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Comparative Study of Slosh Suppression Devices and Techniques for Liquid and Hybrid Rocket Propellant Tanks

Manish K. Bharti[1], Sonia Chalia[2]
[1, 2] Department of Aerospace Engineering, Amity University, Gurgaon, Haryana

Abstract-: The present study reviews and discusses about the undesirable phenomenon of propellant sloshing in propellant tanks of liquid and hybrid rocket engines. The occurrence of unexpected sloshing in propellant tanks usually induces unwanted and additional loads and stresses on the tank structure which may lead to structure failure and sometimes the overall failure of the mission. Sloshing of free liquid in a tank, which is instigated by the manoeuvring and/or acceleration of the launch vehicle, often causes the generation of dynamic instabilities of the whole system. Various devices and techniques have been developed and experimented to counteract or significantly mitigate the sloshing. Such devices and techniques have been discussed and briefly compared in this study to highlight the slosh suppression effectiveness and efficiency of a device.
Keywords- Sloshing, Slosh Suppression, Propellant Tanks, Liquid Rocket Engines, Baffles.

I. INTRODUCTION

Sloshing, the intervallic motion of the free surface of the liquid, in a partly filled propellant tank is of destructive and damaging nature as it leads to the induction of additional vibration and stresses on the tank's structure [1]. Liquid rocket engines utilize fuel and oxidizer in liquid form which is stored in propellant tanks. Similarly, hybrid rocket engines use a combination of fuel and oxidizer in which one of the propellant is stored in solid form while the other is stored in liquid state [2]. In such rocket engines or spacecraft, sloshing of the liquids can occur due to vehicle motion during launching, ascend and manoeuvring [3]. Based on the type of motion and propellant tank's geometry, the free liquid surface can encounter diverse types of liquid motions i.e. planar, non-planar, rotational, and symmetric, asymmetric, etc. [4]. Sudden and significant variations in the acceleration of the vehicle occurring mainly at launching and at burnout conditions may also lead to considerable magnitudes of sloshing to occur in the tanks. The exposure of launch vehicles to unexpected and intense wind shears and gusts also induces sloshing in propellant tanks [5].

The generation of additional and unpredicted vehicle acceleration leads to the generation of undesirable forces and moments when the free surface of the liquid is allowed to move [6]. When the vehicles guidance and control systems sense and accordingly responds to these perturbations, a closed-loop is formed which lead to vehicle's static and dynamic instabilities. These induced instabilities often lead to structure failure and untimely engine shutdown [7]. Loss of significant quantities of propellant through the tank's vent system due to propellant sloshing is also an area of concern. Unexpected loss of propellant may result in underperformance of the whole propulsion systems and/ or may lead to mission failure [8].

In near and zero gravity conditions, minimal slosh frequencies may generate insignificant forces and moments on the vehicle and may adversely affect the guidance and control system operation [9]. The excitation of slosh frequencies and characteristics are governed by the relative position of the center of gravity of the sloshing mass and the vehicle's center of gravity. Propellant sloshing may also cause momentarily uncovering of the propellant drain line [10]. Such occurrence and lack of suitable slosh suppression techniques and devices had led to failure of several booster vehicles. For example, stepped-pitch program may have stepping intervals near the propellant slosh frequency which may cause the vehicle to go out of control due to pitch-reinforced slosh. Slosh-induced instabilities and additional stresses on the structure may also be the cause of structure failure in vehicles. A premature engine shutoff was encountered during the first Saturn-1 flight owing to the induction of rotatory sloshes due to the coupling with the roll-control loop of the guidance system [11].

Slosh suppression devices are employed to damp such unwanted liquid motions and avert any kind of subsequent instabilities [12]. Variation in most of the parameters is cumbersome owing to the inherent propellant sloshing dynamics. The proper choice of control system sensing elements can enhance vehicle's stability thereby reducing damping requirements. Various devices are developed and are currently used to lessen the structural loads induced by the sloshing of the liquid, to regulate location of liquid

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mass within the tank, to deviate the position of liquid-impact loads caused by motions induced by sloshing through deflectors to safeguard tank wall and other structures [13]. Significant alteration in tank design, such as compartmentalization, may lead to the reduction of slosh induced forces and moments. Compartmentalization also results in reduction of sloshing liquid mass and shift of slosh frequencies [14].

II. SLOSH SUPPRESSION DEVICES AND TECHNIQUES

One of the contemporary solutions of the propellant sloshing problem includes the use of slosh suppression devices which significantly decrease the damping intensities of the liquid sloshing instigated by the vehicle motion. Numerous types of such other techniques have been developed although they are not employed for space applications. Various geometrical design and orientations of baffles i.e. rigid-ring baffles, flexible flat-ring baffles, cruciform baffles, conical baffles, etc. are integrated in the structure of the tank, have been used in launch vehicles for the purpose of slosh suppression [15]. Other devices installed and utilized for slosh suppression are deflectors, floating cans (lids and mats), positive-expulsion bags and diaphragms. Damping Factor is usually expressed as single parameter to apprehend the effectiveness of any specific suppression device. This parameter has greatly been utilized in various mathematical models which are designed and developed to simulate slosh impact loads and propellant slosh dynamics [16].

Conventionally baffles are installed in the tank at a location marginally below the expected surface level of the liquid at the time suppression is required. These baffles may be designed as independent devices or they simply can be tank-wall-stiffener rings required for structural reasons and increased in size to provide adequate damping [17].

Lateral baffle are observed to offer strong slosh suppression of under longitudinal acceleration only while oblique baffle are observed to reduce longitudinal as well as lateral slosh forces and moments under combined longitudinal and lateral acceleration of the propellant tank [18].

A. Rigid-Ring Baffles

The most frequently utilized slosh suppression configuration in cylindrical tanks is a series of flat-ring baffles as shown in Figure 1. For a series of flat-ring baffles, linear superposition is utilized to calculate the damping ratios. As spacing between the baffles become smaller, perhaps less than one baffle's width, the superposition is inefficient in accurate prediction of damping. Various other cross-sectional geometries of rigid-baffles in circular cylinder tanks have also been utilized and experimented to analyse the damping provided [19].

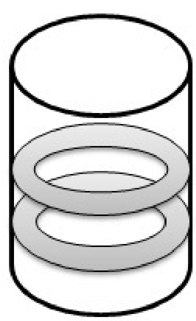

Figure 1: Ring baffles used for slosh suppression

Very little information is available concerning the damping provided by baffles in spherical, oblate and prolate-spheroidal, toroidal and other tanks that differ from circular cylinder [20]. The design of ring-baffle slosh suppression system is based on selecting system's baffle width, spacing and depth of the top baffle to give the required damping ratio ζ as a function of liquid level in the tank [21]. For a flat-rigid baffle in a cylindrical tank, the damping ratio as a function of baffle's depth d should be estimated from Miles' equation (1):

$$\zeta = \frac{\delta}{2\pi} = 2.83\, e^{-4.62\frac{d}{a}} \left[\frac{2w}{a} - (\frac{w}{a})^2\right]^{\frac{3}{2}} \left[\frac{\gamma}{a}\right]^{\frac{1}{2}}$$

Where,

W = width of the baffle,
γ = maximum slosh-wave height at the wall
δ = damping factor (or logarithmic decrement)

The term in bracket is the tank area covered by the baffle. Baffle perforation is of crucial importance for the purpose of weight minimization. Baffle performance depends on both the perforation size of the perforation and the percentage of material removed. Removal of 20% to 25% of the baffle material is considered being near optimum [22].

B. Cruciform Baffles

These types of baffles are generally integrated with the wall structure and are located in the same manner as stringers in the circular cylinder. Such practise provides an advantage of damping of the liquid that is independent of its height. Only a small amount of damping is provided by cruciform baffles, except when the tank is nearly empty. Cruciform baffles are generally utilized to damp rotary motions or vortex formation near the tank drain outlet. In those cases, a suitable method for estimating damping ratio depends upon using an empirical relation for drag coefficient C_D [23]. For flat plates exposed to sinusoidal flow, the following equation 2 can be fitted:

for $2 \leq \left(U_{max}\,\frac{T}{D}\right) \leq 20, \quad C_D = \frac{15}{\left(U_{max}\,\frac{T}{D}\right)^{\frac{1}{2}}}$

for $\left(U_{max}\,\frac{T}{D}\right) \geq 100, \qquad C_D = 2$

where,
U = (U_{max} cos ωt) is the fluid velocity,
T = $\frac{2\pi}{\omega}$ is the period of oscillation, and
D is the depth of the plate.

C. Other Slosh Suppression Devices

Large amplitude liquid motions, excited by sudden engine cut-off or by the throbbing of altitude-control engines during orbital coasts are supressed by the utilization of deflectors. Deflectors are strategically placed above the liquid free surface level and are designed in the shape of wide, inverted or upright conical ring baffles to prevent the liquid propellant from reaching the tank vent and to facilitate efficient propellant drainage. Submerged deflectors have also been experimented to analyse the contribution to slosh suppression. Several other slosh suppression devices which are movable i.e. floating lids, porous mats, etc. and act as liquid's free surface have also been utilized in propellant tanks. However, such devices are found to be comparatively less efficient than conventional baffles and may lead to increased difficulties and unnecessary weight increments [24].

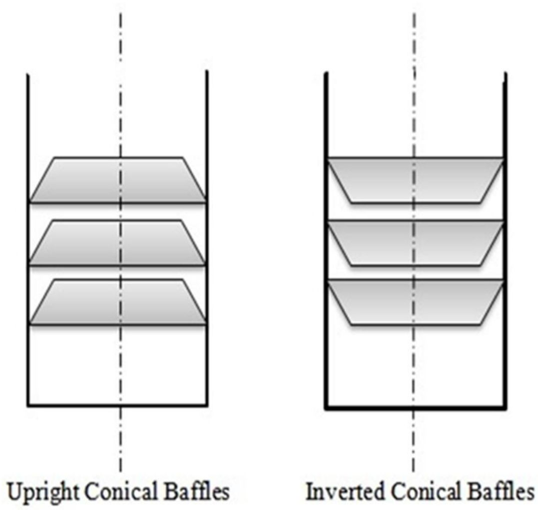

Figure 2: Upright and inverted conical baffles

D. Tank Compartmentalization

Compartmentalization of a cylindrical propellant tank is an efficient technique to shift the liquid resonant frequencies within a more

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desirable range while simultaneously providing significant reduction in the magnitude of the sloshing mass. To achieve the same, a cylindrical propellant tank is compartmentalized into multiple divisions using radial or annular dividers as shown in Figure 3 [25]. Perforation of these radial dividers leads to reduction in the overall weight of the slosh suppression device. The degree of perforation is optimized with respect to perforation size of the perforation and percentage of material removal. Consideration of slosh induced pressure on the walls of compartmentalized tanks is crucial during vehicle's stability analysis as it may lead to roll induced coupling between the propellant and vehicle motion [26].

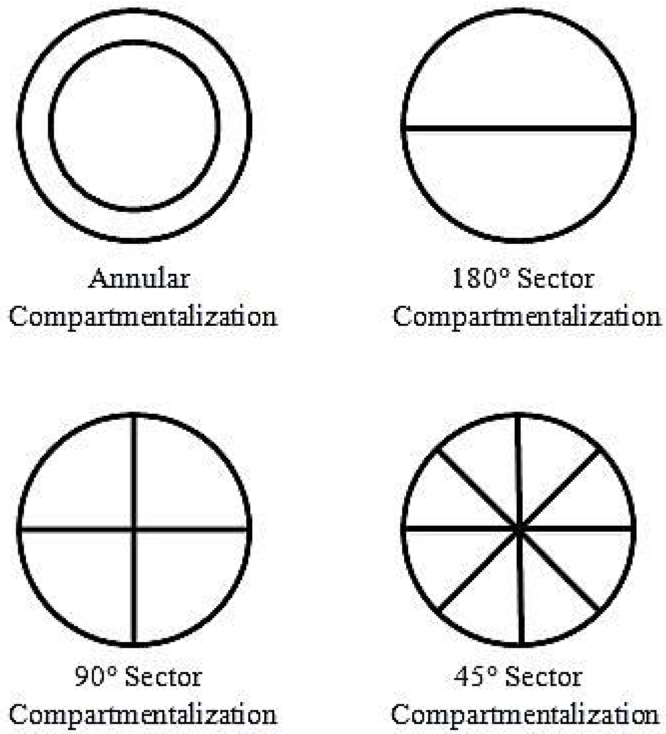

Figure 3: Annular and sectored tank compartmentalization's

III. DESIGN CONSIDERATIONS AND COMPATIBILITY REQUIREMENTS

Proper and efficient liquid drainage during launch and ascent and efficient venting in cryogenic propellants is an important criterion to consider during baffle design. The inclusion of gaps between the baffles and the tank walls, inclined baffles, perforated baffles, or a combination of them are a few efficient measures to achieve the same. A large enough gap size should be present to deliver adequate liquid drainage while simultaneously facilitating efficient slosh suppression. Effective reorientation of the flow pattern in low gravity operations is expected of any baffle design. For some configurations gaps between baffle and wall may be advantageous while for other configurations this technique may not be helpful; care must be exercised in the use of gaps at low Bond-number conditions to avoid fluid entrapment [27].

Compartmentalization in cylindrical tanks tends to the accumulation of the liquid at the tank axis and at the sector wall intersections which aid reorientation of the liquid flow. The amount of propellant trapped by the baffles during relocation, the effect of baffles on the reorientation of the flow and the resulting resettling time must be carefully considered in determining propulsion system performance requirements.

The heat transfer characteristics of internally insulated tanks must be taken into consideration while designing the attachment of the slosh suppression devices to the tank wall. Surface tension and capillary forces of the propellant should be put into considerations and calculations while selecting the size of the deflector to ensure that return of the propellant trapped above the deflector to the tank bottom. Use of reversed conic sections enables the return of the propellant to the tank bottom [28].

IV. CONCLUSION

Numerous computational simulations and experiments have been performed to apprehend the effectiveness of various baffle designs

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and shapes. For example, NASA technical note D-694, briefly discusses experiments involving the damping characteristics of semi-circular plates placed at given intervals around the inside of the tank. Successful suppression of propellant slosh in the tanks of a launch vehicle has been achieved by the use of rigid annular ring baffles. However, significant weight addition to the overall vehicle's weight has been observed due to inclusion of ring baffles of this type. Such unnecessary weight increments due to integration of slosh suppression devices detrimentally bounds the weight of other items on-board the launch vehicle i.e. payload, propellant, equipment, etc. The selection of an effective and efficient propellant slosh suppression device or technique relies on its capabilities to satisfy the slosh suppression requirements while ensuring adequate structural integrity and compatibility with vehicle and vehicle systems.

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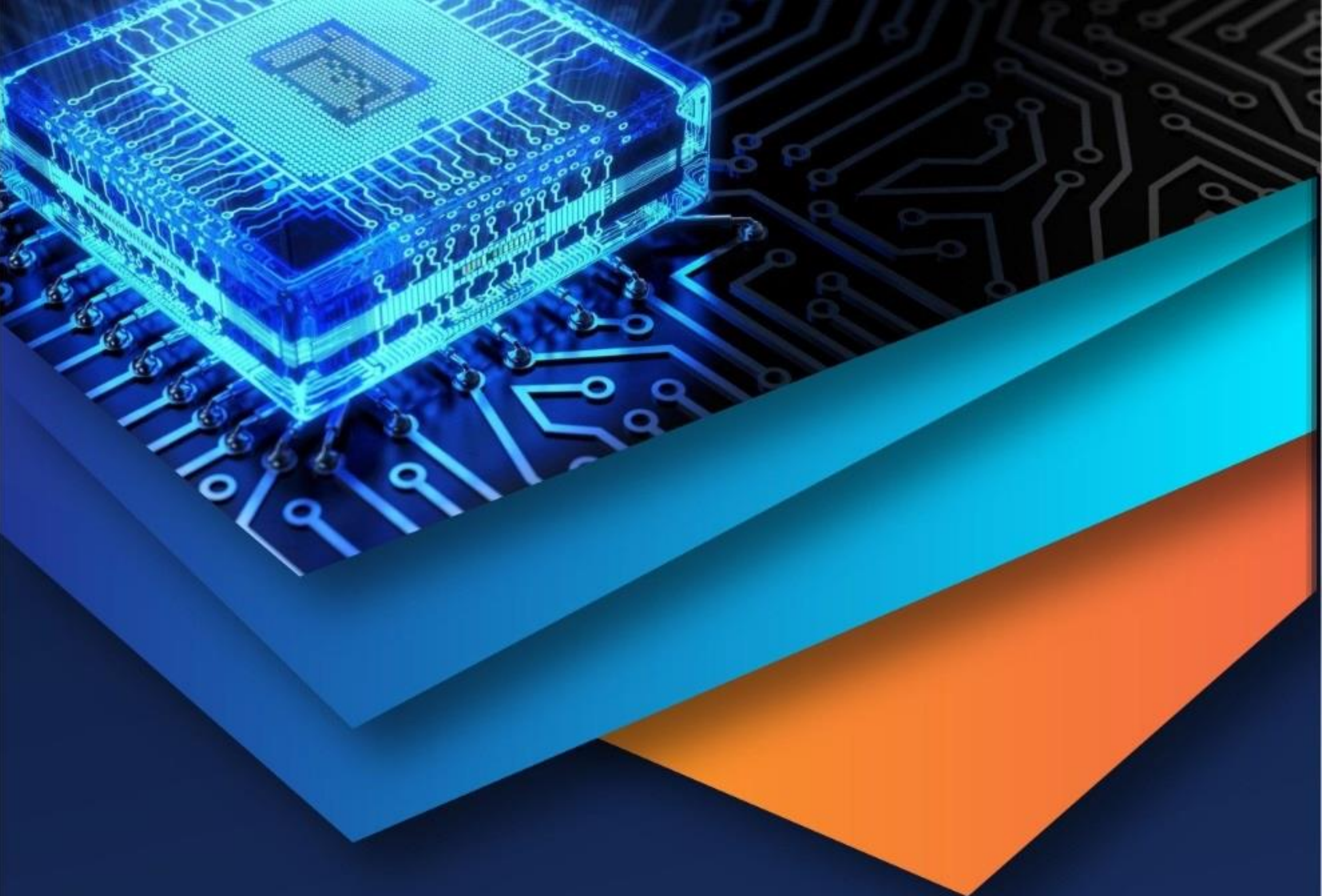

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