Optimization of Disc Baffle Perforation in Sloshing Nitrous Oxide Tanks

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Liquid fuel sloshing during flight introduces destabilizing forces that can compromise a rocket's stability. To mitigate these effects, baffles are employed within fuel tanks to dampen unwanted motion. This study aims to determine the impact of perforation count in disc baffle designs on sloshing behavior of hybrid nitrous oxide fuel, a relatively unexplored variable in multiphase sloshing. The total perforated area in each baffle design is kept constant at 6.59e-3 m² to isolate the effects of the perforation count. The tank geometry features a height of 1.37 m and a diameter of 0.203 m, with three baffles evenly spaced at 0.343 meter intervals. The fuel composition consists of liquid and gaseous nitrous oxide in a 3:1 volume ratio. Sloshing is induced by applying an initial excitation velocity, and metrics such as directional forces and the damping factor are analyzed. Given these conditions, an optimal perforation count that maximizes the damping factor is calculated, demonstrating peak performance at an intermediate level of baffle perforation, with diminishing returns observed at both higher and lower perforation counts. The approach used here can serve as a starting point to gain a better understanding of the dynamic sloshing behavior of multiphase fluid with respect to the perforation count in disc baffles.

I. Nomenclature

c = damping constant
k = spring constant
m = mass constant
c_{crit} = critical damping constant
ζ = damping ratio
HRE = Hybrid Rocket Engine
PRESTO = Pressure Staggering Option

II. Introduction

With the rise of deep space exploration in recent years, rockets are highly dependent on propulsion systems to travel long distances. Among the various propulsion systems, liquid fuel remains the predominant fuel type in the rocket

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industry due to its higher energy density, handling, and controllability in the air. However, the use of liquid propellants introduces a dynamic drawback inside the rocket's fuel tank called liquid sloshing. In fluid dynamics, sloshing is referred to as the motion of a free surface liquid inside a partially filled container. In this case, this dilemma refers to the oxidizer inside the fuel tank of a rocket. Furthermore, as interplanetary missions grow in complexity, understanding the impact of liquid motion within fuel tanks becomes critical for long-duration flights and crewed missions.

This study is part of the development of a 2500N HRE (Hybrid Rocket Engine) for a student rocketry team, Propulsive Landers, at Georgia Tech. A hybrid propulsion system is essentially the combination of elements of a solid and liquid rocket engine [1]. These engines typically use solid fuel grain and liquid/gaseous oxidizer. The solid fuel is stored inside of the combustion chamber and the liquid oxidizer is stored inside of a tank. When thrust is required, the oxidizer is released into the combustion chamber, mixed with the fuel grain, and the combustion reaction follows [1]. The reason why this study uses HRE is because of its advantages over traditional engine types. Hybrid propulsion systems offer the benefits of control that liquid engines provide, without the complexity and cost that many liquid engines require. The propellant of choice for this system is two-phase nitrous oxide, with the propellant in both liquid and gaseous phases simultaneously.

During the launch and flight stages, rockets undergo a wide range of accelerations, vibrations, and maneuvers that cause the propellant inside the fuel tanks to oscillate. These oscillations generate unwanted forces that act on the fuel tank, causing a disruption in the center of mass of the rocket. If these forces are not minimized, sloshing can pose a risk to the rocket's guidance system and engine performance. These oscillations are difficult to accurately predict onboard the rocket, leading to instability. Poor reactive control can result in oscillations that potentially cause the rocket to exceed the critical angle of attack and enter an unrecoverable spin. A common method to mitigate sloshing is through the integration of anti-sloshing baffles placed inside of fuel tanks to dampen the amplitude of the fluid waves. By restricting the flow of propellant from one side of the tank to the other, baffles achieve a more stable center of mass for the rocket and decrease the net force acting on the fuel tank.

The subject of liquid sloshing inside fuel tanks has become an important topic in research due to its extensive applications in engineering and safe transport of liquids [2]. As a result, substantial research has been conducted to reduce liquid sloshing through the use of baffles. Studies have been carried out to analyze the optimal number of baffles inside fuel tanks [3]. According to a study by Tang et al., the inclusion of baffles decreases the sloshing force and sloshing time of the propellant. Their study showed that a 3-layer 15mm baffle has a dampening ratio that is at least 18.3 times that of a tank without baffles under certain conditions. Typically, baffles are constrained to the walls of the tank containing the liquid in motion. These baffles may range in designs such as T-shaped, vertical, double-sided curved, or ring-like. Zhu et al. investigated the performance of a T-shaped, vertical, and double-sided curved baffle under surge and pitch excitation [4]. They found that the T-shaped baffle was more effective in reducing sloshing under surge excitation than the vertical baffle. However, both baffles had similar damping effects during pitch excitation. Their study also concluded that the double-sided curved baffle exhibited higher wave suppression than that of the T-shaped baffle. Fuel tanks will typically contain few baffles that cover a substantial diameter of the tank. However, research has also suggested the implementation of increasing the number of baffles while decreasing their size. These designs include semicircular, radial, annular, and enclosed baffles. A study by Deshmukh et al. investigated the effect of enclosed baffles inside a hydrogen fuel tank at 50% fill [5]. Their study discovered that these enclosed baffles reduced the sloshing force by approximately 50%. Researchers have also begun to break away from the idea of fixed baffles and analyze the performance of floating baffles [6]. Despite extensive research in the field of anti-sloshing baffles, a relatively unexplored variable in multiphase sloshing is the influence of perforation count in disc baffle designs on sloshing behavior.

To address the research gap, this paper examines a fuel tank setup consisting of three equally spaced circular baffles to ensure that propellant waves have several obstacles to overcome as they traverse the tank. Each of these baffles is perforated with a constant area. Although the total area of perforation remains constant throughout each trial, the number of individual perforations varies between different configurations. This approach allows for an exploration of how the number of perforations influences the dampening of fluid motion without changing the net area. Investigating the effect of baffle perforations is critical since the size and distribution of perforations can dramatically alter the flow path of propellant and energy dissipation within the tank.

III. Methodology

The simulation was conducted using computational fluid dynamics (CFD) software, Ansys Fluent. The objective was to evaluate the effect of perforation count in disc baffles on the sloshing behavior of a hybrid nitrous oxide fuel tank.

The tank was modeled as a vertical cylinder with a height of 1.372 m and a diameter of 0.2032m, approximately the dimensions required for the 2500 HRE. Three disc baffles, each with a total perforated area of 6.59e-3 m^2 to balance the structural integrity while maintaining the flow region, were placed parallel to the horizontal plane at equal intervals of 0.3429 m. Perforation counts of 1, 3, 5, 7, 9, 11, 13, 17, and 37 were tested, allowing a well-spread data set while reducing the necessary resources. The volume of the tank was composed of a 3:1 volume ratio of liquid and gaseous nitrous oxide, a potential configuration of fuel under hybrid rocket conditions after take-off.

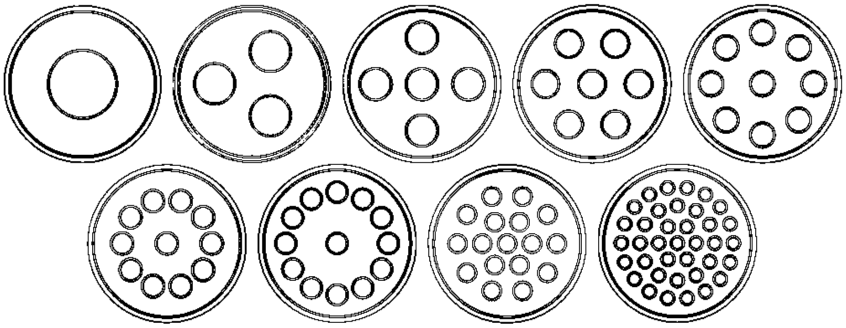

Fig. 1 Baffle perforations 1, 3, 5, 7, 9, 11, 13, 17, and 37, respectively.

The tank is oriented in an upright position, mirroring its operational alignment in flight, with gravity acting downward on the tank with value $g = 9.807 m/s^2$. A cross-section isometric view of one tank geometry is shown below, incorporating the 11 hole baffle design. Small fillets of radius 2.54e-3 m are included to represent welds during the construction of the tank and to ensure smooth fluid flow within the simulation.

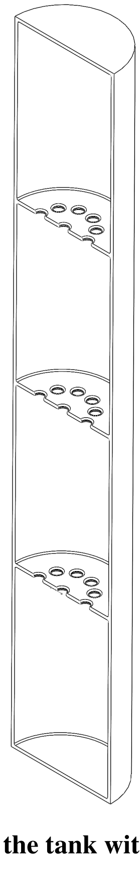

Fig. 2 Section view of the tank with 11 perforation baffles.

The physical properties of nitrous oxide, including density, viscosity, and surface tension, were incorporated to ensure realistic fluid behavior. Sloshing was initiated by applying an initial horizontal velocity of 1 m/s to simulate the excitation forces encountered during flight. 1 m/s was chosen to initiate sloshing, as higher velocities were shown to cause extremely violent sloshing, which is unrealistic for the flight of the hybrid rocket.

The inhomogeneous Eulerian model was selected to account for the interactions between the liquid and gaseous phases of nitrous oxide, as it gives a distinct treatment of each phase's velocity, pressure, and volume fraction, allowing precision especially in cases where the phases do not follow the same velocity field.

The SST k-ω model was used to handle free-stream flows and boundary layer effects with precision. Although the k-ϵ model excels in the free-stream regions, it performs poorly in areas near walls. Conversely, the k-ω model provides better resolution near walls but lacks efficiency in free-stream conditions. The SST k-ω model integrates the strengths of both approaches for accurate simulation of the transition between flow regions.

Spatial discretization is used to approximate partial differential equations over a computational domain by dividing the geometry into smaller, discrete elements and then solving the governing equations within each discrete element. We implemented a least-squares cell-based method for gradients, approximating gradients at cell centers. The PRESTO! (Pressure Staggering Option) pressure calculation scheme is used to estimate face pressures. PRESTO! mimics the benefit of a staggered grid within Fluent's collocated array of variables. In a staggered grid approach, pressure is stored at cell centers while velocity components are stored at cell-face locations. This helps maintain a strong coupling between velocity and pressure and reduces numerical oscillations. Momentum, volume fraction, turbulent kinetic energy, and specific dissipation rate all utilized First Order Upwind, which is a more robust calculation method compared to higher-order upwinds, minimizing numerical instabilities.

The simulation incorporated the specific physical characteristics of nitrous oxide in both the liquid and gaseous states, at 20°C and 50.5 bar.

Table 1 lists the various constants of the physical characteristics of the phase of nitrous oxide under the conditions stated.

N2O Phase	Density	Viscosity	Surface Tension
Liquid	785	6.82e-5	2.06e-3
Gas	158	1.79e-5	N/A

Table 1 N2O Constants for Simulations

Metrics such as tank pressure distribution, directional forces, and damping ratio were calculated to evaluate the sloshing dynamics. The impact of varying the perforation counts on these metrics was analyzed to identify configurations that maximized damping.

Linear sloshing behavior in tanks can be modeled with a mass-spring-damper model [7],

$$mx'' + cx' + kx = 0 \tag{1}$$

The forces collinear to the sloshing direction of the simulation can be expected to follow a similar function, allowing us to use linear regression to fit the data to the solution of the spring-mass-damper model,

$$y = e^{-ax} * (A\cos(bx)) + B\sin(bx), \tag{2}$$

where a, A, b, and B are constants. With this, damping ratio ζ for each baffle design is calculated as

$$\zeta = \frac{c}{c_{crit}} = \frac{c}{2\sqrt{mk}} \tag{3}$$

IV. Results and Discussion

The key characteristic evaluated from the various tank designs was the force exerted by the liquid and gas on the tank parallel to the direction of the initial excitement. The horizontal force observed was the most significant force acting on the tank, as expected. The initial excitement on the tank was a velocity of 1 m/s in a horizontal direction, causing the hybrid mixture to begin a sloshing motion.

Figure 3 illustrates the horizontal force on the tank for each of the baffle designs:

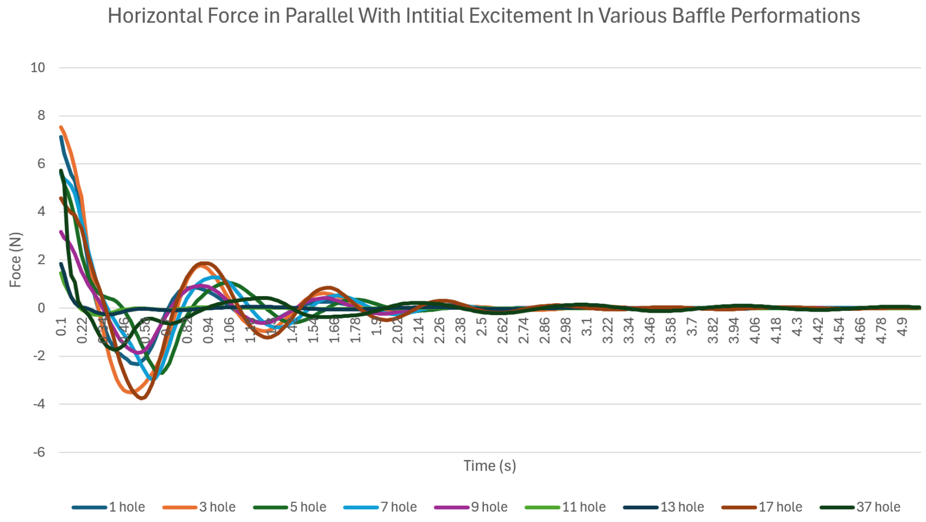

Fig. 3 Horizontal Force on Tank During Sloshing

As seen in Figure 3, the perforation count significantly affects the horizontal forces that impact the tank and therefore the rocket flight path. It can be discerned that members on either extreme, such as 1 hole and 17 hole both have comparatively large forces, decreasing as they move closer to a moderate number. However, the 37-hole baffle is an outlier to this trend, perhaps due to the different behavior of baffles as they become more similar to a filter, resulting in forces such as surface tension gaining a greater impact on the sloshing behavior of the fluid. The baffles show relatively similar behavior in terms of damping, approaching relatively insignificant forces in the same general range of oscillations.

Another characteristic recorded from the simulations was the vertical force exerted on the tank due to the sloshing motion. The resting force due to the nitrous oxide was subtracted from the total force acting on the tank. Although not as significant as horizontal forces, vertical force is still potentially significant, especially in cases of more violent sloshing. The vertical force exerted on the tank can be seen in Figure 4.

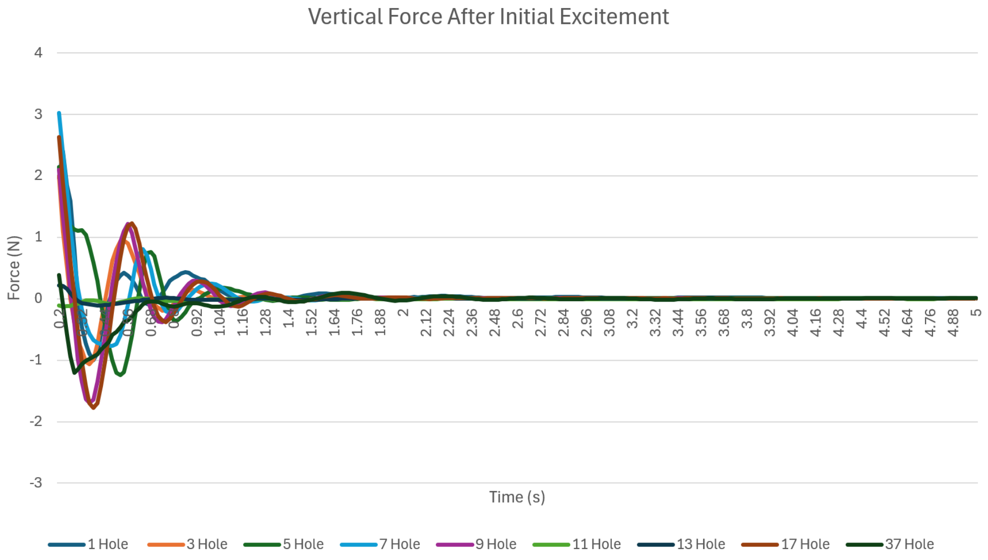

Fig. 4 Vertical Force on Tank During Sloshing

Similar to the horizontal forces, the vertical forces exhibit a tendency to decline as they approach a more moderate value from both extremes, again with the largest hole value as an outlier, most likely due to a higher impact of surface tension on the sloshing behavior. The vertical force dampened faster than the horizontal force, with a larger damping ratio and a seemingly larger oscillation rate. This holds empirically, as gravity is able to oppose the vertical sloshing much more effectively than the horizontal sloshing.

The horizontal force curves were fit with linear regression to a spring-mass-damper system to determine the damping ratio. Each curve was adapted with a coefficient of determination of $R^2 > 0.95$, with the exception of design 11. Figure 5 shows an example of a fitted curve, using the 9-hole baffle design data.

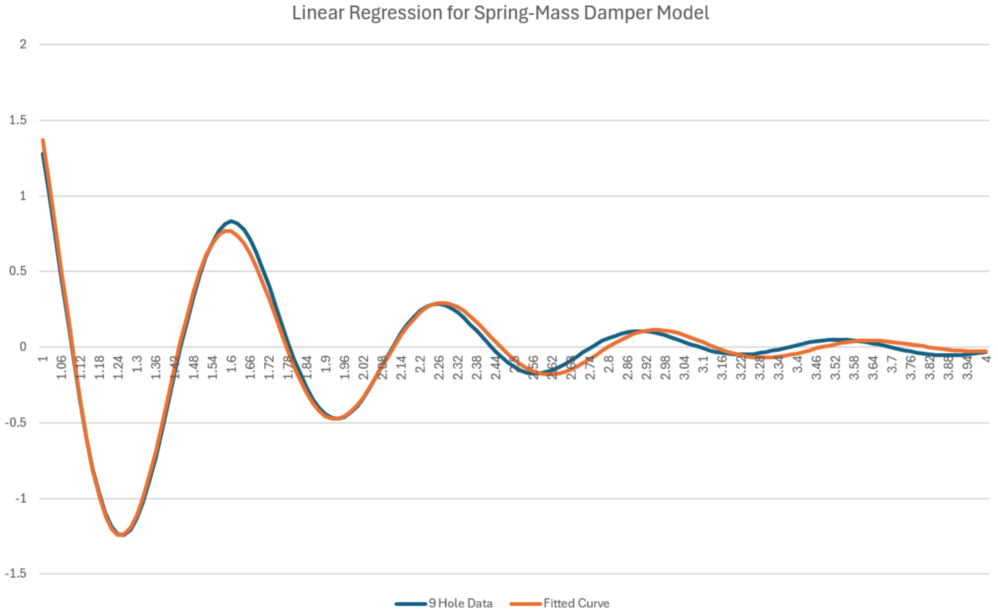

Fig. 5 Spring-Mass-Damper curve (orange) fit to 9 hole (blue), $R^2 = 0.991$

The coefficient of determination and the damping ratios are shown in the table below.

Perforation Count	Fit Correlation (R^2)	Damping Ratio (ζ)
1	0.978	0.536
3	0.978	0.648
5	0.987	0.528
7	0.993	0.691
9	0.991	0.823
11	0.908	0.852
13	0.961	0.744
17	0.994	0.639
37	0.955	0.787

Table 2 Damping ratios and coefficient of determination for each fitted curve.

Figure 6 illustrates the damping ratios by perforation count, visualizing the trend.

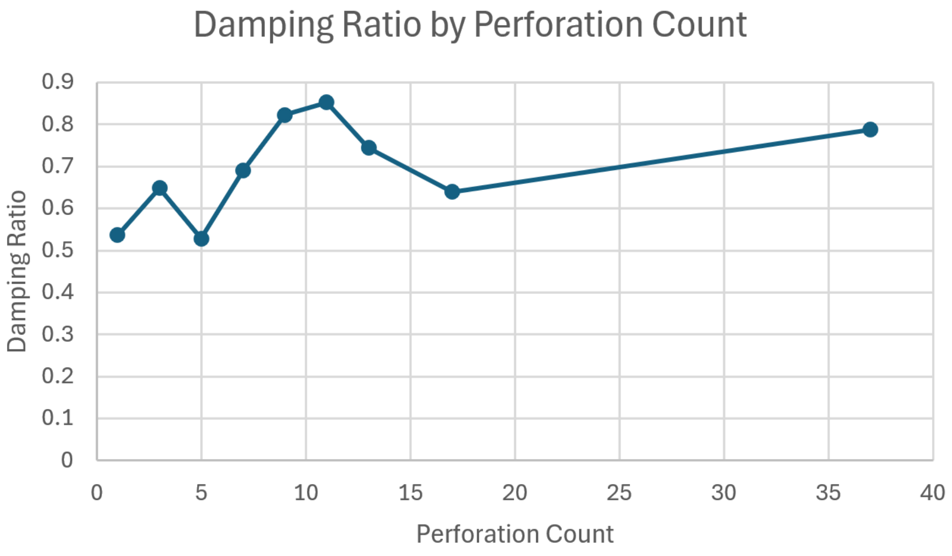

Fig. 6 Damping ratios by perforation count.

There appears to be an optimal perforation count within the selected perforations' distributions that lies in the range of 7 to 13 holes, with an increasing damping ratio as the perforation approaches an extremely high count. However, this trend is still unclear due to the lack of data and could benefit from further study. These results are heavily dependent on many factors that could be changed to further minimize force oscillations, such as the distribution of perforation within the baffle itself.

V. Conclusion

This paper investigates the effect of various perforations in a disc baffle on the dynamic behavior of the linear sloshing of a multiphase nitrous oxide solution within a 3D tank. By analyzing the system response to an initial velocity excitation, we determined the damping ratios based on the resulting force exerted on the tank walls. A total of nine different disc baffle configurations were examined, with perforation counts ranging from 1 perforation to 37 perforations, allowing for a comprehensive understanding of how different perforation counts affect the damping of the sloshing motion.

The results demonstrate that the number and distribution of the perforations in the baffle play a critical role in the sloshing dynamics. Specifically, we observed that the damping behavior is not a linear function of the perforation count but rather follows a trend where an optimal perforation count exists. The findings indicate that with our tank conditions, a baffle with approximately 10 perforations provides the highest damping efficiency. This suggests that at this level of perforation, the balance between fluid momentum transfer and energy dissipation reaches an optimal point, mitigating excessive wave motion within the tank.

Beyond this optimal perforation count, damping performance exhibits a decreasing trend as perforations become either too sparse or too numerous. When the number of perforations increases significantly, there is a potential for a secondary increase in damping efficiency: as shown in Figure 6. This is likely due to increased surface tension effects and enhanced wave breaking, which may contribute additional energy dissipation mechanisms beyond those observed in lower perforation baffles. However, further investigation is required to quantify these effects and determine whether they become dominant at extremely high perforation counts.

Ultimately, these results provide valuable insight into the design of slosh mitigation strategies in aerospace fluid applications. By carefully selecting the perforation configuration of the disc baffles, engineers can optimize the damping behavior to enhance the stability and performance of fluid storage systems subjected to dynamic motion. Future work should focus on refining these findings through experimental validation, exploring additional perforation geometries, and seeing the impact of different excitation conditions on damping behavior.

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