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Numerical Simulation of Cryogenic Fluid Sloshing In Propellant Tank and Influence of Damping with Ring Baffles Under Forced Excitations

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Abstract **-** Sloshing phenomena in fluid systems have emerged as a significant challenge with wide-ranging implications across various engineering domains, including aerospace and cryogenic storage. This paper presents a comprehensive study of sloshing effects in cryogenic propellant tanks, focusing on the behaviour of liquid oxygen as the working fluid. Sufficient works are present in literature demonstrating predictability of sloshing dynamics without phase change. Specific parameters governing the evaporation and condensation of cryogenic fluids introduces distinct challenges. In this paper, the numerical behaviour of sloshing is simulated using Ansys Fluent with a Volume of Fluid (VOF) model and the Lee model to handle phase change. Through numerical simulations, the study investigates the effect of baffles with different sizes under various excitation frequencies, to enhance our understanding and mitigation strategies for sloshing-related issues in cryogenic fluid systems. Selection of an appropriate baffles in cryogenic propellant tanks is a concern for safe operation during the entire flight duration in aerospace vehicles.

Keywords**:** Sloshing, Cryogenic, Liquid Oxygen, Ring Baffles, Damping

1. Introduction

Typical sloshing constitutes nonlinear oscillations of liquid-free surfaces occurring in partially filled tanks when disturbed from the equilibrium state by a steady or time variant force field. In many situations, the associated force generated due to the sloshing of liquid could be detrimental to the structure on which the container is secured. It is important that these sloshing dynamics are modelled appropriately, and a feasible damping option is evaluated and implemented. In aircraft and space vehicles the dynamic effects of fuel in the fuel tank, the associated shift in the centre of gravity of the fuel tank in addition to the influence of resonant frequency of fuel oscillation could impede safe flight operation. The interesting coupling of phase change with sloshing in cryogenic propellant tanks introduces additional challenges in the predictability of sloshing. These movements can disrupt the vehicle’s trajectory control and navigation, requiring a careful evaluation of sloshing dynamics [1]. In space vehicle fuel tanks where liquid fuel encounters its vapor, there is significant ullage pressure variations due to wave motion at the interface. The sloshing of these tanks affects the equilibrium temperature of the tank due to which pressure changes occur. It has been observed in the Ariane 5 flight that there is a pressure drop in the liquid hydrogen tank [2]. Experiments were done to study the effect of sloshing on liquid hydrogen in a 62 cubic feet tank to characterize the thermodynamic response of the system under normal gravity conditions [3]. It was observed that for various amplitudes and frequencies of excitation, there is a change in ullage pressure drop which shows the dependence of external parameters on thermodynamics. Zhang et al. [5] reports a numerical study on the sloshing of liquid oxygen in a spherical tank indicating an increase in pressure in the ullage region. The effect of T baffles is also investigated in this numerical study. Ludwig et al. [4] presents a sloshing experiment with liquid nitrogen as the working fluid. Experimental data were compared with analytical results derived from a revised interfacial mass transfer model. A novel sloshing Nusselt number was defined, correlating with a sloshing Reynolds number, and compared to experimental and literature data. Studies in the literature typically report pressure drop in the ullage of propellant tanks influenced by the sloshing dynamics. The effect of baffles in slosh dynamic under different acceleration levels has been studied extensively by Chinalapati et al. [6]. It was observed that in low gravity fields, surface tension and capillary action dominate even in large booster-size tanks, and simple Bond number scaling is not adequate. This study also showed that

the models can be used to help determine a baffle geometry and location within the tank that should be employed to minimize bulk fluid motion, as well as the effect of having a gap between the tank wall and the baffle. Different types of baffles have been used for damping the oscillations in the propellant tank. The experimental and numerical study reported by Peddu et al. [7] indicates that tanks with horizontal and vertical baffles provide much more damping than other configurations (asperities). Damping can be increased or controlled by using multiple baffles and configuring the orientation of the baffle. Works involving numerical studies for sloshing in cryogenic tanks are limited. Efforts have been made by Zhan Liu et al [8] to mitigate the effect of sloshing in the propellant tank with liquid oxygen as propellant, however, their validation of the numerical model was conducted on the water as the working fluid. Modelling the realistic behaviour of sloshing in a cryogenic propellant tank involves the requirement of a proper phase change model as the challenge appears to ascertain the proper workability of a model over a wide range of frequencies and amplitude of oscillations. This directly affects the proper choice of the baffle for an intended purpose.
In the current work, we employ the VOF model coupled with the Lee model for phase change and incorporate the Lee constant [9] that is appropriately tuned to predict the published experimental pressure transients. We systematically present the sloshing dynamics of an appropriate 3D geometry of the chosen propellant tank [8] under different excitations. Ring baffle is considered in the present study to assess the damping behaviour [6].

2. MODEL AND METHODOLOGY

2.1 Mathematical Model

Sloshing of liquid typically has a distinct interface making the Volume of Fluid (VOF) model very handy to use. In the current work, we have used VOF method incorporated in Ansys Fluent solver [9]. VOF method is primarily a mixture model. The flow field is typically solved for primary variables as an incompressible mixture. Navier-Stokes equations along with volume fraction equations with appropriate boundary conditions handle the flow field. Typical mixture properties are calculated based on void fraction as per equation (1).

$$\psi=\alpha_2\psi_2+(1-\alpha_2)\psi_1 \tag{1}$$

where α_2 is the void fraction of the secondary phase (phase 2) and ψ is any arbitrary mixture property.

The continuity is then given by,

$$\frac{\partial(\rho_l\alpha_l)}{\partial t}+\nabla.(\alpha_l\rho_l V)=\dot{m}_{lv}-\dot{m}_{vl} \tag{2}$$

where ρ_l is density of liquid, α_l is the void fraction of liquid, $\dot{m}_{lv}$ and $\dot{m}_{vl}$ is the mass flow rate of evaporation and condensation respectively.
The momentum equation is given by,

$$\frac{\partial(\rho V)}{\partial t}+\nabla.(\rho VV)=-\nabla P+\nabla.\mu_{eff}\left[V+V^T\right]+F_{vol}+\rho\overline{g} \tag{3}$$

where V is the velocity field, P is the pressure, μ_{eff} is the effective turbulent viscosity and F_{vol} is the body force. For the current simulation large Re flow is assumed and RANS based (k-ω SST) turbulence model is employed.

The motion of liquid due to density gradient within the tank is incorporated using Boussinesq approximation. The body force at the liquid F_{vol} is given as $F_1 = \rho_1 \left(1 - \beta \left[T - T_R\right]\right) g$ where β is the thermal expansion coefficient with the value of 0.00505 K^{-1}as indicated in Barron [10] and T_R is the reference temperature which is 300 K. The energy equation is given as,

$$\frac{\partial}{\partial t}(\rho E) + \nabla . \left[v(\rho E + P)\right] = \nabla . (k \nabla T) + S \tag{4}$$

where E is the energy, k is thermal conductivity of the liquid and S is the source term.

In this study, liquid oxygen (LOX) is treated as incompressible while gaseous oxygen (GOX) is treated as compressible gas and assumed to follow the ideal gas equation of state. To consider the mass transfer happening at the interface due to evaporation and condensation, the Lee Model is employed in the simulation. As the phase change is in the bulk of fluid, Lee Model becomes an appropriate choice. In the Lee model, liquid vapor transport is governed by the vapor transport equation. During the phase change process, the temperature is changing as a function of pressure $T = f(P_{sat})$ this relation is taken from NIST data [11].

If $T_l < T_{sat}$ (evaporation), then the term $\dot{m}_{lv}$ is calculated as,

$$\dot{m}_{lv} = n_e \alpha_l \rho_l \frac{T_{sat} - T_l}{T_{sat}}$$

If $T_l > T_{sat}$ (condensation), then the term $\dot{m}_{vl}$ is calculated as,

$$\dot{m}_{vl} = n_c \alpha_l \rho_l \frac{T_l - T_{sat}}{T_{sat}}$$

where n_e, n_c are Lee model constants that require tuning with experimental results. The value of n is taken to be 0.05 s^{-1} by validating with the experimental results.

2.2 Benchmark and Grid Independence Test

The numerical model employed to analyse the process of sloshing in a LOX propellant tank is validated against the experimental results by Lacapere et al. [12]. The tank used for simulation is a cylindrical 3D geometry considered to be adiabatic. The height of the tank is 0.8 m and the diameter of the tank is 0.19 m. Forced excitation is provided in the horizontal direction in the form of $A\sin(\omega t)$, where A = 3 mm and f = 2.1 Hz as shown in Fig. 1.

Liquid height is taken as 472 mm. Structured mesh with a refined grid for 300 mm length, 150 mm on either side of the free surface is meshed with a mesh size of 3 mm in the refined region and 5mm in the remaining region. To ensure grid independence, three different grids were utilized for the study, with number of grid equal to 117407, 366625, and 731640. Following a thorough evaluation, the grid with 731640 elements was selected for further simulation, offering the required resolution for precise and dependable results. Transient simulations are done with time steps of 0.001 s.

Lee Model constant is chosen and its influence on ullage pressure drop is shown in Fig. 2. The simulation shows n_e = n_c = 0.05s^{-1} reasonably predicts the ullage pressure. The predictability of ullage pressure is presented in Fig. 3.

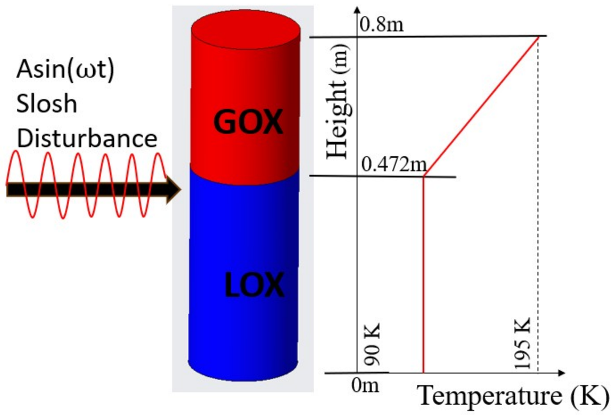


Fig. 1: Computation domain with boundary condition for experimental validation

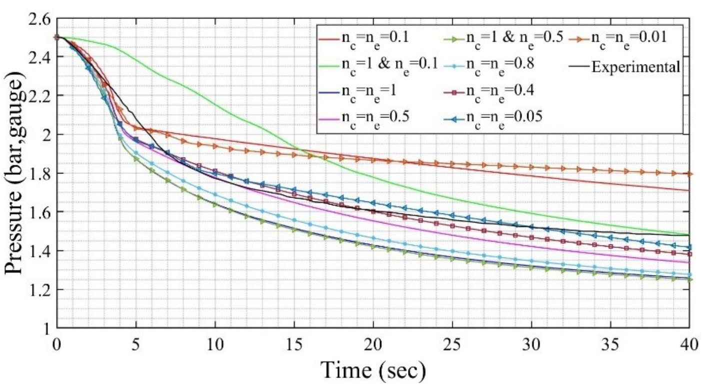


Fig. 2: Effect of Lee constant on ullage pressure

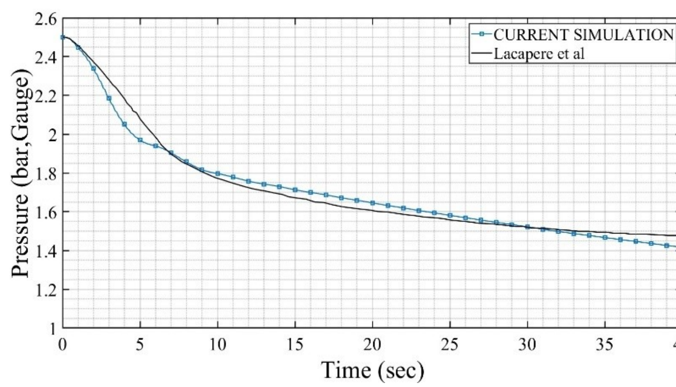


Fig. 3: Comparison of pressure variation in ullage

2.3 3D Propellant Tank Simulation

Having benchmarked the mathematical and numerical methodology, we now present the evaluation of sloshing dynamics in a 3D LOX tank. The 3D geometry of the propellant tank shown in Fig. 4 is used for the simulation of sloshing [8]. The structure of the tank consists of 2 ellipsoidal domes with a height of 1.5 m and a central cylindrical section measuring 2 m in height and 3.5 m in diameter. A full 3D model is used in this study because it represents actual phenomena happening inside the tank for both hydrodynamics and thermodynamics.

Ring baffles are introduced in the propellant tank to control the free surface elevation. The schematic of the tank with baffles is shown in Fig. 5. In the current 3D simulation influence of ring baffles is studied with width and thickness as a parameter. We have chosen two different widths and thickness of 500 mm & 750 mm and 50 mm & 75 mm to assess the effectiveness of damping. Several monitor points within the tank are predefined in the geometry to monitor ullage pressure, temperature, and void fraction near the free surface. The schematic of the location of monitor points is shown in Fig. 6.

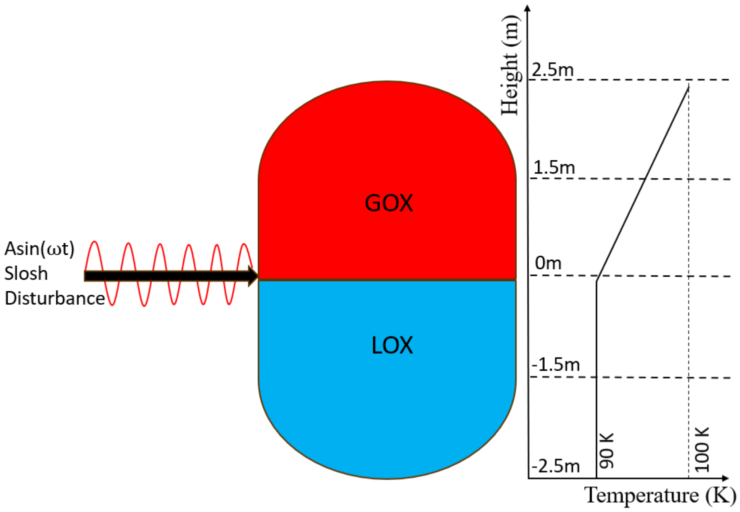


Fig. 4: Diagram of liquid oxygen tank

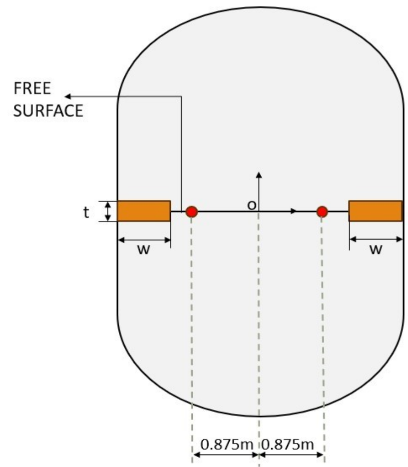


Fig. 5: Schematic of baffle

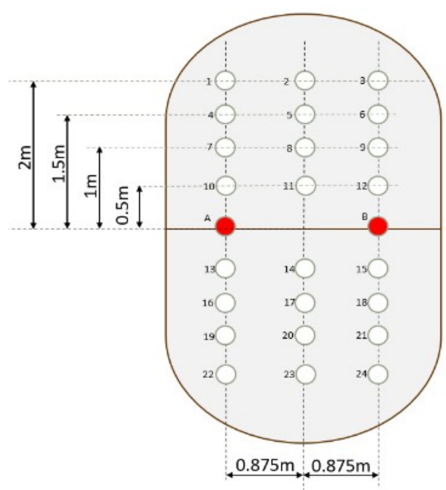


Fig. 6: Monitor points

Initial and Boundary Conditions

The initial condition used are as follows.

The pressure inside the tank is maintained at 1.3 bar(gauge). The temperature in the liquid oxygen is maintained at 90 K and thermal stratification is modelled in the vapor region, where temperature varies linearly from 90 K to 100 K in the vertical direction as shown in Fig. 4. Considering the heat leakage, the external heat transfer coefficient is given, and the ambient temperature is 300 K. The external heat transfer coefficient is calculated using the correlation [13].

$$Nu = 0.11 (Gr \cdot Pr)^{1/3} \tag{7}$$

$$h = \frac{Nu\, k_a}{l} \tag{8}$$

where k_a denotes the thermal conductivity of air, Nu is Nusselt's number, Pr is Prandtl number, Gr is Grashoff number, l denotes the characteristics height of the tank. The conduction resistance in the walls of the tank is neglected as the thickness of the wall is very thin. Slosh excitation is provided to the tank in X direction in the form of $A\sin(\omega t)$. The value of the amplitude is taken as 10 mm, and the value of frequency is taken such that the oscillations are in the stable region according to Mathieu's equation [14]. This is with an approximation that the influence of the viscosity of LOX is negligibly small, and the natural frequency is chosen as the critical frequency. This serves as a guide to ensure simulations are carried out near the stable region. In the present study, the first mode of natural frequency is taken as critical frequency. As the viscosity of LOX is comparatively low, the natural frequency is chosen as the critical frequency. The natural frequency is calculated from the following equation [15];

$$\omega_m = \sqrt{\frac{\zeta_m g}{r} \tan h\left(\frac{\zeta_m h}{r}\right)} \tag{9}$$

where r denotes the radius of the tank, g denotes acceleration due to gravity, and h denotes the fill height in the tank. The value of ζ_m for the first mode is 1.841. For the sloshing excitation, three different frequencies are considered, and amplitude is kept constant in all three cases. The three different frequencies are $0.4\omega_n$, ω_n and $1.3\omega_n$.

3. RESULTS AND DISCUSSION

It is interesting to observe the influence of phase change on the evolution of ullage pressure. We demonstrate this using the 3D geometry considered in section 2. Fig.7 presents the transient pressure evolution when the energy equation is solved and otherwise. It turns out that for the current simulation, with the amplitude of oscillation equal to 3 mm and the frequency equal to 2.1 Hz, condensation dominates in the ullage of the tank. However, when the energy equation is kept off no such variation takes place. This is expected as phase change cannot be modelled without solving the energy equation. The wave height along the diameter of the tank at mid plane is shown in Fig. 8.

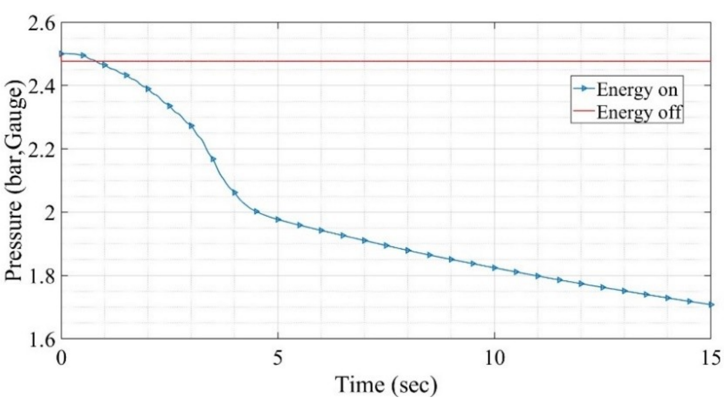


Fig. 7: Effect of energy equation on ullage pressure

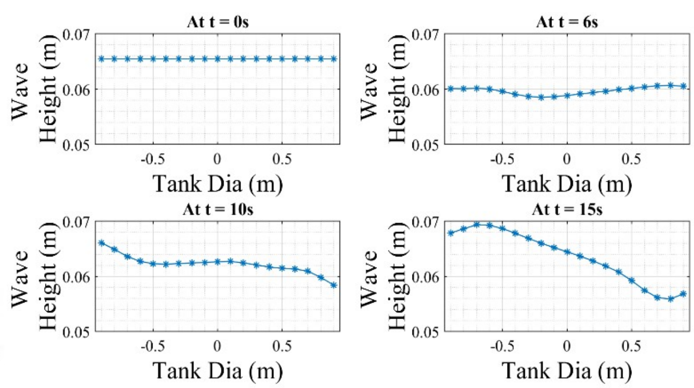


Fig. 8: Location of Free Surface

3.1 Sloshing dynamic in 3D propellant tank (without baffle)

To generate sloshing, excitation with different frequencies is imposed on the tank as mentioned in section 2.2 and pressure variation is monitored at point 5 in ullage as shown in Fig. 6. The transient evolution of ullage pressure for different excitations is presented in Fig. 9. The trend of pressure evolution has a marked distinction from the behaviour in actual sloshing situations where the ullage pressure drops over time due to the dominance of condensation. For the current simulation, the amplitudes and frequency chosen are small, and evaporation seems to dominate leading to pressure rise in ullage with time. For the case of excitation frequency equal to ω_n ,it is observed there is pressure rise for first 10 seconds, but it starts to drop due to condensation. The violent motion of the tank at resonance brings out peculiar trend in pressure transience.

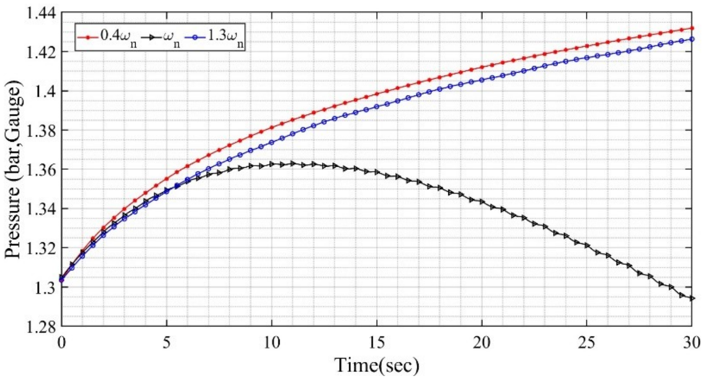


Fig. 9: Pressure variation in ullage for different excitations

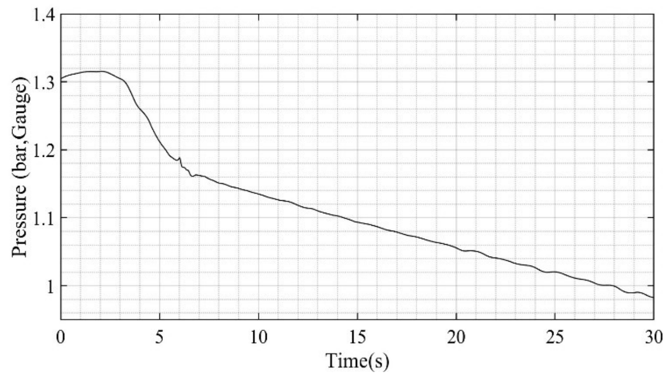
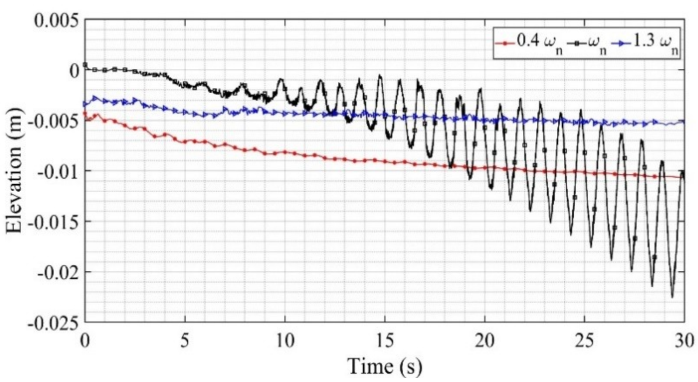
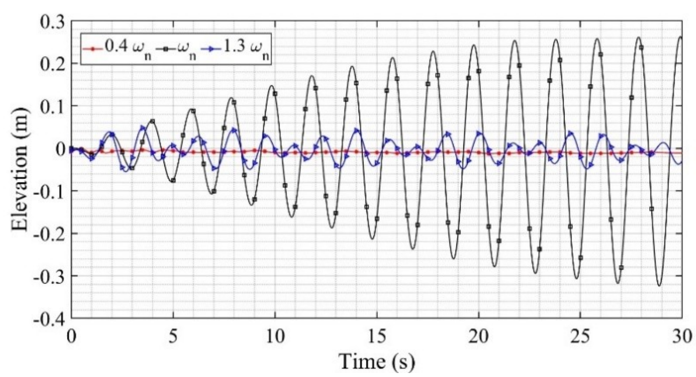


Fig. 10: Pressure variation in ullage for high amplitude (ω_n)

To examine the impact of amplitude on the pressure evolution with time the amplitude was raised to 0.2m, and sloshing was conducted at ω_n. Notably, at this amplitude and frequency, a pressure decrease in the ullage was observed, indicating condensation as shown in Fig. 10. The evolution of interface height at monitor points A and B, as depicted in Fig. 6, is shown in Fig. 11. The data reveals that the elevation is not symmetric about the axis, indicating that a 3D geometry is the most effective approach for studying sloshing with phase transfer.



(a) Point A



(b) Point B

Fig. 11: Free surface elevation evolution with time for different excitations at pt. A and B

For the frequency ω_n, the elevation exhibits a higher amplitude compared to the other two cases. In the $1.3\omega_n$ scenario, beat phenomena are observed. Conversely, in the $0.4\omega_n$ case, the oscillations are minimal due to the low magnitude of excitation. The frequency and amplitude of excitation is selected based on the Mathieu's [14] criteria. The selected points are shown on Mathieu's chart in Fig. 12.

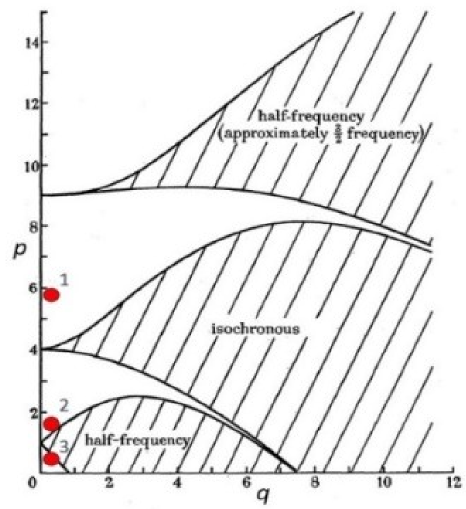
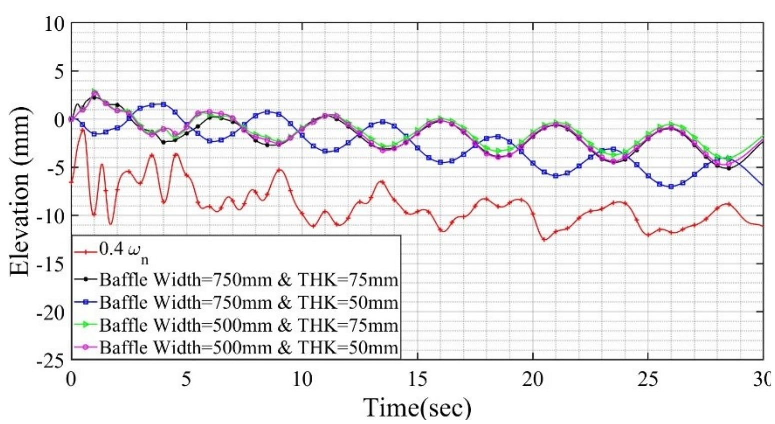


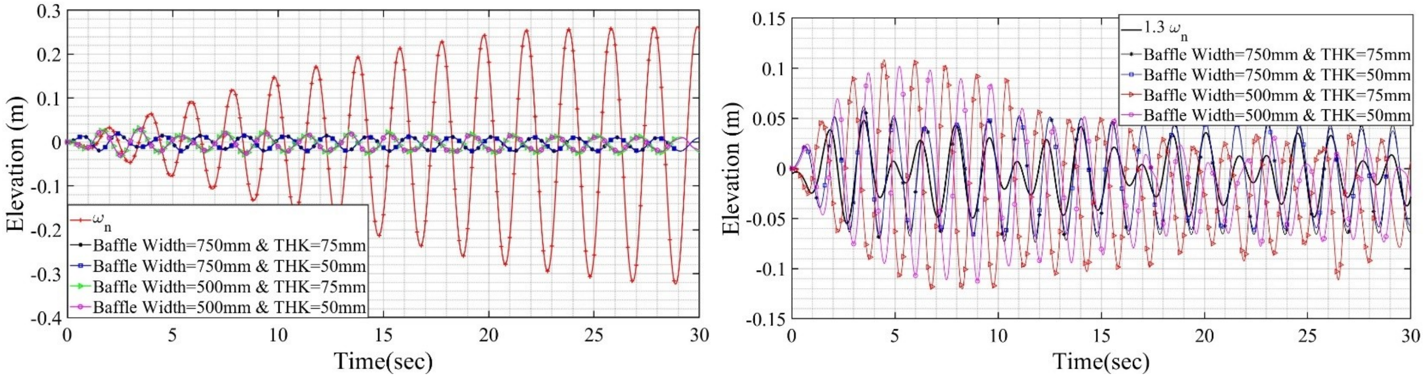
Fig. 12: Mathieu's stability chart. Points for simulation are denoted as 1 to 3. [14]

3.2 Slosh behaviour in propellant tank (With Baffle)

Baffle rings are crucial for damping oscillations within propellant tanks. In the present study we use a circular baffle which is firmly attached to the tank wall. We have selected two widths of the baffle; 500 mm and 750 mm to study the influence of size and two thicknesses;50 mm and 75 mm. With the baffle width of 500 mm and 50 mm thickness damping is prominent. For $0.4\omega_n$ the damping is approximately 72%, although the magnitude of oscillations is much lower, but the baffles are effective to damp the oscillations. In case of ω_n, the oscillations are very high compared to other two cases, here also the damping by baffle width of 500 mm and 50 mm thickness damp out the oscillation up to 92%. For $1.3\ \omega_n$ the oscillation exhibits a beat phenomenon, with amplitude being much lower than ω_n. For $1.3\omega_n$ baffle of 500 mm width and 50 mm thickness there is initial increase in amplitude but as the time progresses the oscillations are damped out by 58%.



(a)



(b) (c)

Fig. 13: Free surface elevation evolution with time for excitation frequency (a) $0.4\omega_n$ (b) ω_n and (c) $1.3\omega_n$

4. CONCLUSION

In the present work, we presented the results of numerical simulation of sloshing dynamics in the cryogenic propellant tank and discuss the influence of ring baffles that could dampen the liquid oscillations. The numerical methodology has been first validated with an experimental transient pressure evolution in the LOX propellant tank. This ascertains the predictability of sloshing dynamics and the appropriateness of the phase change model employed. The sloshing dynamics in the 3D propellant tank has been systematically assessed. The amplitude and frequency of the excitation are typically chosen to be near the stable regimes of oscillation. Natural frequency was calculated for the current simulation using standard dispersion relation, Equation (9). For ω_n excitation, the free surface elevation has very high magnitude as compared to $0.4\omega_n$ and $1.3\omega_n$ case in the chosen range of amplitude and frequencies. From 4 chosen baffles, baffle of 500mm thickness and 50mm width dampens the oscillation for selected range of frequencies and amplitude.

REFERENCES

[1] M. V. S. C. D. K. a. H. G. Ran Zhou, "Experimental and numerical investigation of liquid slosh behavior using ground-based platforms," *Journal of Spacecraft and Rockets,* pp. 1194-1204, 2012.

[2] C. Montsarrat, *Fluid motion analysis in the cryogenic tanks of the upperstage of ariane 5 during the ascent phase,* 2017.

[3] N. B. M. M. T. K. M. S. H. a. G. A. S. Matthew E Moran, "Experimental results of hydrogen slosh in a 62 cubic foot (1750 litre) tank," in *Joint Propulsion Conference*, 1994.

[4] M. D. a. E. H. Carina Ludwig, "Pressure variations in a cryogenic liquid storage tank subjected to periodic excitations," *International Journal of Heat and Mass Transfer,* no. 66, pp. 223-234, 2013.

[5] H. C. X. G. X. P. Q. H. J. X. a. J. C. Hanyue Zhang, "Numerical study on behaviors of the sloshing liquid oxygen tanks," *Energies,* 2022.

[6] S. C. a. D. Kirk, "Parametric study of a propellant tank slosh baffle," in *AIAA/ASME/SAE/ASEE*, 2008.

[7] T. M. P. S. a. a. S. N. G. Avaneesh Peddu, " An investigation of baffles and asperities on slosh behavior in propellant tanks of spacecraft and launch vehicles," in *AIAA/ASMe/ASCE/AHS/SC Structures, Structural Dynamics, and Material conference*, 2014.

[8] Y. F. G. L. a. Y. Zhan Liu, "Hydrodynamic performance in a sloshing liquid oxygen tank under different initial liquid filling levels," *Aerospace Science and Technology ,* no. 85, pp. 544-555, 2019.

[9] ANSYS Fluent, *Ansys fluent theory guide,* USA, 2011.

[10] R. F. B. a. G. F. Nellis, Cryogenic Heat Transfer, CRC Press, 2017.

[11] P. J. L. a. W. G. Mallard, "The nist chemistry webbook: A chemical data resource on the internet," *Journal of Chemical & Engineering Data,* no. 46(5), pp. 1059-1063, 2001.

[12] J.Lacapere and a. B. B.Vielle, "Experimental and Numerical Results of Sloshing With Cryogenic Fluids," in *Progress in Propulsion Physics*, 2009.

[13] Y. Z. a. J. R. H. Amir Faghri, Advanced Heat and Mass Transfer, Global Digital Press, 2010.

[14] B. T. a. U. FJ., "The stability of a plane free surface of a liquid in vertical periodic motion," in *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 1954.

[15] R. A. Ibrahim, Liquid sloshing dynamics: theory and applications, Cambridge University Press, 2005.

[16] Y. F. G. L. ,. Y. L. Zhan Liu, "Hydrodynamic performance in a sloshing liquid oxygen tank under different initial liquid filling level," *Aerospace Science and Technology,* vol. 85, pp. 544-555, 2019.

[17] J. W. Miles, "Resonantly forced surface waves in a circular cyllinder," *Journal Fluid Mechnanics,* no. 149, pp. 15-31, 1984.