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Study of different parameters governing the sloshing of liquid in partially filled tank: A review

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Abstract- Numerous engineering applications exhibit the sloshing phenomenon, including water towers, storage tanks subjected to excited ground motion, large dams, LNG ship containers, and automobiles carrying oil tanks, etc. Excessive liquid motion within a container can cause localised pressure concentration on the tank walls, leading to structural damage. Additional liquid sloshing may affect the vehicle's stability and lead to a serious collision. One of the most critical problems that is closely connected to tank vehicle stability is the presence of liquid forces and moments as a result of liquid sloshing. Sloshing that occurs in sections of the tank that are stable often generates cyclic stress and fatigue in thin-walled tank structures. On the other hand, sloshing that occurs in regions of the tank that are unstable can result in catastrophic ullage collapse or ballast. Baffles are known to lower the amplitude of fluid slosh in tanks that are only partially filled. This effect is particularly noticeable during deceleration and acceleration. The sloshing phenomenon is governed by various factors, including tank shape, abrupt braking, baffle plate design, baffle plate placement, etc. In the present study, the research conducted on these factors, as well as the various experimental and numerical studies, are summarised. The article concludes with a summary of the article's most significant findings.

Keywords- Vehicle rollover; Sloshing behaviour; Baffle plates; Abrupt braking; Experimental study; Numerical simulations.

1. INTRODUCTION

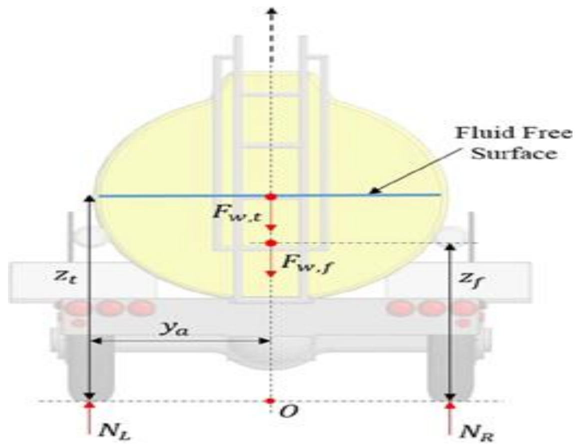
The higher centre of gravity of tanker trucks makes them more susceptible to rollovers versus passenger cars. Approximately 78 % of tanker truck rollovers are caused by driver mistakes. Other causes include vehicle and road characteristics, load size, and vehicle and road conditions. Tanker trucks commonly transport hazardous products, and accidents where the tank is damaged and the contents are expelled can result in environmental and infrastructural damage, explosion hazards, as well as human injuries and deaths. According to the most current report from the World Health Organization (WHO) for 2018 [1], India accounted for 11% of worldwide road accidents and ranked #1 in terms of road deaths. Despite comprising only 5% of the nation's road network, Indian National Highways are responsible for 55% of road fatalities and 61% of road fatalities. Commercial Vehicles (CV) or trucks deliver the majority of freight on these roadways, which increases their collision risk. In the next few years, the country's economy is anticipated to expand; hence, the requirement for CVs that fit with international classification in the supply chain will be vital. In 2019, a total of 23314 accidents (5.2%) were ascribed to car overturns or rollovers, resulting in 9011 deaths, or 6% of all fatal crashes [2].

Sloshing is the motion of liquid in a partially filled container generated by the erratic movement of the container and the sound of splashing. Numerous engineering applications exhibit the sloshing phenomenon, including water towers, storage tanks subjected to excited ground motion, large dams, LNG ship containers, and automobiles carrying oil tanks, etc. In addition to civil engineers and seismologists, researchers in the aerospace and nuclear industries, design engineers, mathematicians, and physicists are also interested in the phenomenon of liquid sloshing. Excessive liquid motion within a container can cause localised pressure concentration on the tank walls, leading to structural damage. Additional liquid sloshing may affect the vehicle's stability and lead to a serious collision. The phenomenon of sloshing was theoretically investigated by Lamb [3] in 1879. Beyond this, the earliest study of sloshing was conducted in 1761 by Euler [4]. In the past 50 years, academic researchers have become significantly more interested in liquid sloshing issues. Early researchers employed equivalent mechanical models to investigate and develop solutions for liquid sloshing.

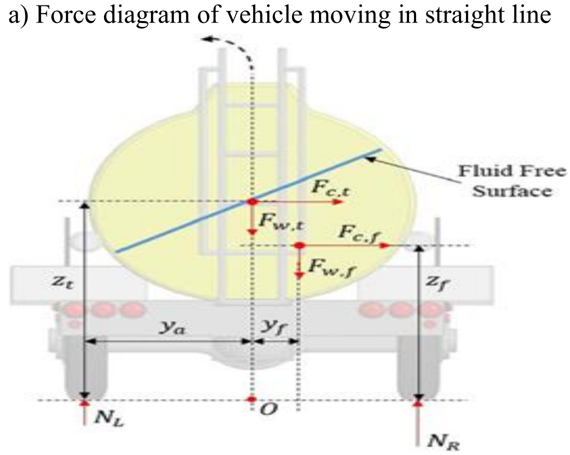
The sloshing phenomenon is governed by various factors, including tank shape, abrupt braking, baffle plate design, baffle plate placement, etc. In the present study, the research conducted on these factors, as well as the various experimental and numerical studies, are summarised. An attempt has been made to review the current state of knowledge regarding the phenomenon of sloshing, its causes, and its effects on vehicle rolling stability.

2. VEHICLE ROLLOVER AND SLOSHING

The measured values of cargo load shift in the pitch and roll planes are strongly dependent on tank size, tank cross-section, fill volume, as well as the magnitudes of longitudinal and lateral acceleration. The liquid bulk's mass moments of inertia fluctuate the most noticeably when the bulk is subjected to brake deceleration, but the influence of lateral acceleration is quite minor. The detrimental effect of liquid cargo shift is demonstrated by comparing the dynamic characteristics of a partially filled liquid cargo vehicle during braking in a turn maneuver to that of an equivalent rigid cargo vehicle. This performance is derived in terms of the vehicle's directional and roll performance parameters, as well as its braking performance. Under increasing degrees of steering and braking input, the liquid freight vehicle displays a greater amount of liquid load shift as well as variations in axle loads. This is because the vehicle experiences more lateral and longitudinal accelerations. When driving on a road that is completely dry, applying the brakes during a turn has the effect of dramatically increasing the LTR, and as a result, the probability that a vehicle that is only partially loaded with liquid cargo may roll over [5]. However, considering that only the inner trailer wheels lock up, the liquid freight vehicle does not have much of an effect on the yaw response. The application of braking force throughout a turn on a dry road does not cause yaw instability; however, it does significantly reduce the braking performance of a vehicle transporting liquid cargo. This is because it causes a sharp increase in the wheel-slip reaction of the trailer wheels, which is caused by increased load transfer due to the movement of the liquid. On a wet or slick road with lowered friction possibility, the substantial load transfer in the situation of a liquid cargo vehicle induces lockup of both the inside and outside wheels of the trailer. This results in a severe drop in the lateral forces that provokes a violent yaw motion of the trailer, which indicates that there is potential for the trailer to swing. The combination of a tank that is only partially full and the vehicle will start to demonstrate yaw instabilities well before the rollover limit is reached.



a) Force diagram of vehicle moving in straight line



b) Force diagram of vehicle taking turn

Fig. 6 Vehicle movement Force diagram [6]

Fig. 6 a) is a force diagram for a vehicle model in linear direction. In this diagram, F_{wt} represents the gravity force acting on the tank at its centre of mass, which is located at a vertical distance z_t from the ground; F_{wf} represents the gravity force acting on the fluid at its centre of mass, which is located at a vertical distance z_f from the ground. Fig. 6 b) is a force diagram for a vehicle model in curved motion. N_L and N_R are the normal forces acting on the left and right wheels, respectively, and they are positioned y_a units away from the origin point O. When moving in a straight line, no lateral nor centrifugal forces are acting on the fluid nor the vehicle because there is no rotational motion taking place. These steady-state normal forces are determined to be by taking the moments of the forces about point O, as was anticipated; the results are as follows:

$$N_L = N_R = (F_{wt} + F_{wf})/2 \qquad (1)$$

This indicates that each wheel is responsible for carrying one-half of the overall weight of the vehicle.

Compare this to the force diagram shown in Figure 6b, which shows that the vehicle has moved into an anti-clockwise constant-radius circle. This is denoted by the dashed arrow that is located above the diagram. Centrifugal forces The F_{Ct} and F_{Cf} forces are applied, respectively, on the tank and the fluid. Both tyres experience lateral friction forces F_f that act in the opposite direction from one another. It is possible to construct the following equations for the left and right tyre contact forces by making use of the moments that are induced by these forces.

$$N_L = F_{wt} + F_{wf} - N_R \qquad (2)$$

$$\text{and } N_g = (X_a\,(F_{ct}Y_t + F_{cf}Y_f + F_{wf}X_f) + (F_{wt} + F_{wf})/2 \qquad (3)$$

Kang et al. [5] developed a three-dimensional quasi-dynamic model of a half - filled tank with a circular cross-section and incorporate it into an extensive three-dimensional model of an articulated vehicle to study the directional response of the vehicle to varying amounts of steering and braking input data, fill volumes, and road surface friction. The goal of this research is to better understand how an articulated vehicle responds to changes in these factors. When lateral (*a/y*) and longitudinal (*a/x*) accelerations are applied, the free surface of the liquid in a circular tank that is only partially full can take on a number of different configurations, such as the one seen in Fig. 7. The free surface of the liquid in a tank with a length L is represented by the notation ABDC, and its gradients with respect to the tank's fixed longitudinal (X) and lateral (Y) axes are respectively represented by the angles α and ϕ. In a three-dimensional tank axis system, the equation of hydrostatics can be utilised to obtain the equation of the liquid free surface in terms of x and z coordinates (OXYZ).

$$f_s\,(x, z) = \frac{(C_0 - F_x x - F_z z)}{F_y} \qquad (4)$$

Where, f_x, f_y and f_z are body forces per unit mass of the liquid along OX, OY and OZ directions, respectively, and C_0 is a constant.

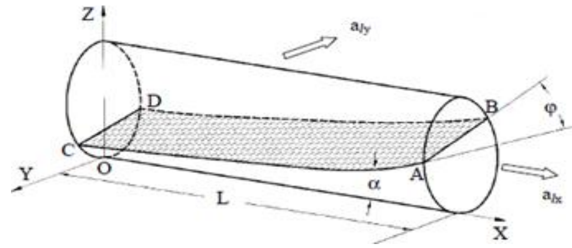


Fig. 7 Free surface of liquid under application of longitudinal and lateral accelerations [5]

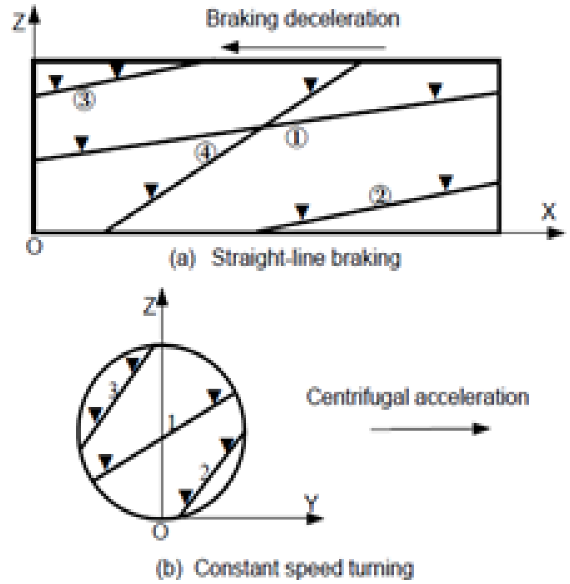


Fig. 8 Patterns of free surface of liquid cargo in the tank subject to longitudinal and lateral accelerations

The free surface of a liquid can take on a wide range of various patterns, and these patterns are determined by the magnitudes of the lateral and longitudinal excitations, the fill volume, and the geometry of the tank. Some of these patterns are illustrated in Fig. 8 depicting pitch and roll planes. During a braking maneuver that is performed in a straight path, the liquid free surface may take one of four different patterns, which are represented in Fig. 8. (a). Pattern 1 could've been realised under circumstances of medium fill volume and low deceleration; patterns 2 and 3 arise under circumstances of extremely low fill volume and high fill volume, respectively. Pattern 4 of the displaced fluid volume relates to a circumstance of intermediate fill and strong deceleration. This condition was observed when the fluid was being deflected. During steady turning manoeuvres, the liquid free surface in the roll plane of a tank with a circular cross-section might take one of three unique patterns, as shown in Figure 8. (b). Pattern 1 has a moderate fill volume and modest roll angle and lateral acceleration resonances. It also has a moderate lateral acceleration. Figure 7 shows that under very low and high fill volumes, the free surface of liquid may sit on only one side of the vertical axis of the tank. This is indicated by patterns 2 and 3. (b).

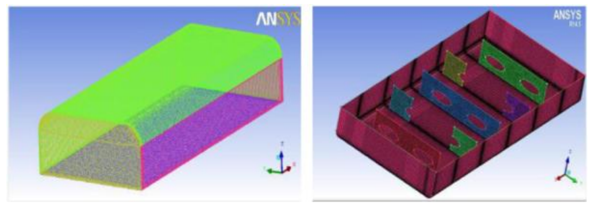
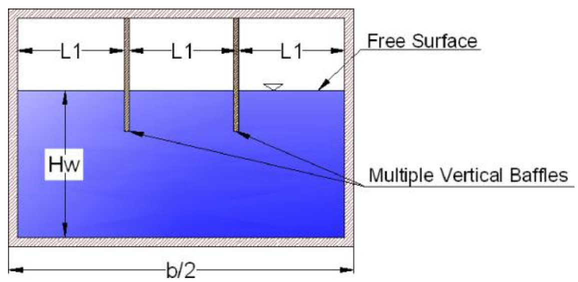
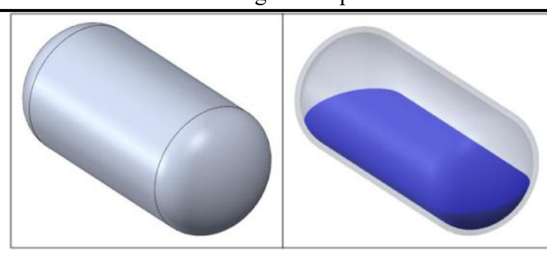
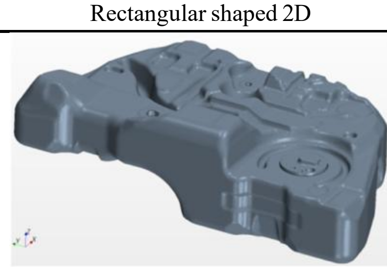
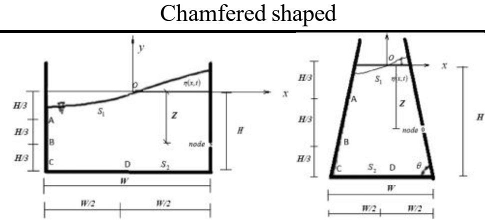
Dai et al. [7] created a model of the liquid flowing inside the cargo container by applying the theory of potential flow to the situation. The findings suggest that large oscillatory forces are applied to the wheels of the car throughout the braking process. These forces are likely caused by the motion of the liquid as it sloshes around. When trying to come to a complete stop, a train carrying liquid freight needs a higher ideal braking torque than a train carrying solid cargo. Emanuele et al. [8] analyse the impact that crude oil sloshing has on the longitudinal stability of a train by taking into account a variety of braking scenarios, one of which being electronically controlled pneumatic (ECP) braking. It takes less time for the coupler force response to the sloshing excitations induced by ECP braking to achieve steady state as the viscosity of the fluid being braked increases. In addition, the installation of bulkheads in tank cars can decrease the maximum coupler force by as much as seventy percent and more uniformly distributes normal contact forces to both the front and back wheels. The model that was used by Otremba et al. [9] considers the concatenation of the roll and pitch independent reactions, and all four wheels of the vehicle are fitted with brakes that are part of an Anti-lock Braking System (ABS). The impact of cargo sloshing on a vehicle's performance can range anywhere from 2% to 9%, according to the studies, and this range is dependent on the performance metric that is being studied.

3. DIFFERENT TANK SHAPES USED FOR THE STORAGE OF LIQUID

One of the most critical problems that is closely connected to tank vehicle instabilities is the presence of liquid forces and moments as a result of liquid sloshing. Sloshing that occurs in sections of the tank that are stable often generates cyclic stress and fatigue in thin-walled tank structures. On the other hand, sloshing that occurs in regions of the tank that are unstable can result in catastrophic ullage collapse or ballast. In partially filled tanks, baffles are known to reduce the amplitude of fluid slosh, particularly during braking and acceleration. Toumi et al. [10] created an analytical model for a cylinder-shaped tanker by employing the Navier-Stokes equations to analyse its dynamic stability behaviour. The correlations study's outcomes are sufficient for single or double lane change maneuvers. Chitkara et al. [11] utilised a rectangular-shaped fuel tank with chamfered corners and a fuel-to-air ratio of 60:40. In comparison to a tank without baffles, the use of baffles reduces the velocity distribution within the tank by a significant margin. A neural network response prediction utilised by Mahmod et al. [12] for a rectangular-shaped tank illustrates the required width of the tank when excitation is applied in one of the primary directions. The study also found that two or four evenly spaced baffles can reduce the sloshing effect by half compared to the original. In order to compute the response of the vehicle during a lane change maneuver, Barton et al. [13] use CFD and MBD solvers that are connected in both directions. A calculation is made on the distribution of the liquid inside the cargo tank structured like a capsule. Once the transition into the new lane is complete, the fluid's motion within the tank will come to a stop. It was found out that the quantity of fluid in the tank has a direct effect on the solver's ability to resolve the free surface. This was a really interesting discovery. Cao et al[14] .'s research on a 2D rectangular model of a tank subjected to sloshing focuses primarily on the difficulties encountered by the Smoothed Particle Hydrodynamics (SPH) model. Even though SPH is a mesh-free method for solving large deformation, the kernel function renders it inaccurate and unstable, according to the study. Also, it was discovered that baffle plates reduce the sloshing height by nearly 90 percent compared to when none are used.

Table 1. Summary of research work performed on effect of tank shape on sloshing

Sr. No.	Authors	Tank shape used	Parameters studied
1.	Toumi et al. (2009)	Cylindrical	Dynamic stability behaviour

2.	itkara et al. (2013)	 Rectangular shaped with chamfer	Velocity distribution
3.	mood et al. (2013)	 Rectangular shaped	hing behaviour, ANN response prediction
4.	arton et al. (2014)	 Capsule shaped	distribution within the tanker
5.	Cao et al. (2014)	Rectangular shaped 2D	SPH model, sloshing behaviour
6.	haval et al. (2014)	 Arbitrary shaped	Pressure distribution
7.	Ikeda et al. (2015)	Rectangular shaped	Liquid distribution within tank
8.	Joshi et al. (2016)	Chamfered shaped	FSI study, pressure distribution
9.	Saghi et al. (2016)	 Rectangular and trapezoidal shaped	Free surface fluctuation, pressure distribution
10.	Jena et al. (2017)	Rectangular shaped 2D	Sloshing wave amplitudes, pressure distribution

A numerical model of the VOF model used by Dhaval et al. [15] with the LS- DYNA solver for an arbitrary-shaped fuel tank. According to the results, the pressure distribution on the tank's surface can indicate the sloshing acoustic. Ikeda et al. [16] conducted research on nonlinear rectangular tanks that were excited with horizontally oblique harmonic waves. The probability of liquid overflow can be determined by looking at distribution charts of the maximum liquid surface elevation that have been calculated in three dimensions. In addition to this, we look into how the frequency response curves are affected by the orientation of the horizontal excitation direction relative to the tank side. A Fluid-Structure Interaction (FSI) study was carried out by Joshi et al. [17] on sloshing liquid and its impact on the tank's stability, taking into consideration a number of reducing factors. It was determined that air pockets, hydraulic leap, roof hit, and flip through were key elements affecting the dynamic stability of the cargo carrier. The comparison of the simulated results demonstrates that there is a significant drop in the impact pressure (either maximum or average) in a slightly curved tank with baffles at the bottom. An examination of the free surface displacement that occurs in rectangular and trapezoidal tanks as a result of sloshing was provided by Saghi et al. [18]. According to the findings, the free surface fluctuations in trapezoidal storage tanks reach their maximum value considerably more quickly than they do in rectangular storage tanks. The findings also indicate that the horizontal force that is imposed on the tank perimeter in trapezoidal tanks is significantly less than that which is exerted on the tank perimeter in rectangular tanks, and that the vertical force that is imposed on the tank perimeter in trapezoidal tanks is significantly less than that which is exerted on the tank perimeter in rectangular tanks. Jena et al. [19] made five adjustments to the traditional Moving Particle Semi-implication (MPS) approach in order to investigate the sloshing behaviour that occurs in a rectangular tank that is only partially filled with liquid. In order to compute the sloshing wave amplitudes and the pressure that is exerted on the tank walls, the model is applied successfully to a tank that is only partially filled and is subjected to horizontal sinusoidal excitation.

4. EFFECT OF BAFFLE DESIGN ON SLOSHING

Yan et al. [20] studied the function that four different transverse baffles concepts had in preventing slosh using a verified CFD model. The transverse baffles raise the frequency of the slosh that occurs in the longitudinal mode while simultaneously lowering the longitudinal force and pitch moment. When it comes to reducing or eliminating turbulent flow in a fluid, the form and location of orifices in baffles are two of the most important factors. Panigrahy et al. [21] studied the pressure distribution at several sites with variable fill depths in a square tank fitted with horizontal and vertical baffles. Their findings are illustrated in Figure 9, which can be found below. When the tank is only partially full, the maximum free surface displacement of the liquid in the tank increases at a rate that is greatest relative to the excitation frequency. According to the research, ring baffles are more efficient than traditional horizontal baffles in a number of ways. The reason for this is that the ring baffles take in energy from all of the walls and then distribute it to the other walls.

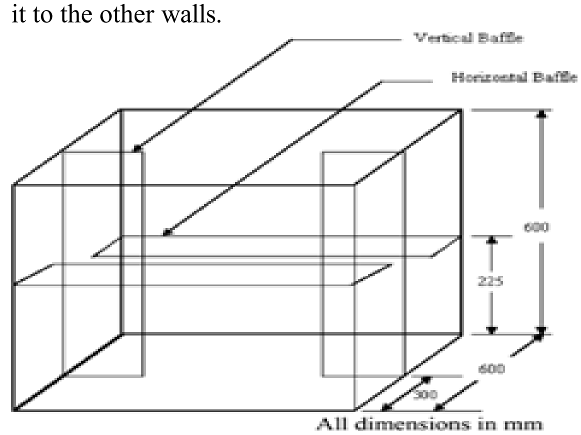
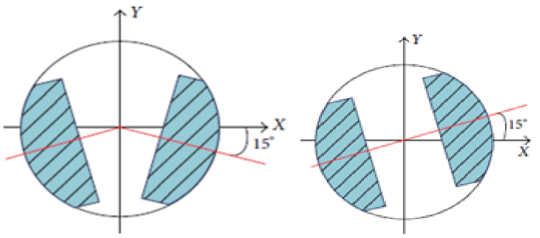


Fig. 9 Tank depicting baffles arrangement [21]

Zheng et al. [22] conducted research on the impact of transverse baffles on the sloshing of liquids in partially filled tank vehicles. Their findings are represented in Figure 10. The staggered baffle is the one that is shown to be the most effective at reducing the sloshing of liquid when compared to the other three baffles chosen from each type of baffle. The baffle is going to be more effective at preventing sloshing around if it has a wider anti-sloshing area. Additionally, the distance between neighbouring baffles can considerably contribute to the development of liquid sloshing; as a result, it is recommended that the distance be made as low as possible. Reddy [23] utilised a few vertical porous baffles to cut down on the amount of sloshing that occurred within the tank when the diesel fuel was being stored. The elliptical form of the tank that was employed in this investigation significantly cuts down on the amount of internal sloshing that occurs. The effects of a partially perforated baffle on the dynamic response of the tank are computed by Kumar and Sinhamahapatra [24] for three different arrangements of perforation. The optimal perforation layout is found to provide the best dynamic benefits and decreased weight penalty without sacrificing rigidity or stiffness, and it is found that this configuration can be achieved through the use of a partially perforated baffle. The forces exerted near the free end of the bottom-mounted baffle is stronger than the forces applied on the surface-piercing baffle, which is why the surface-piercing baffle is preferable to the bottom-mounted baffle.

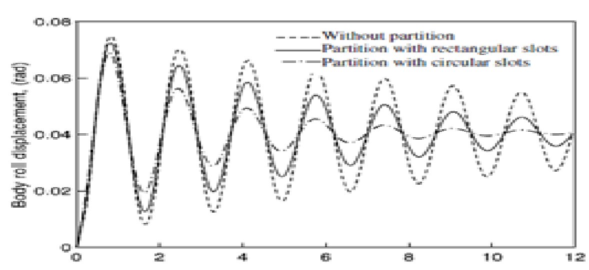


a) The reverse staggered baffle
b) The similar staggered baffle
Fig. 10 Types of baffle used for study [22]

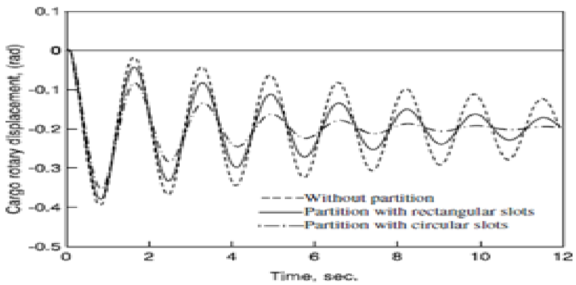
A numerical analysis on circular water tanks containing and without baffle walls was carried out by Chaudhari et al. [25] for the purpose of analysing hydrodynamic forces and historical earthquake data. The total deformation of the tank is reduced in vertical baffled tanks as well as ring baffled tanks when compared to tanks that do not have baffle walls. Using a rectangular tank with varied porosities, lengths, and submersion depths, Cho et al. [26] arranged a few baffles in the centre of the tank as well as on both of its edges. When compared to a baffle that is positioned in the tank's centre, horizontal porous baffles that are installed at both of the tank's walls are much more effective in suppressing violent resonant sloshing responses. Sloshing of liquids in gravity-driven baffled and unbaffled rigid tanks is the primary focus of the method that was used by Gnitko et al. [27]. The baffles that were employed in the study consisted of a circular flat plate with an opening in addition to conical baffles that were positioned throughout the tank in a variety of sizes and orientations. Alexandro et al. [28] examined how the sloshing behaviors of liquid cargo in the reservoir of a roadgoing tank were affected by the arrangement of lateral baffles inserted in the reservoir of the tank. These baffles were installed in the reservoir of the tank. The weakest stresses were found in the case of a perforation partition with a convex shape that had a considerable radius of curvature in the region that was closest to the connection to the tank shell and a much lower radius in the portion that was further away from the connection. Kim et al. [29] investigated the effectiveness of an air-trapping system in reducing the effects of sloshing in two-dimensional rectangular tanks that were either equipped with baffles or did not have any. The tanks were excited horizontally. In order to investigate the effects of sloshing on impact pressure suppression within the tank, five different scenarios with fixed baffle spacing and varied baffle lengths were tested. The dimensionless factor BR (G/L) in geometry was taken into consideration. According to the findings, an effective reduction in the sloshing impact pressure could be achieved with a BR value of 0.5.

5. EXPERIMENTAL STUDY OF SLOSHING MECHANISM

The slosh forces that are generated by the motion of liquid inside of partially full containers have an effect on the roll dynamic characteristics of tank vehicles. When designing a simple test rig setup for the dynamic truck roll model, Ibrahim et al. [30] took into consideration the suspension's degree of flexibility as well as the nonlinear dynamics of the motion of liquid cargo. Both the body roll displacement and the cargo angular displacement can be greatly reduced by using baffles that have circular slots. This was discovered through the measurement of both metrics. Figure 12 is a representation of the experimental setup that was utilised by Fabella et al. [31] in order to determine the longitudinal sloshing force. The sloshing force is significantly affected more by partial filling levels of 50% and 75% than it is by a full level of 94%. In point of fact, the filling level at 75 percent has the most significant impact. In addition, the utilisation of baffles at a fill level of 94% has no appreciable effect on the amount of sloshing that occurs.



a) Body roll displacement



b) Cargo angular displacement

Fig. 11 Results obtained anti-slosh damper for cylindrical tank trucks [30]

Fig. 12 Scaled experimental test set up used to study the sloshing mechanism [31]

Xue et al. [32] calculated the free surface fluctuation and pressure distribution of the shaking table by adjusting the frequency of the external excitation. The wave-maker consisted of a wave generator that was operated by an electro-hydraulic servo system. Therefore, tiny amplitude liquid sloshing in a rectangular two-dimensional tank that is subjected to harmonic excitation is taken into consideration in the investigations. The horizontal cosine motion, which is broken down into its component parts below, is applied to the liquid tank:

$$X(t) = -a\cos(\omega t) \quad (1)$$

For a rectangular liquid tank with length *L* and water depth *h*, the n^{th} order natural frequency as follows

$$\omega_n = [g k_n \tanh(k_n h)]^{\frac{1}{2}} \quad (2)$$

Considering the potential advantage of the perforated baffle in allowing the LNG tanker payload to be increased without compromising safety, it is considered to be an efficient baffle arrangement in tanks for reducing the sloshing amplitude at higher excitation frequencies. This is because the perforated baffle, when combined with a suitable orifice size, is regarded as an effective baffle arrangement in tanks.

Rajamani et al. [33] contrasted the numerical analysis with an experimental test setup that was created to investigate the performance of free wave propagation in 50% and 60% full tanks with and without baffle. These results are displayed in Figure 3 a) and b). The use of a non-dimensional parameter for height H* as the study parameter in a tank with double baffles results in a parameter value that is found to be minimal. Agawane et al. [34] evaluated the impact of crucial aspects such as filling level and acceleration/deceleration amplitude on the noise generation process. They did this since this phenomena is garnering attention in an age where electric vehicles are becoming more commonplace. Sloshing noise can be thought of as a nonlinear function of the fill level as well as acceleration and deceleration. An examination of the microphone data using a spectrogram reveals that the majority of the noise is low-frequency impact noise. Using dynamic response data, we were able to calculate the sloshing period for both the non-linear and linear regimes, and then we compared our findings to analytical outcomes. The sloshing behaviour that is observed in fuel tanks is a component of a wider NVH (Noise, Vibration, and Harshness) analysis that is being conducted [35] with the goal of developing automobiles that function more smoothly and silently. The sound of "splashing" is produced when waves of fluid collide with one another. When wave fronts come into contact with the tank wall, this results in a "hit." The sound of a "clunk" is created when the sudden compression of air volumes by sloshing liquid. The noise that is made by the sloshing is illustrated in figure 13. During the course of the tests, the level that had the greatest acceleration and pressure also produced the most noise. This suggests that the assessment of these parameters is a significant step toward the assessment of acoustic emission caused by sloshing, which is still in the virtual phase of product development. The computational and experimental findings for the investigation of the location impact of baffles within the fuel tank to decrease sloshing noise showed a positive trend, which bodes well for the final product.

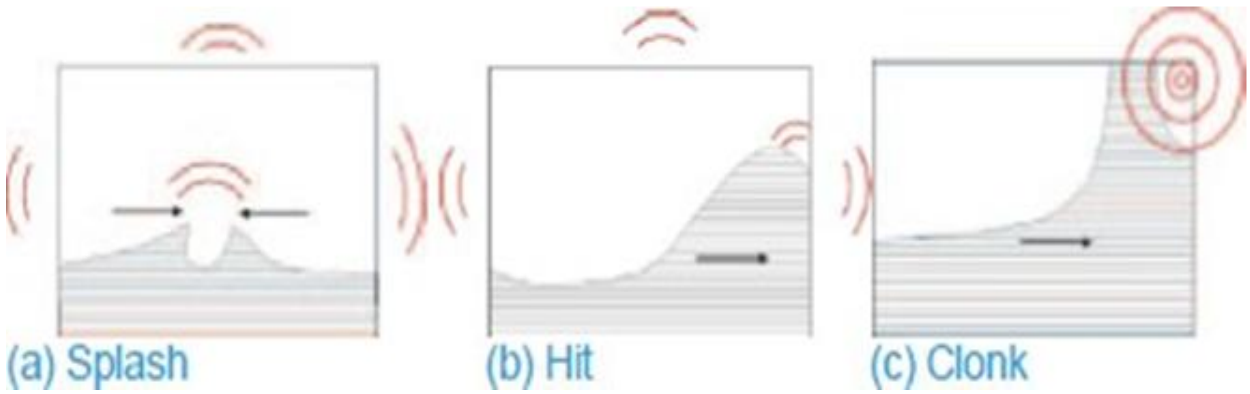


Fig. 13 Types of sloshing noise [35]

In order to investigate the free surface performance of a fuel tank in the physical world, Emma et al. [36] used both experimental and numerical techniques, as can be seen in Figure 14. The comparison found that the largest error percentage between the data was no more than 5.6%, which held true for both the estimation of the fluid's centres of gravity and its free surfaces. The energy absorption performance of a number of different slot layouts was analysed and compared by Demiral and Aral [37], as shown in Figure 15 and Figure 16. The slot-baffle design has the potential to greatly minimize wave displacement and minimize the effects of resonance sloshing when the system is oscillating. This comparison reveals that this particular sort of slot arrangement has a minimal effect on decreasing wave displacements during the oscillation period. This is demonstrated by the fact that there is no significant difference between the two. Suppression and solidity ratio are two examples of system performance measures that were discovered as a result of the research carried out by Yu and colleagues [38]. The contrast between the clean tank and the perforated plates reveals that all three varieties of perforated plates are successful at reducing the run-up and collision pressure along the bulkhead. According to the results of the parametric analysis, out of the three various configurations, the perforated plate that has the median solidity ratio is the one that does the best job of preventing sloshing.

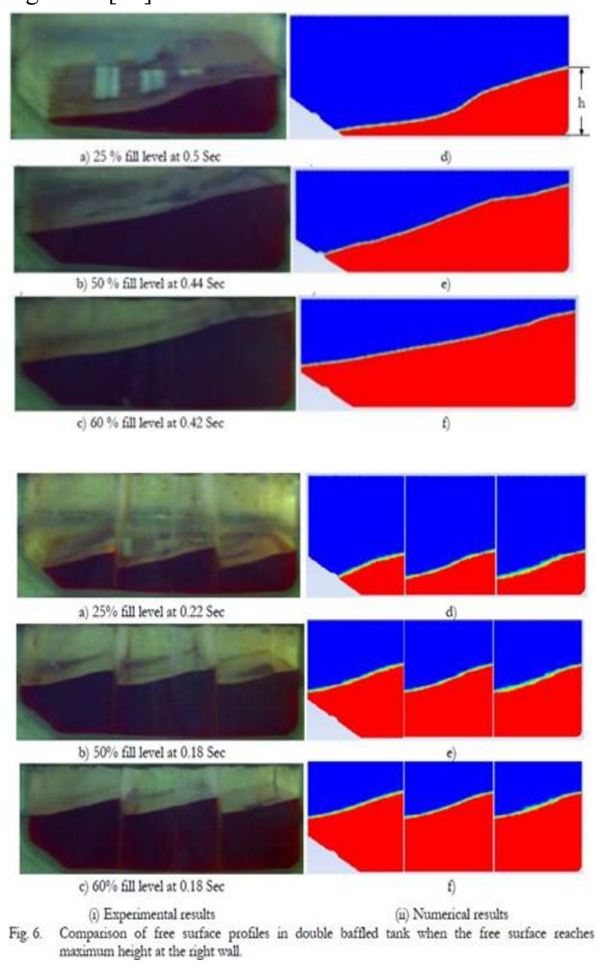


Fig. 14 Comparison of free surface profiles in unbaffled and baffled tanks with CFD and experimental analysis [36]

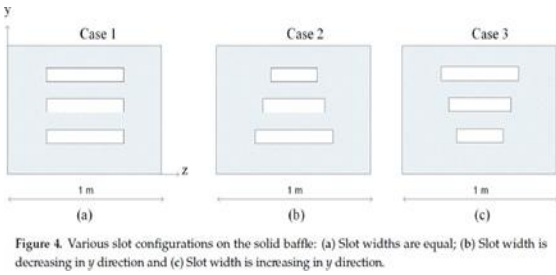


Fig. 15 Different slot configurations used on baffle a) Equal slot width b) Ascending slot width vertically c) Descending slot width vertically [37]

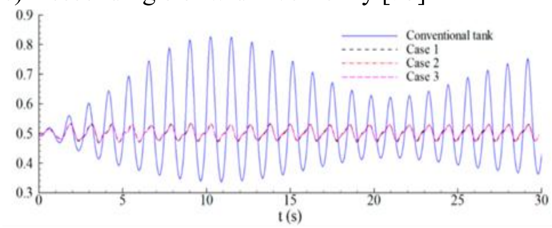


Fig. 16 Comparison of waveform on wall for different slot width [37]

6. NUMERICAL STUDY ON SLOSHING PHENOMENA IN VEHICLE TANK

In order to investigate the fluid-structure interaction in a three-dimensional elliptical tank, Gurinder et al. [39] created a two-dimensional model of the fuel truck in the COMSOL multiphysics software. This model was used to test their hypotheses. When there is one vertical baffle and two horizontal baffles, the fluid pressure on the walls of the container is reduced by 5.06%, but the reduction is 8.65% when there is only one vertical baffle. Figure 17 depicts the flow of fluid across the combined baffles configuration at a number of distinct time stamps. Yu et al. [40] investigated the effects of nonlinear external excitation on the liquid sloshing model of a partially filled tank. As the amount of liquid in the tank increases, the level of quality that it possesses will also improve. In the event that the liquid ratio is lower than 50%, the moment of roll, yaw, and pitch will be less than it would be otherwise. However, if the liquid ratio is greater than fifty percent, the three-axis force and moment will be significantly different. Hamid et al. [41] use a computational method to evaluate the dampening effect that horizontal baffles have on the vibrations that occur within a liquid storage tank. In most circumstances, an increase in the damping ratio can be expected whenever the baffles are brought into closer proximity to the free surface. The sloshing motion can be effectively suppressed by the horizontal baffles, which in turn results in a significant reduction in the Maximum Sloshing Wave Height (MSWH). On average, the cases that were considered for this study were successful in achieving a reduction of 40 percent in MSWH. A simulation of a gasoline tank that was only partially filled with kerosene was carried out by Singal et al. [42] using the Volume of Fluid (VOF) multiphase model. The tank was set in motion by applying an acceleration in the direction of +X that was 9.81 metres per second for a period of 1.5 seconds. In the direction Z-negative, gravity was also exerting its influence on the fuel. The CFD transient simulations of the kerosene liquid interface revealed that the addition of baffles to the fuel tank significantly reduced the amount of sloshing that occurred within the fuel tank. This was discovered after the baffles were installed. During the sloshing testing performed on a fuel tank with a capacity of 350 litres, Dhole et al. [43] found cracks on the centre baffle and weld spot failure. During the course of the physical test, the places of weld failures and cracks that were found on the centre baffle and shell matched pretty well with the results of the simulation.

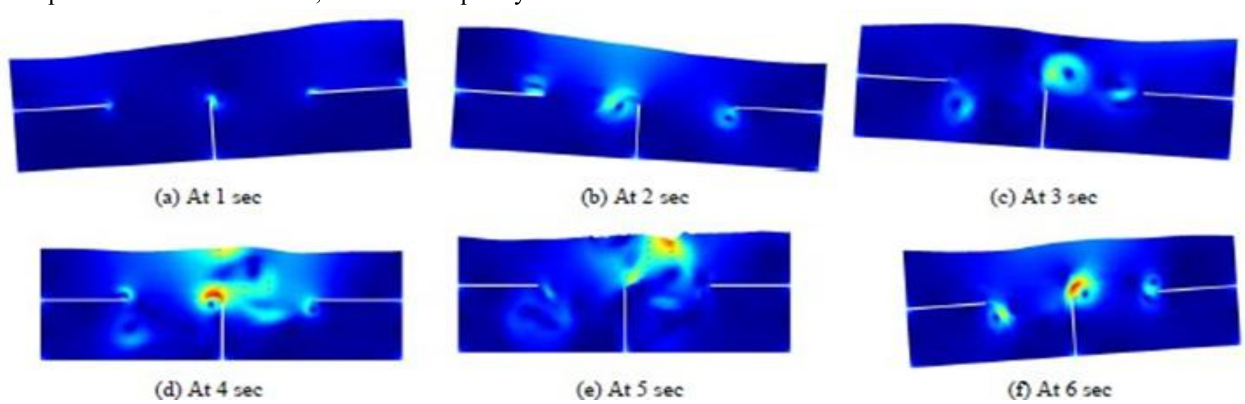


Fig. 17 Fluid dynamics inside tank for combination of vertical and horizontal baffles at different times [39]

For the sloshing analysis of the tank, Soli et al. [44] employed the ALE (Arbitrary Lagrangian Eulerian) model in conjunction with the SPH (Smooth Particle Hydrodynamic) model. According to the findings of the study, the SPH model is able to produce the same precise results as the ALE formulation, although having a comparatively finer mesh. According to the findings of an investigation that was carried out by Maryana and colleagues [45], it was discovered that the perforated partition of a convex shape with a large radius of curvature at the core part and a significant narrower radius in the area of link to the tank shell exhibits minimal stress. This was demonstrated by the fact that Fig. 18 depicts this phenomenon. Sanapala et al. [46] use methodical computational simulations to examine the sloshing movements of liquid in a storage tank that is subjected to seismic stimulation. These simulations were carried out in order to better understand the sloshing dynamics. It was determined, on the basis of the reaction to an induced harmonic excitation, that the vertical baffle plate located in the middle of the tank was effective. The dimensions of this plate are currently being carefully improved. Shao et al. [47] carried out a computational investigation by employing a tried and tested enhanced smoothed particle hydrodynamics (SPH) model. When considering the trade-off between the performance of sloshing mitigation and the complexity of structure and design, I-shaped and T-shaped baffles can be good options to choose from when trying to reduce the effects of sloshing. Using a method of fluid-structure interaction called as "Dynamic Fluid Body Interaction (DFBI)," Vaishnav et al. [48] modelled the dynamic forces that were acting on the float as well as the motion that resulted from those forces. The Fluid-Structure Interaction (FSI) method accurately simulates the effect of fuel slosh, and it can be incorporated into the process of product development for the purpose of evaluating the effect of various tank features, baffles, and float shapes in order to guarantee a reliable fuel indication system. Guan et al. [49] employed the volume of fluid (VOF) approach to mimic the sloshing process in order to explore the sloshing problem that occurs within a cuboid container. While the waves behave in a predictable manner during the mixing process, the surface displays an unpredictable pattern of activity over time. The size of the wave is directly proportional to the size of the wave amplitude, while the frequency of the wave is inversely proportional to the size of the wave. Following optimization, it was discovered that the findings exhibit periodicity and may be partitioned into a number of distinct categories. Jiadong et al. [50] conducted an investigation using analytical methods on the phenomenon of liquid sloshing within a partially liquid-filled circular cylindrical container that was equipped with several rigid baffles. Extensive parametric research reveals that the responses of the liquid are affected by the baffles' properties as well as the pitching excitation frequency.

The angular acceleration and the Stokes-Joukowski potential are the primary factors that determine the resultant force and moment when the pitching excitation frequency is quite high.

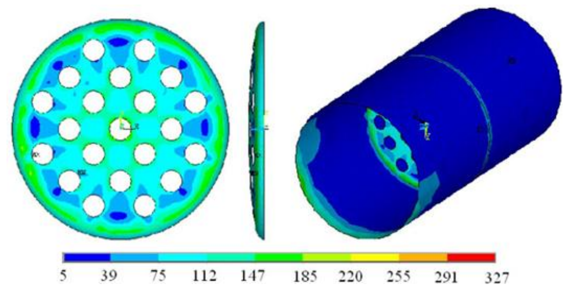


Fig. 18 Stresses (MPa) in the perforated baffle of convex form with perforation holes. [45]

7. CONCLUSION AND FUTURE SCOPE

When there is an excessive amount of liquid motion within a container, this can result in a localised pressure concentration on the tank walls, which can then cause structural damage. One of the most serious problems that is closely connected to tank vehicle instability is the presence of liquid forces and moments because of liquid sloshing. Sloshing that occurs in regions of the tank that are stable typically causes cyclic stress and fatigue in thin-walled tank structures. The sloshing phenomenon is controlled by a number of different factors, such as the shape of the tank, the abruptness of the braking, the design of the baffle plate, the placement of the baffle plate, and so on. The present study provides a summary of the research that has been done on these factors, as well as the various experimental and numerical studies. The authors have used different shapes of tank, various designs of the baffle plates and their positioning to study the sloshing behavior inside the tank which still can be improved by varying the combinations of baffles and giving more attention on orientation of the baffle plates to reduce the sloshing effect. An attempt had been made by several researchers to create a real world experimental test set up for the analysis of sloshing, pressure and forces acting on the wall. The experimental test set up used by the previous researchers has some scope of improvement such as use of magnetic field to create the seismic effect in the tank. The numerical simulation comprises three primary models *viz.* VOF, SPH and ALE. Though SPH is a meshless model it has some disadvantages according to the past research work. Out of these three the most suitable model and mostly used model for the numerical study is VOF model. Very little attention is given on use of optimization tools such as Taguchi, ANOVA etc. a modern statistical tool can be used for the optimization of performance parameters which are significantly affecting the sloshing behavior in tank.

REFERENCE

[1] Kumaresh, G., Saldanha, F., Lich, T., & Moennich, J. (2021). *Overview of Truck Accidents in India and Its Economic Loss Estimation* (No. 2021-26-0007). SAE Technical Paper.

[2] Road Accidents in India, 2020. https://morth.nic.in/road-accident-in-india

[3] Lamb, H. (1945). Hydrodynamics. -Cambridge University Press, 1932. *Burnham, DC and Hallock, JN: Chicago Monostatic Acoustic Vortex Sensing System*, *4*, 395-411.

[4] Euler, L. (1761). Principia motus fluidorum. *Novi commentarii academiae scientiarum Petropolitanae*, 271-311.

[5] Kang, X., Rakheja, S., & Stiharu, I. (2000). Directional dynamics of a partly-filled tank vehicle under braking and steering. *SAE transactions*, 765-775.

[6] Nicolsen, B., Wang, L., & Shabana, A. (2017). Nonlinear finite element analysis of liquid sloshing in complex vehicle motion scenarios. *Journal of Sound and Vibration*, *405*, 208-233.

[7] Dai, J., Han, M., & Ang, K. K. (2019). Moving element analysis of partially filled freight trains subject to abrupt braking. *International journal of mechanical sciences*, *151*, 85-94.

[8] Grossi, E., & Shabana, A. A. (2018). ANCF analysis of the crude oil sloshing in railroad vehicle systems. *Journal of Sound and Vibration*, *433*, 493-516.

[9] Otremba, F., Romero Navarrete, J. A., & Lozano Guzmán, A. A. (2018, August). Modelling of a partially loaded road tanker during a braking-in-a-turn maneuver. In *Actuators* (Vol. 7, No. 3, p. 45). MDPI.

[10] Toumi, M., Bouazara, M., & Richard, M. J. (2009). Impact of liquid sloshing on the behaviour of vehicles carrying liquid cargo. *European Journal of Mechanics-A/Solids*, *28*(5), 1026-1034.

[11] Chitkara, T. K., Kittur, Z., & Soman, R. (2013). *Computational simulation of fuel tank sloshing using CFD techniques* (No. 2013-01-2868). SAE Technical Paper.

[12] Hosseini, M., Vosoughifar, H., & Farshadmanesh, P. (2013). Simplified dynamic analysis of sloshing in rectangular tanks with multiple vertical baffles.

[13] Barton, M. S., Corson, D., Quigley, J., Emami, B., & Kush, T. (2014). *Tanker truck sloshing simulation using Bi-directionally coupled CFD and multi-body dynamics solvers* (No. 2014-01-2442). SAE Technical Paper.

[14] Cao, X. Y., Ming, F. R., & Zhang, A. M. (2014). Sloshing in a rectangular tank based on SPH simulation. *Applied Ocean Research*, *47*, 241-254.

[15] Vaishnav, D., Dong, M., Shah, M., Gomez, F., & Usman, M. (2014). Investigation and Development of Fuel Slosh CAE Methodologies. *SAE International Journal of Passenger Cars-Mechanical Systems*, *7*(2014-01-1632).

[16] Ikeda, T., Harata, Y., & Osasa, T. (2016). Internal resonance of nonlinear sloshing in rectangular liquid tanks subjected to obliquely horizontal excitation. *Journal of Sound and Vibration*, *361*, 210-225.

[17] Joshi, A. Y., Bansal, A., & Rakshit, D. (2017). Effects of baffles on sloshing impact pressure of a chamfered tank. *Procedia engineering*, *173*, 940-947.

[18] Saghi, H. (2016). The pressure distribution on the rectangular and trapezoidal storage tanks' perimeters due to liquid sloshing phenomenon. *International Journal of Naval Architecture and Ocean Engineering*, *8*(2), 153-168.

[19] Jena, D., & Biswal, K. C. (2017). A numerical study of violent sloshing problems with modified MPS method. *Journal of hydrodynamics*, *29*(4), 659-667.

[20] Yan, G. R., Rakheja, S., & Siddiqui, K. (2008). Baffle design analysis for a road tanker: transient fluid slosh approach. *SAE International Journal of Commercial Vehicles*, *1*(2008-01-2670), 397-405.

[21] Panigrahy, P. K., Saha, U. K., & Maity, D. (2009). Experimental studies on sloshing behavior due to horizontal movement of liquids in baffled tanks. *Ocean engineering*, *36*(3-4), 213-222.

[22] Zheng, X. L., Li, X. S., Ren, Y. Y., Wang, Y. N., & Ma, J. (2013). Effects of transverse baffle design on reducing liquid sloshing in partially filled tank vehicles. *Mathematical Problems in Engineering*, *2013*.

[23] Reddy V. T. (2015). CFD Analysis of Sloshing within a Tank with Porous Baffles. *International Journal of Science and Research (IJSR),* 2319 – 7064.

[24] Kumar, A., & Sinhamahapatra, K. P. (2016). Dynamics of rectangular tank with perforated vertical baffle. *Ocean Engineering*, *126*, 384-401.

[25] Chaudhari, K., Bhilare, S. L., & Patil, G. R. (2017). A study of dynamic response of circular water tank with baffle walls. *Int Res J Eng Technol*, *4*.

[26] Cho, I. H., Choi, J. S., & Kim, M. H. (2017). Sloshing reduction in a swaying rectangular tank by an horizontal porous baffle. *Ocean Engineering*, *138*, 23-34.

[27] Gnitko, V., Naumemko, Y., & Strelnikova, E. (2017). Low frequency sloshing analysis of cylindrical containers with flat and conical baffles. *International Journal of Applied Mechanics and Engineering*, *22*(4).

[28] Shimanovsky, A. O., Kuzniatsova, M. G., & Yakubovich, V. I. (2018). Dynamics of tank trucks with baffles for transportation of viscous liquids. *International journal of mechanical engineering and robotics research*, *7*(4), 438-443.

[29] Kim, H., Parthasarathy, N., Choi, Y. H., & Lee, Y. W. (2018). Reduction of sloshing effects in a rectangular tank through an air-trapping mechanism–a numerical study. *Journal of Mechanical Science and Technology*, *32*(3), 1049-1056.

[30] Ibrahim, I. M. (1999). Anti-slosh damper design for improving the roll dynamic behavior of cylindrical tank trucks. *SAE transactions*, 535-541.

[31] Fabela-Gallegos, M. J., Ramirez-Valencia, A., Favela-Gallegos, C. A., Vazquez-Vega, D., & Martinez-Madrid, M. (2005). *Experimental assessment of baffles and their effect on the longitudinal sloshing force in a scaled elliptical tank* (No. 2005-01-3577). SAE Technical Paper.

[32] Xue, M. A., Lin, P. Z., Zheng, J. H., Ma, Y. X., Yuan, X. L., & Nguyen, V. T. (2013). Effects of perforated baffle on reducing sloshing in rectangular tank: experimental and numerical study. *China Ocean Engineering*, *27*(5), 615-628.

[33] Rajagounder, R., Mohanasundaram, G. V., & Kalakkath, P. (2016). A study of liquid sloshing in an automotive fuel tank under uniform acceleration. *Engineering Journal*, *20*(1), 71-85.

[34] Agawane, G., Jadon, V., Balide, V., & Banerjee, R. (2017). An experimental study of sloshing noise in a partially filled rectangular tank. *SAE International Journal of Passenger Cars-Mechanical Systems*, *10*(2).

[35] Moretti, F. L., Silveira, M. E., Lamin, P. C., Brito, J. N., & Pockszevnicki, B. C. (2014). *Numerical and Experimental Evaluation of Sloshing in Automotive Fuel Tanks* (No. 2014-36-0122). SAE Technical Paper.

[36] Frosina, E., Senatore, A., Andreozzi, A., Fortunato, F., & Giliberti, P. (2018). Experimental and numerical analyses of the sloshing in a fuel tank. *Energies*, *11*(3), 682.

[37] Demirel, E., & Aral, M. M. (2018). Liquid sloshing damping in an accelerated tank using a novel slot-baffle design. *Water*, *10*(11), 1565.

[38] Yu, Y. M., Ma, N., Fan, S. M., & Gu, X. C. (2019). Experimental studies of suppressing effectiveness on sloshing with two perforated floating plates. *International Journal of Naval Architecture and Ocean Engineering*, *11*(1), 285-293.

[39] Brar, G. S., & Singh, S. (2014). An experimental and CFD analysis of sloshing in a tanker. *Procedia Technology*, *14*, 490-496.

[40] Yu, D., Li, X., Liu, H., & Dong, J. (2015). Research on liquid sloshing model of partially-filled tank by nonlinear external excitation.

Journal of Vibroengineering, *17*(6), 3224-3236.

[41] Babaali, H. R., Goudarzi, M. A., & Jafariye, F. (2013). Numerical Investigation of a Horizontally Baffled Rectangular Tank Subjected to Seismic Excitation. *Journal of Seismology and Earthquake Engineering*, *15*(3 and 4), 183-193.

[42] Singal, V., Bajaj, J., Awalgaonkar, N., & Tibdewal, S. (2014). CFD analysis of a kerosene fuel tank to reduce liquid sloshing. *Procedia Engineering*, *69*, 1365-1371.

[43] Dhole, A., Raval, C., & Shrivastava, R. (2015). *Fluid Structure Interaction Simulation of Automotive Fuel Tank Sloshing using Nonlinear Fluid Properties* (No. 2015-26-0240). SAE Technical Paper.

[44] Xu, J., Wang, J., & Souli, M. (2015). SPH and ALE formulations for sloshing tank analysis. *The International Journal of Multiphysics*, *9*(3), 209-224.

[45] Kuzniatsova, M., & Shimanovsky, A. (2016). Definition of rational form of lateral perforated baffle for road tanks. *Procedia Engineering*, *134*, 72-79.

[46] Sanapala, V. S., Velusamy, K., & Patnaik, B. S. V. (2016). CFD simulations on the dynamics of liquid sloshing and its control in a storage tank for spent fuel applications. *Annals of Nuclear Energy*, *94*, 494-509.

[47] Shao, J., Li, S., Li, Z., & Liu, M. (2015). A comparative study of different baffles on mitigating liquid sloshing in a rectangular tank due to a horizontal excitation. *Engineering Computations*.

[48] Vaishnav, D., Buerkle, I., Ali, S., Dong, M., & Simpson, A. (2016). *Development of Fluid-Structure Interaction CAE Method to Assess Effect of Fuel Slosh on Fuel Level Sensor* (No. 2016-01-1379). SAE Technical Paper.

[49] Guan, H., Xue, Y., Wei, Z., & Wu, C. (2018). Numerical simulations of sloshing and suppressing sloshing using the optimization technology method. *Applied mathematics and mechanics*, *39*(6), 845-854.

[50] Wang, J., Wang, C., & Liu, J. (2019). Sloshing reduction in a pitching circular cylindrical container by multiple rigid annular baffles. *Ocean Engineering*, *171*, 241-249.