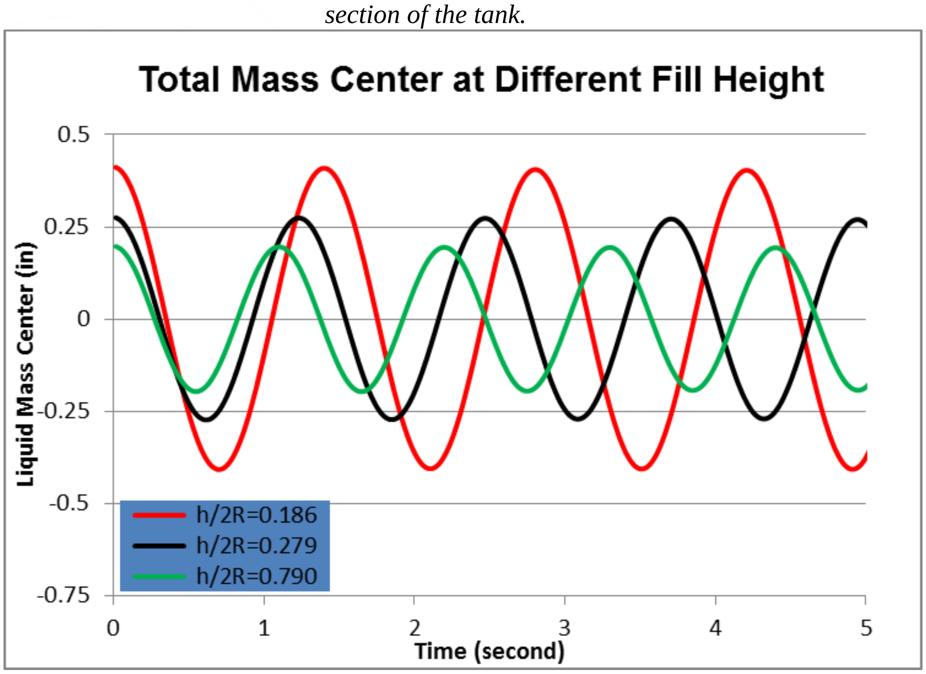


Figure 6. Total mass center displacement at different liquid fill levels inside the straight cylinder, R=21.5".

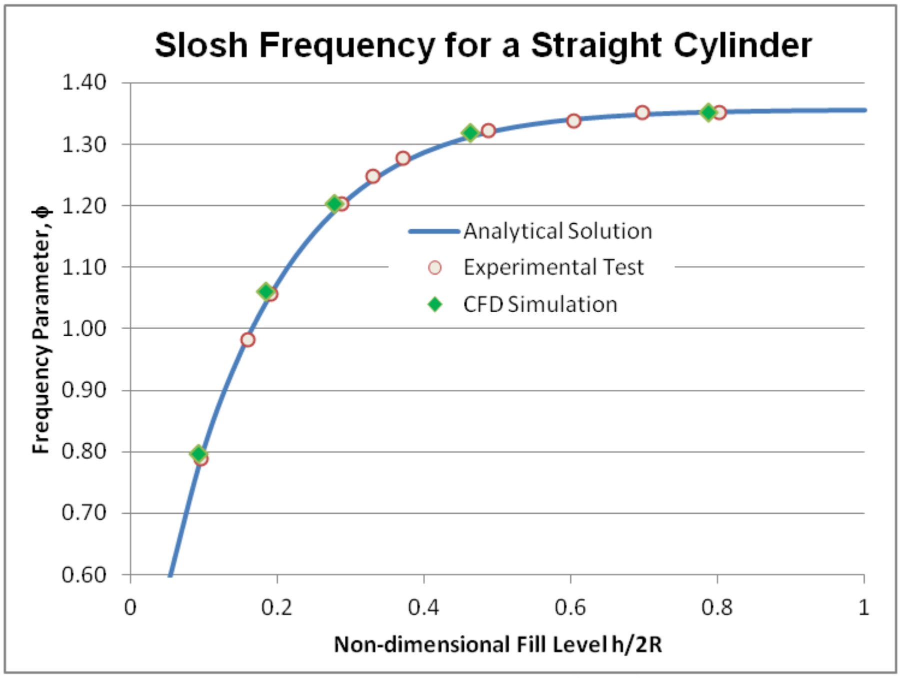


Figure 7. Frequency as a function of liquid fill level in a straight cylinder.

CFD Validation of Slosh Damping for Smooth Wall Cylinder

In our previous study [14], it was shown that the determination of slosh damping in a given tank configuration is a very challenging task. First, an analytical solution does not currently exist for the slosh damping due to high nonlinearity of the problem. While slosh frequency can be computed using linear potential theory, the damping physics involves the vorticity dissipation that requires the full solution of the nonlinear Navier-Stokes equations. Previous investigations and knowledge of damping characteristics were mainly carried out by extensive experimental studies.

Previous Slosh Damping Correlation for Smooth-Wall Cylindrical Tank

Four extensive experimental studies have been carried out on viscous damping in circular cylinders [21-24] during 1960's, and the damping values have been correlated with a functional form of:

$$\zeta = C\sqrt{\mathrm{Re}} \tag{2}$$

where Re is a dimensionless parameter analogous to an inverse Reynolds number [2]:

$$\mathrm{Re} = \frac{\nu}{\sqrt{gR^3}} \tag{3}$$

and C is a constant, ζ is the damping ratio or the critical damping ratio of the amplitude of the free surface oscillation. R is the tank radius, g is the gravity acceleration and ν is the kinetic viscosity of the liquid.

Mikishev and Dorozhkin [24] proposed the following correlation from their tests:

$$\zeta = 0.79\sqrt{\mathrm{Re}}\left[1+\frac{0.318}{\sinh(1.84h/R)}\left(1+\frac{1-h/R}{\cosh(1.84h/R)}\right)\right] \tag{4}$$

where h is the liquid depth. For large depth of h/2R > 1.0, the above equation may be approximated by:

$$\zeta = 0.79\sqrt{\mathrm{Re}} \tag{5}$$

A similarly extensive but independent study by Stephens *et al.* [23] found a slightly different correlation:

$$\zeta = 0.83\sqrt{\mathrm{Re}}\tanh(1.84\frac{h}{R})\left[1+2\frac{1-h/R}{\sinh(3.68h/R)}\right] \tag{6}$$

When the liquid depth is large, Equation (6) reduces to:

$$\zeta = 0.83\sqrt{\mathrm{Re}} \tag{7}$$

The above correlations have become industry standard methodology to compute slosh damping value over a smooth wall.

In order to make comparison to experimental damping value, we need first develop a damping extract technique from CFD. During the previous slosh damping tests, the following quantities have been measured as a function of time: the force acting on the tank due to slosh; lateral displacement of the tank and platform; amplitude of the surface wave at the wall; and the vertical force on the ring baffle. Due to different quantities measured, there are five different methods of extracting slosh damping [1,2,and 26]: ring force method; drive force method; wave amplitude response method; wave amplitude decay method; and wave force decay method. The methods the most related to the current study are:

a) *Wave Amplitude Decay Method*, by which the free surface wave heights at the wall are measured after the excitation has ceased. From the ratio of successive wave heights the logarithmic decrement and damping ratio are obtained.

b) *Wave Force Decay Method*. The tank is driven at a frequency close to the resonant frequency of the principal slosh mode. The motion of the tank is abruptly stopped after the wave height is sufficient and the drive link firmly anchored. The force in the drive link is recorded. If the system is assumed to be linear, then the peak wave amplitudes are proportional to the peak force amplitudes. The ratio of successive peak forces can be used to compute the damping ratio.

To have a better understanding of the extraction of slosh damping, let us look at the mass-spring-damper equation of:

$$m\ddot{x} + c\dot{x} + xk = 0 \tag{8}$$

Or, in the critical damping form:

$$\ddot{x} + 2\zeta\omega_0\dot{x} + \omega_0{}^2 x = 0; \quad \omega_0 = \sqrt{\frac{k}{m}}; \quad \zeta = \frac{\mathrm{c}}{2\omega_0 m} \tag{9}$$

The solution to the above equation is as follow, and it is represented in Figure 8.

$$x(t) = c_1\exp\left[(-\zeta + i\sqrt{1-\zeta^2})\omega_0 t\right] + c_2\exp\left[(-\zeta - i\sqrt{1-\zeta^2})\omega_0 t\right] \tag{10}$$

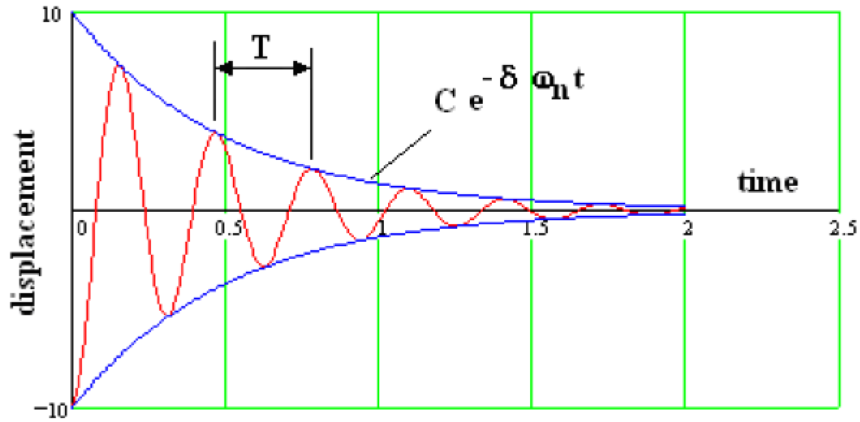


Figure 8. Free decay of an under damped system

For an ideal system with constant damping as shown in Figure 8, the critical damping ratio can be computed by:

$$\zeta = \frac{1}{2\pi n} \ln \frac{A_m}{A_{m+n}} \tag{11}$$

where A_m is the amplitude of the m^{th} cycle. However, for a real dynamic system, the amplitude does not necessarily follow the curve shown in Figure 8. As an example, the natural log of the force amplitude, shown in Figure 5, as the number of cycle is given in Figure 9. This wavy form of wave peak amplitude can be caused by the non-linearity in the system, and/or by the initial high modes in the system. Apparently, depending on the selection of m and n, one can have different damping value. In our approach, the damping ratio is computed by first recording the positive and negative peak values and then by plotting the natural log of the absolute peaks as a function of peak index as depicted in Figure 9. The slope of the best fit line is the damping factor. The damping percent is computed by multiplying the damping factor by 100 divided by the quantity 2 times PI.

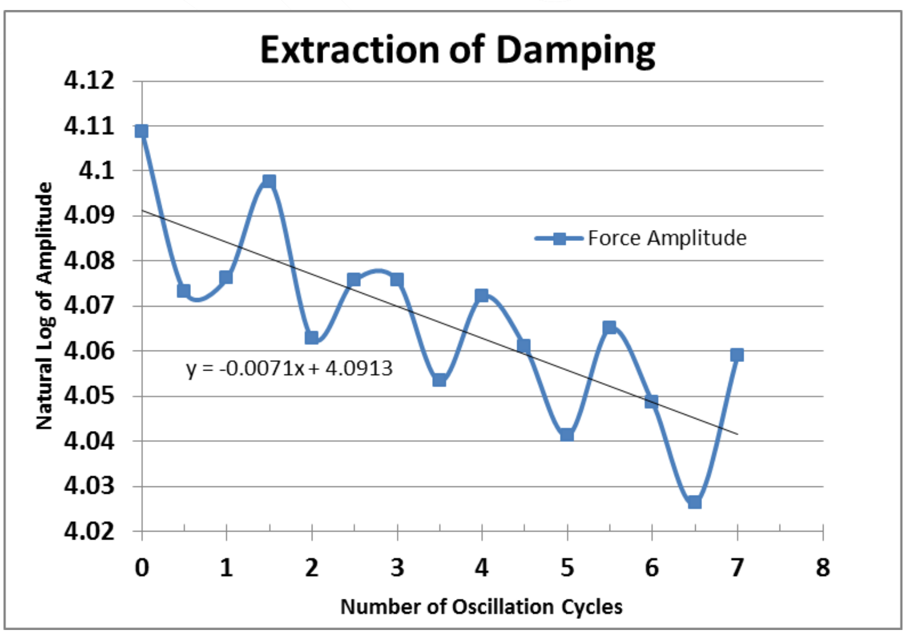


Figure 9. Computation of damping ratio by linear fit of the natural log of the absolute peak values.

The results of the empirical correlations, experimental data, and CFD simulation results of Loci-STREAM-VOF for the straight cylinder at different fill levels are shown in Figure 10 for the critical slosh damping. At high fill level of h/2R near 1.0, the damping is almost a constant value. As fill level decreases, there is an increase in the wetted area to the slosh volume, so that damping increases. The CFD simulation matches with the experimental data really well for all fill levels. The Root-Mean-Square error between CFD and experiment is 4.79% and the maximum error is 8.33%. One can see that the empirical correlation under-predicts the critical damping at low fill levels.

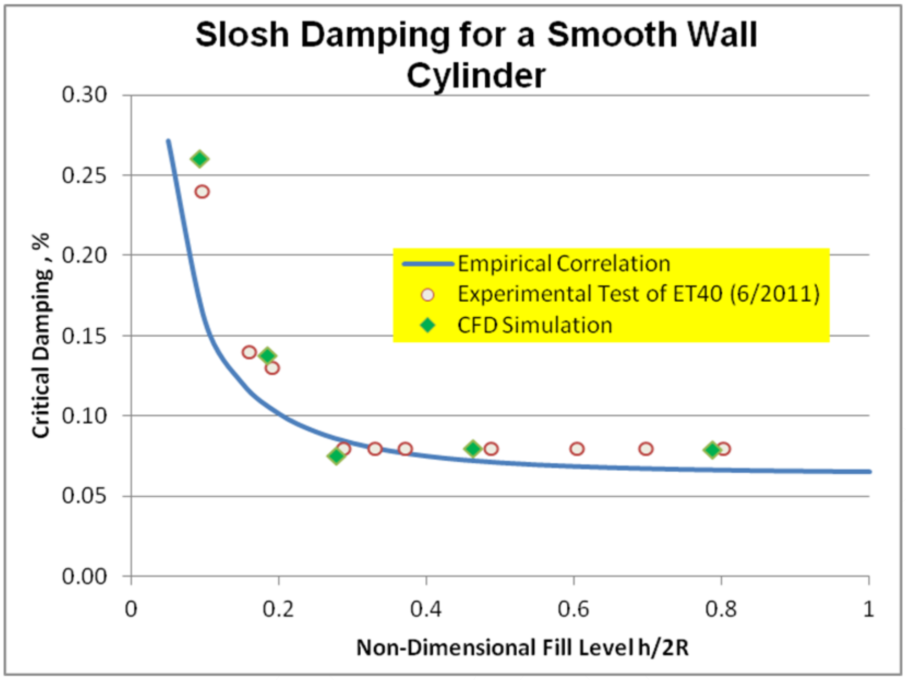


Figure 10. Critical damping as a function of liquid fill level in a straight cylinder

CFD Validation for Baffled Tank

Next, we study the case when the liquid fill level is above the baffle. A hexahedral mesh was constructed with a total of 5.7 Million cells. This number of cell count is based on a previous study for a similarly sized tank [14]. The nature of the mesh is depicted in Figure 4. The baffle has a width to tank radius ratio of w/R=0.204. The fluid initial condition chosen was a linear profile rotated an angle with respect to the gravity vector that was oriented downwards. The velocity and initial pressure conditions were quiescent and constant pressure respectively. The baffle is located at a tank height of h/R=2.042. The fill levels investigated were all above the baffle station and were: h/R=2.086, 2.119, 2.169, 2.236, 2.286, 2.381, and 2.474. The initial condition of the interface is an inclined flat surface with a wave height of 1.0" at the wall when the liquid surface is close to the baffle and a wave height of 0.6" when it is away from the baffle. The damping value when the wave reaches 0.5" is computed and compared to experimental measurement around the same wave height of 0.5".

A snapshot of the CFD solution for the fill level of h/R=2.086, where $h_s/R=0.044$, is shown in Figure 11. Here the liquid level is just above the baffle. The liquid surface's interaction with the baffle has resulted in a significant deformation of the fluid-gas interface, leading to surface roll-up and trapped gas bubbles above and below the baffle. Velocity vectors indicate significant secondary flows above the baffle. The strong vorticity inside fluid contributes to high slosh damping. A similar complex flowfield with the interaction of vorticity from baffle and free surface are visible from Figure 12 at h/R=2.169, or at $h_s/R=0.127$.

The interaction of vorticity inside fluid field with the free surface leads to high slosh damping of the fluid motion. It is expected that damping is not only a function of distance from free surface to the baffle, but also the wave amplitude. As the experimental data were processed around 0.5" inch wave height, we will extract the damping at the same wave height value. Shown in Figure 13 is the mass center variation with time at h/R=2.287, $h_s/R=0.244$. The approximate wave height from flow visualization is also plotted on the right. The mass center displacement represents the bulk fluid motion, and is used in reduced order slosh dynamics, because of this, the damping will be evaluated from the free decay of mass center displacement rather than from the wave heights.

Because the damping is a function of wave amplitude for the baffled tank, we will take three peaks, including both positive and negative peaks (see Figure 14), to compute the local damping value. As one can see, at 0.5" wave height, CFD-predicted slosh damping, 3.55%, agrees with experimentally measured damping of 3.68%.

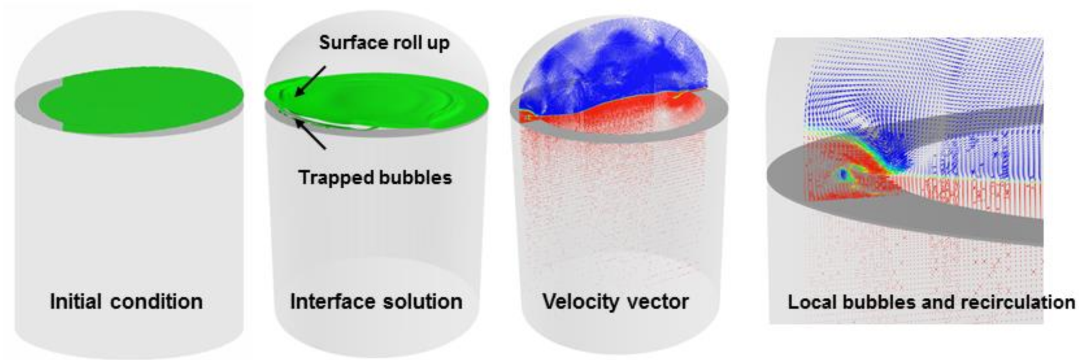


Figure 11 Details of CFD flow field for the fill level of h/R=2.086, h_s/R=0.044. The fluid-gas interface is shown in upper left. The velocity vectors are colored by fluid density with red indicating liquid phase.

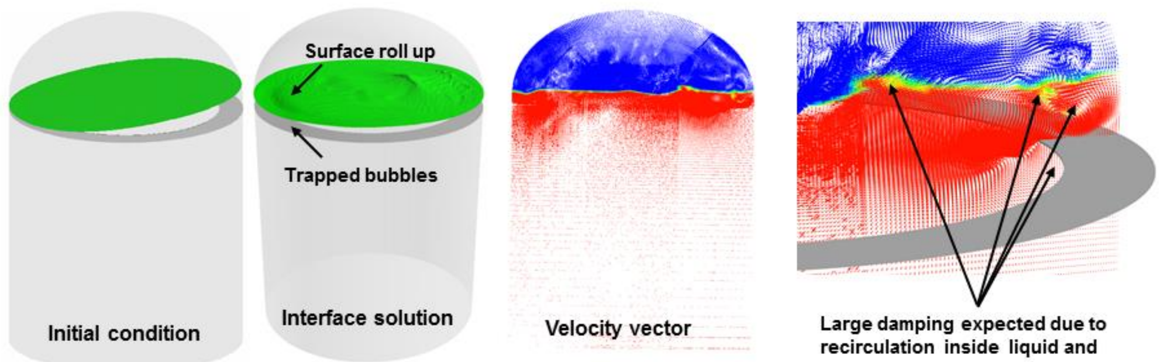


Figure 12 Details of CFD flowfield for the fill level of h/R=2.169, h_s/R=0.127. The fluid-gas interface is shown in upper left. The velocity vectors are colored by fluid density with red indicating liquid phase.

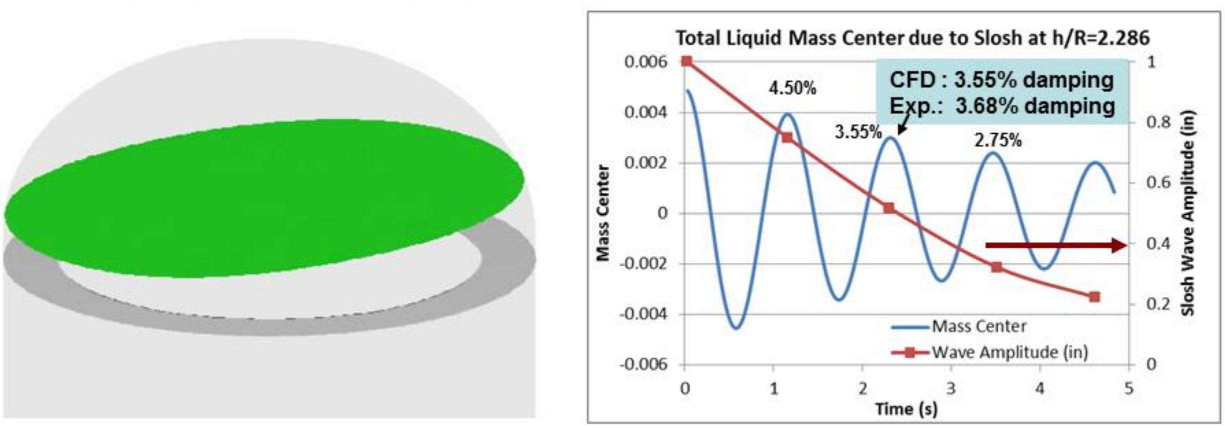


Figure 13. Total mass displacement due to slosh. The damping value computed from the decay and comparison to experiment at h/R=2.286, h_s/R=0.244.

A snapshot of the CFD solution for the fill level of h/R=2.236 (h_s/R=0.194) is shown in Figure 14. Now during the oscillation cycle the interface will stay on the top of the baffle. The damping value is lower than the previous cases. The damping mechanism is again due to the vorticity around the baffle.

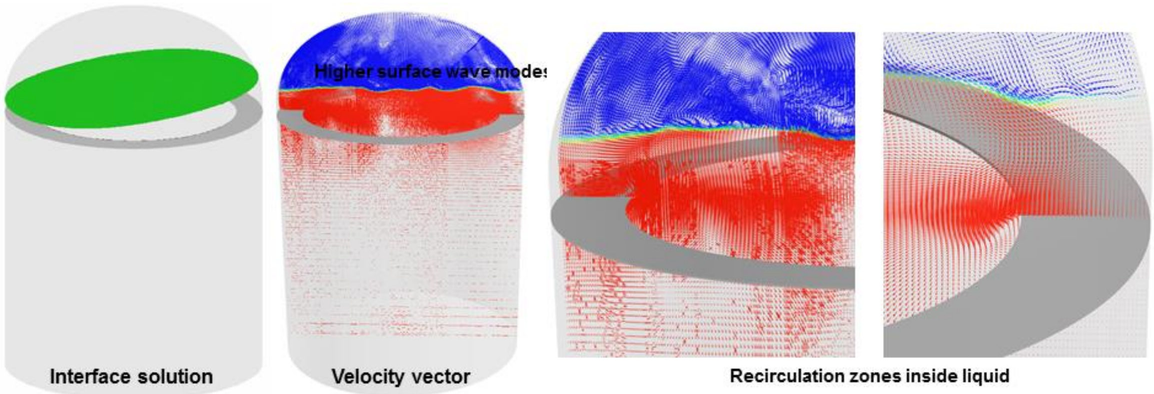


Figure 14 Details of CFD flow field for the fill level of h/R=2.236. The fluid-gas interface is shown in upper left. The velocity vectors are colored by fluid density with red indicating liquid phase.

CFD extracted damping values at 0.5" wave height at different liquid levels and those from experiment are shown in Figure 15. The horizontal axis is non-dimensional liquid fill level above the baffle (h_s/R). Near the baffle, the damping is rather high, and the effect of the baffle decreases as liquid surface is further away from the baffle. CFD results are in very good agreement with experimental data at all fill levels, thus we can conclude that using Loci-STREAM-VOF with the present procedure for the purpose of predicting slosh damping due to a baffle is validated. The Root-Mean-Square error between CFD and experiment is 4.20% and the maximum error is 8.38%.

To ensure the grid independent solution from CFD, grid refinement study is conducted with two more grid cells of 7.4 Million and 9.2 Million. This corresponds to 10% and 20% increase, respectively, in cell counts in each dimension. The fill level is at h/R=2.47. The results are shown in Figure 18. It is apparently that the current solution is indeed grid independent.

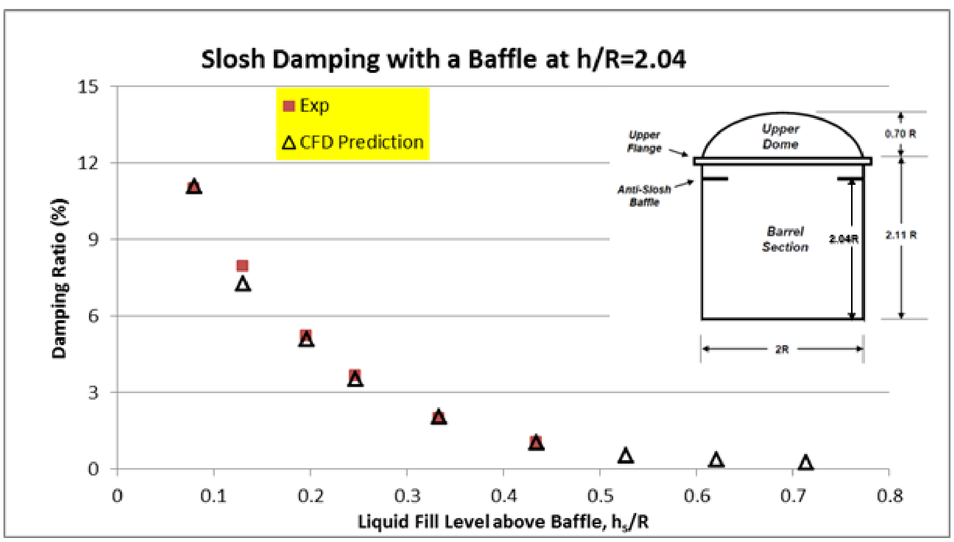
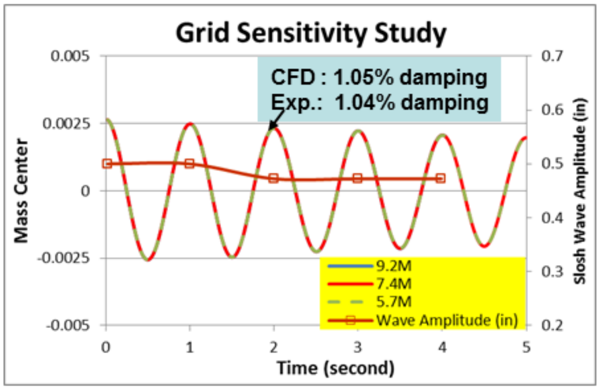


Figure 15. Comparison of damping ratio from CFD and experiment due to an anti-slosh baffle at 0.5" wave height.



Grid refinement Study at h/R=2.47

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%

Solution is grid independent

Figure 16. Grid sensitivity study for the baffled tank.

Evaluation of Miles Equation for the Upper Dome

The original Miles Equation

Baffles are extensively used in various industrial applications to suppress sloshing, modify dynamic features of the coupled 'fluid-structure' mechanical systems and to increase the overall structural damping. Fuel-slosh damping by ring baffles in cylindrical tanks has been investigated both theoretically and experimentally [1-15]. A survey of damping measurements obtained in various experiments shows many apparent discrepancies. The most widely used damping equation at present is the one derived by Miles [3] which is based on experiments of Keulegan and Carpenter [4]. The equation is written as:

$$\zeta = 2.83e^{-4.6(h_s/R)}C_1^{3/2}(\frac{\delta}{R})^{1/2}; \qquad C_1 = \frac{w}{R}(2-\frac{w}{R}) \tag{12}$$

Here, h_s, w, and C_1 respectively denote the baffle depth, width and blockage ratio, while δ, R denote the slosh wave amplitude and local tank radius. These symbols are shown in Figure 17. On the right-hand side of Figure 17 is the comparison of the above equation to the test data [2].

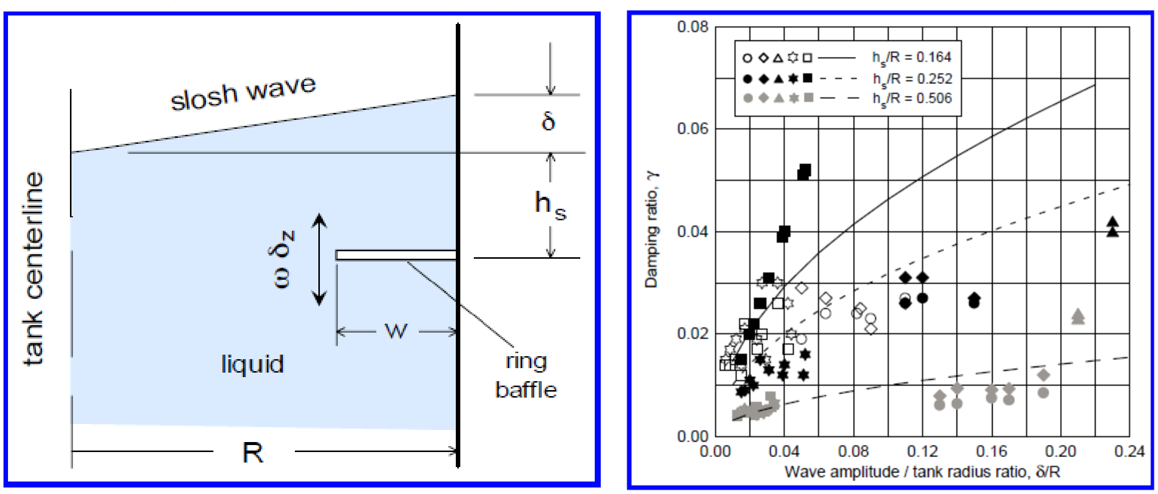


Figure 17. Schematic of ring baffle and damping in a cylindrical tank

The Generalized Miles Equation for the Upper Dome of a Tank

The above Miles equation is derived from a straight cylinder. A generalized damping theory has been derived as [2,20]:

$$\zeta = \frac{15(4/3\pi)^2 C_1 A f_d^{\,2.5} \sqrt{\delta w}}{2\sqrt{\pi}(m_s/\rho)\Gamma^2} \tag{13}$$

m_s is the slosh mass, A is the tank cross-sectional area, Γ is number that depends on the tank shape. It relates slosh mass displacement to the wave height:

$$x_{\max} = \Gamma \delta \tag{14}$$

f_d is a depth function

$$f_d = e^{-1.84 h_s / R} \tag{15}$$

Shown in Figure 18 are the damping curves from Miles equation and the generalized Miles equation. The experimental data and CFD simulation values are also given. As noted above, the original Miles equation was derived for the barrel section of a cylindrical tank. At h_s/R =0.079, where the fill level is just above the barrel, Mile equation agrees with experimental data rather well. However, as the liquid fill level further reaches into the dome section, the original Miles equation deviates from experimental data, and consistently over predicts the damping value. A modification or a different formulation must be derived to prevent the non-conservativeness in the baffle design. One of the modifications is to use the generalized damping equation (13). It is seen from Figure 18 that the generalized Miles equation predicts the damping rather well in the first part of the dome where the h_s/R <0.3. For fill level when deep into the dome, the generalized Miles equation gives almost zero damping from the baffle. This is not what is seen from CFD solution. One expects continuous contribution of the baffle on the slosh. In a practical baffled tank design, there is a minimum damping requirement for the dome section. The prediction using the generalized Miles equation fails to provide physical damping in the upper dome due to the presence of a baffle. There is need to further develop a reliable semi-empirical correlation for the upper dome.

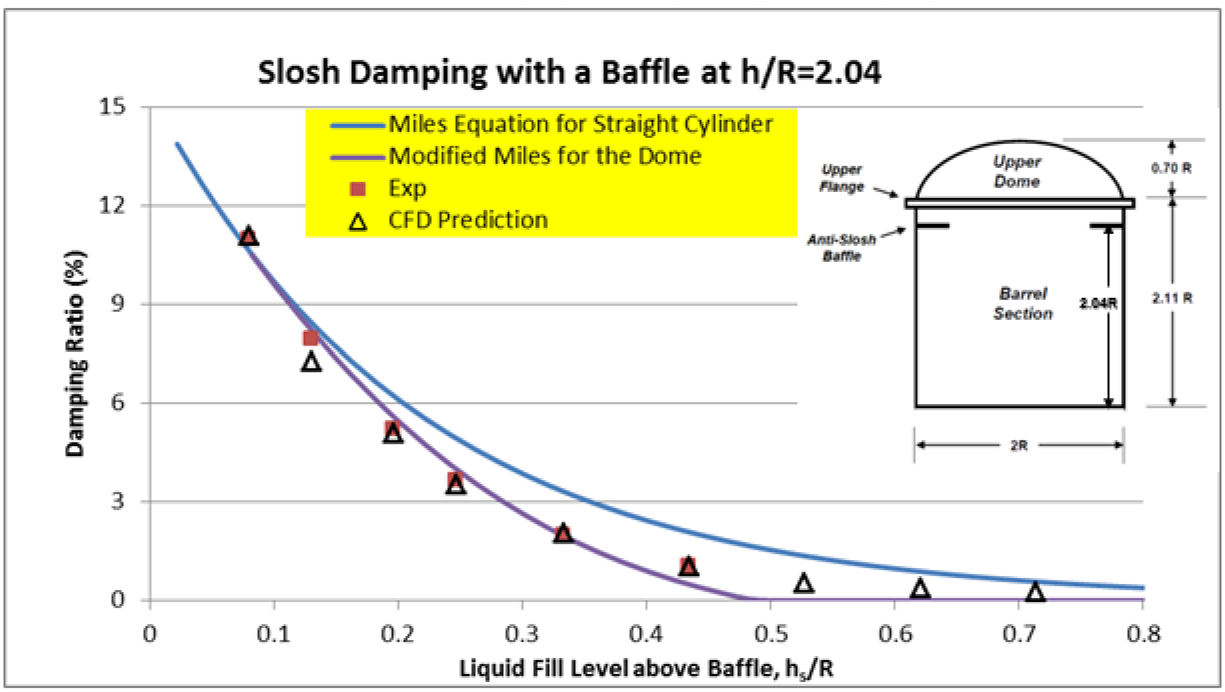


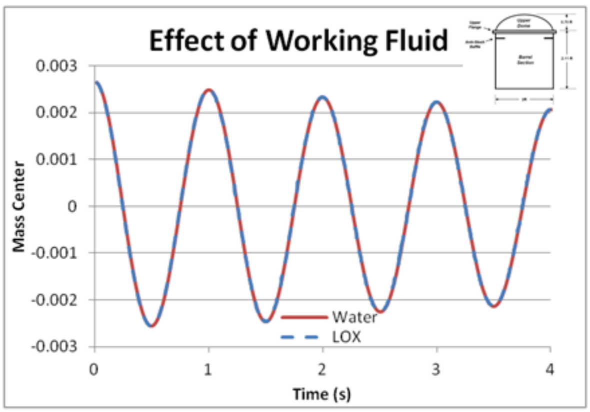
Figure 18. Comparison of damping ratio from CFD, experiment, and various versions of Miles equation due to an anti-slosh baffle.

Evaluation of Working Fluid and Tank Size on Baffle Damping

It is noted that the majority of previous baffle damping experiments were conducted using water at subscale. The question is : can the results be applied to full scale tank and to the working fluids of either LOX or LH2. The above validation study builds confidence on using CFD tool to study the scalability of baffle damping.

First we study the effect of working fluid. The main variation is to change the fluid density from water to LOX, or from 103kg/m^3 to 1141 kg/m^3, and to change the dynamic viscosity from 855x10^{-6} kg/m-s to 268x10^{-6} kg/m-s. It should be pointed out that LOX viscosity is almost 3times less than that of water. Given in Figure 19 is the results of mass center displacement at a fill level of h/R= 2.40. Even with a viscosity ratio of 3, the slosh responses from water and from LOX are almost the same. Unlike the smooth wall case, slosh damping with baffle is nearly independent of the working fluid in this case. It is, therefore, reasonable to apply water test data to the LOX when the damping from baffle is dominant. For the smooth wall, however, the damping value must be scaled according to the Reynolds number.

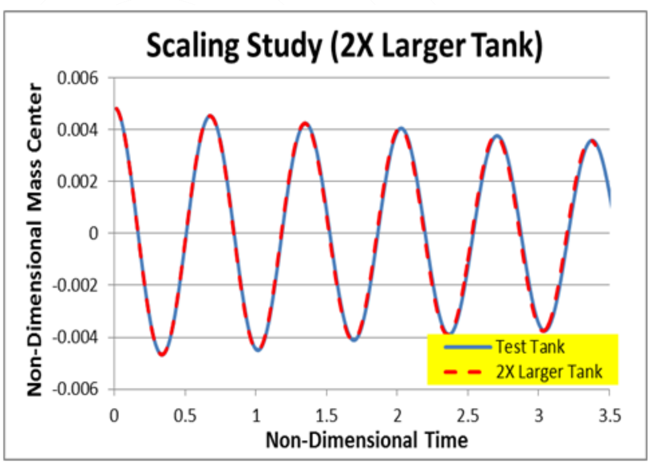
To study the tank size effect, the original grid is scaled by a factor of 2, where the tank radius is doubled. The total grid cell number keeps the same. The initial wave amplitude will also be doubled. As the frequency is the function of the tank size, the time will be scaled by $2\pi\sqrt{R/g}$. The dimensionless mass displacements for two tanks with different sizes are shown in Figure 20. One can see that the slosh damping with baffle is scalable. This exercise verifies the previous damping correlation for the baffled slosh tank. It is reasonable to apply subscale test data to the full scale tank.



Effect of Working Fluid from Water to LOX at h/R=2.47
(density: 1000-> 1141 kg/m3, viscosity: 855x10-6 to 268x10-6 kg/m-s)

Fluid	Water	LOX	Exp.
Damping	1.05%	1.04%	1.04%

Figure 19. Study of working fluid for baffled tank.



Effect of Tank Size at h/R=2.47
(Increase Tank Radius from 21.5" to 2X of 43")

Tank Size	R 21.56"	R (2X) 43.12"	Exp. 21.56"
Damping	1.05%	1.05%	1.04%

Figure 20. *Study of tank size for baffled tank*

IV. Conclusion

A fundamental first principles-based approach has been undertaken to validate a highly parallel CFD solver, Loci-STREAM-VOF developed at NASA MSFC. Comparisons are made against experimental data whenever possible. The cases include a flat bottom cylindrical tank with different fill levels, and a baffled cylindrical tank with an upper dome. The prediction of slosh frequency, amplitude and damping rate for smooth wall and baffled tanks has been presented and compared to experimental data . Based on all our studies, the Root-Mean-Square Error of our CFD simulation in estimating slosh damping for all the above cases is less than 4.8%, and the maximum error is less than 8.5%. The CFD study also finds that for smooth wall tanks, the slosh damping is a strong function of fluid properties (viscosity and density). Unlike the smooth wall, slosh damping with baffles is almost independent of the working fluid at fill levels where the baffle damping contribution is dominant, one has to be very careful in interpreting damping from water to LOX due to the above points. On slosh damping scalability, slosh damping with baffle is scalable. The results from this study support the use of subscale data for the development of damping correlations for baffled tanks. It is reasonable to apply subscale test data to the full scale tank.

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