

# Gas Phase Effects on Slosh Dynamics

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**Gas phase effects on slosh dynamics were quantified using computational fluid dynamics (CFD) simulation for a range of propellant and ullage gas combinations. Historical slosh modeling using potential flow solutions typically neglects gas phase effects. Regardless, the results have been shown to compare well with slosh ground tests typically performed with water and air at standard temperature and pressure. CFD analysis reveals that as the liquid-to-gas density ratio decreases, slosh dynamics change due to the relative increase in gas inertia and thus influence on liquid motion. The result is a profound impact on slosh dynamics over certain parameter spaces particularly for liquid hydrogen. Gas phase effects on slosh dynamics should be considered in slosh models especially for liquid hydrogen propellant tanks.**

## I. Introduction

The Fluid Dynamics Branch at the NASA Marshall Space Flight Center supports slosh model development for 1<sup>st</sup> and 2<sup>nd</sup> stage propellant tanks of the Space Launch System (SLS) rocket among other customers. Historical modeling approaches based on potential flow theory [1][2] are used for many slosh model parameters which are supplemented by recent theoretical, computational, and experimental work for damping quantification [3]. CFD simulation of liquid hydrogen (LH2) propellant tanks at flight-like conditions resulted in differences from both historical modeling approaches and the breadth of water-and-air ground test data even when corrected for liquid properties [1][4]. A study was begun to identify the cause of the observed differences in slosh model parameters.

Parametric study of slosh dynamics for a generic large propellant tank reveals that liquid-to-gas density ratio is the primary reason for the observed differences. CFD simulation was shown to compare very well with potential flow solutions of non-damping slosh model parameters for high liquid-to-gas density ratios. For fluid properties like water and air ground test setups or typical liquid oxygen (LOX) propellant tanks, liquid dynamics dominate the bulk slosh motion. Gas inertia and thus dynamics become important as fluid properties move towards those for high pressure liquid methane (LCH4) and LH2 propellant tanks. Slosh model parameter dependencies on liquid-to-gas density ratio are provided here to help inform the aerospace community of the need to account for this effect in future modeling efforts.

## II. Background

*Descriptions of slosh modeling procedure and model parameter calculation from simulation results will be placed here. A description of a mechanical analogue for the slosh system and method of prediction of slosh model parameters with low liquid-to-gas density ratios will also be added.*

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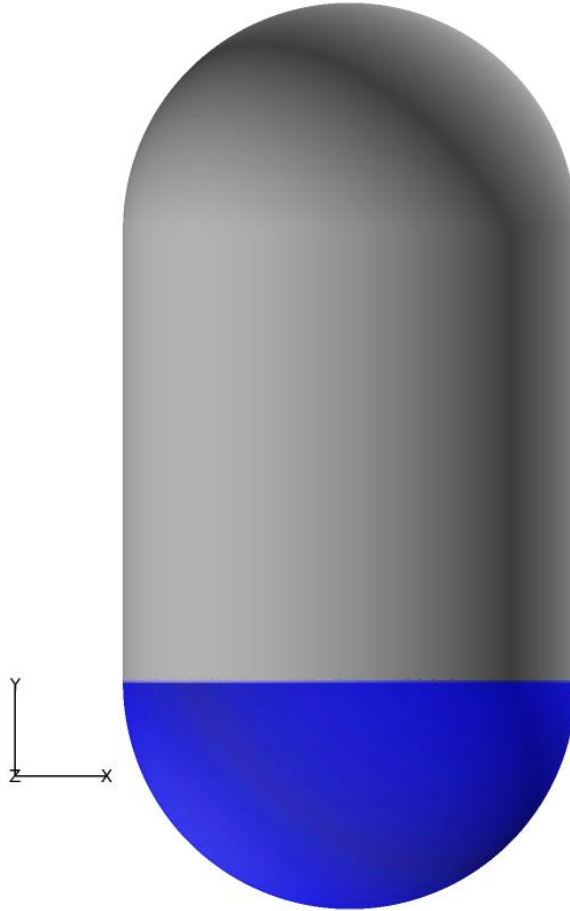
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### III. Computational Methodology

CFD simulations were conducted using a cryogenic propellant tank representative of a large-scale main tank for an orbital rocket. The radius of the tank is 2 meters, the total height from end to end is 8 meters, the barrel section is 4 meters, and the forward and aft dome sections are 2 meter radius hemispheres. An illustration of the tank, along with coordinate axes and a 20% liquid fill level by volume, is shown in Fig. 1. The origin of the coordinate system is at the geometric center of the tank, but the coordinate axes are labeled outside of the tank for visibility. Tank configurations with and without rigid anti-slosh ring baffles were analyzed.



**Fig. 1 Cryogenic propellant tank geometry with a representative liquid fill level (blue).**

The extent of gas phase effects on slosh dynamics was demonstrated through a parametric study of liquid level, wave amplitude, and liquid-to-ullage density ratio variation for the tank configurations mentioned. Most density ratios were obtained by setting tank pressure to achieve a particular ratio. This enabled a smooth transition between realistic conditions for common cryogenic propellant tanks which were also directly analyzed.

#### A. Computational Tools

Loci/STREAM, a pressure-based solver, was used in the preparation of these results. Loci/STREAM [5][6] is an all-speed CFD code for generalized grids in the rule-based programming framework called Loci [7]. The Loci framework allows the solver to integrate new multidisciplinary physics using a modular manner and automatic handling of massively parallel computing. The Loci/STREAM code has been applied and validated over a wide range of problems, including incompressible laminar flows to compressible turbulent flows with heat transfer. Loci/STREAM has been shown to also scale very well on significant problems [5][6]. Loci/STREAM is a pressure-based solver with SIMPLE, SIMPLEC, and PISO algorithms available for pressure-momentum coupling. Also available are various turbulence models that can be executed in Reynolds-Averaged Navier-Stokes (RANS) or Large Eddy Simulation (LES) mode. It has support for reacting flows and flamelet models for turbulent combustion. Loci/STREAM supports first and second-order discretization for inviscid fluxes as well as first and second-order

temporal discretization. The code has been in use at NASA MSFC for large-scale simulations of low-speed flows, turbulent combustion, cavitation, and other problems.

The code employs multiple methodologies to represent distinct fluid phases and their shared interface. The volume of fluid (VoF) method distinctly represents a liquid and gaseous phase in the same simulation by tracking the volume of a particular fluid and the geometric liquid interface in each cell of the discretized computational domain. This simulation technique can capture gas-liquid interface deformation and breakup and has been applied extensively to propellant tank dynamics and cryogenic fluid management applications. The VoF method was used in the present analysis.

## B. Computational Mesh

*Descriptions of the as-analyzed mesh will be placed here.*

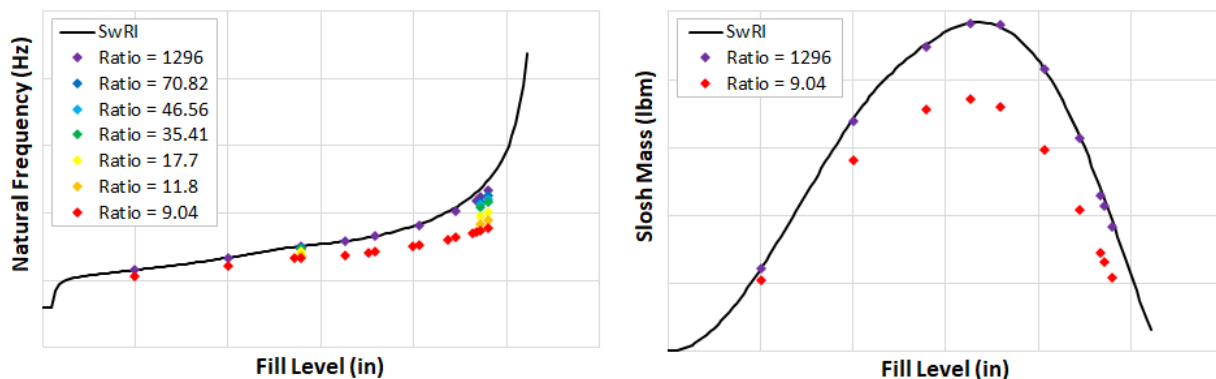
## C. Simulation Inputs

*Descriptions of the simulation inputs including fluid properties used to achieve target liquid-to-gas density ratios will be placed here.*

## IV. Computational Results

Low wave amplitude slosh dynamics in free decay were simulated at liquid levels spanning the tank for numerous density ratios. Simulation results show that slosh frequency, slosh mass, and slosh mass location decrease with decreasing liquid-to-vapor density ratio in LH2 tanks. Frequency and mass variations are shown in Fig. 2. Slosh parameters resulting from the potential flow solution for the subject tank were produced using the SLOSH code developed by the Southwest Research Institute (SwRI).

Fluid properties change in propellant tanks throughout typical missions. As a result, it is suggested to model density ratio variation as an uncertainty on slosh model parameters that can be applied in Monte Carlo simulations of vehicle trajectories.



**Fig. 2 Natural frequency (left) and slosh mass (right) variation with liquid-to-gas density ratio.**

*Data scales for Fig. 2 were removed as this data was generated for a different tank than that shown previously. Simulation results for the described tank will be added in the final manuscript. The data trends shown will hold. Of course, additional data including demonstrations of flow field variables will be provided as well.*

## V. Conclusion

*Conclusions will be placed here.*

## Acknowledgments

*Acknowledgements will be placed here.*

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*References will be added and reordered as necessary.*