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Numerical Investigation of Sloshing Characteristics in Long Moving Vessels with Embedded Concave Rigid-ring Baffle in Gravity Environment

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Flat Rigid–ring Baffle [1] (FRB) is a common slosh suppression device in Long Moving Vessel (LMV) to mitigate against oscillation-induced instability due to sloshing of its content but, its relative low performance is unacceptable for desirable safety standard thus, necessitating continuous efforts to investigate other baffle configurations. Investigation of Concave Baffles of varying geometries was carried out and analysed with the ANSYS/CFX [2] and the Computational Fluid Dynamics (CFD). Results were post-processed with the help of Mat lab [3-5] in a gravity milieu. This work was therefore designed to study the sloshing characteristics of Water-Carrying Cylindrical (WCC) tank equipped with three baffles. Model governing equations based on conservation of mass and momentum were developed and solved using Finite Element Analysis (FEA) technique. The model was used to evaluate Damping Ratio (DR) from Mile's equation [1] at 72, 66 and 59 percent standard positions, in a 75 percent filled WCC tank with slenderness ratio of 1.5 excited at a frequency of 2 Hz. The investigated baffles were Concave Rigid-ring Baffle-1 (CARB1) 0.02 m pitch, Concave Rigid-ring Baffle-2 (CARB2) 0.04 m pitch and Flat Rigid-ring Baffle, FRB (control). Data were presented in term of non dimensional DR and as the main performance index. Numerical results were obtained and compared with FRB results also obtained numerically. The results showed that, the concave baffles exhibited [better damping characteristics at 72 and 59 percent water-filled positions of the cylinder which mostly the critical states hence, Concave-Rigid-ring Baffle have better damping effectiveness than Flat-Rigid-ring Baffle.

Keywords: *Sloshing; damping-ratio; gravity; instability.*

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1. INTRODUCTION

Liquid movement in partially-filled storage tank or vessel as a result of its inertial forces induced oscillatory motion from the motion of the container such as stage separation and trajectory correction of a launch vehicle, mostly referred to as propellant slosh. Liquefied Natural Gas (LNG) truck moving on a rough road, water tanker are good examples of the illustration of this phenomenon. Also, storage tanks containing water on high-rise buildings could be employed as Tuned Liquid Dampers (TLD) to suppress external excitation caused by earthquakes and other natural phenomenon that could be a source of disturbance [6]. Sloshing due to propellant is a very dangerous of source of perturbation very significant l to the stability of space vehicles. The slosh dynamics are usually modelled by a spring mass damper mechanical system. This model is included in the equation of motion of the entire vehicle for Guidance, Navigation and Control system design [7]. hence, Dynamic Systems (DS) designer require information from the analysis of this phenomenon for stability and instruments placement. Elastic body frequencies, and the fuel-slosh frequencies must all be reasonably separated, in most cases it is not so. If the dominant fuel-slosh frequencies are close to any of the control system frequencies, an instability in the flight characteristics can result; while if the fuel-slosh frequencies are close to the elastic body bending frequencies, a large amplitude dynamic response problem may arise [8].

Slosh magnitude is a function of the container geometry, fluid properties, fluid-filled level, perturbing motion of the container, acceleration field and damping capability of the system. Sloshing problem revolves primarily on measurement of hydrodynamic pressure distribution, forces, moments and natural frequencies of the free-liquid surface. To eschew catastrophic sloshing in LMVs, its frequencies must be widely separated from the sloshing-fluid frequencies [9].

Non-linear nature of sloshing necessitates the use of Experimental and Computational Fluid Dynamic (CFD) [10]. The objective of this study is to investigate possible baffle configuration that can reduce vibration-induced sloshing in a LMVs hence, the specific objective is:

Investigation of the effect of Concave Ring-ring Baffles on sloshing characteristics in a LMVs, and the results were compared with a FRB numerically.

2. LITERATURE REVIEW

Much attention were given to sloshing phenomenon over the years by researchers, engineers and scientists since the mid-1950s. The initial area of study was aeronautics as the response of aircraft was dynamically disturbed due to sloshing of fuel inside the tank. In the recent time, much interest were shown in the study of this phenomenon as it affects maritime applications, aerodynamic, seismic stabilization of high buildings and acoustic effect of sloshing of fuel in automobile tank as stated by Graham and (Rodriguea, 1952).

Motions of liquid in a storage with free surface are of great challenges in many engineering applications and devices e.g., fuel tank of airplanes, launch vehicles spacecrafts and automobiles. The size of tank increases proportionately to the hydrodynamic forces and moments at the neighbourhood of Resonances Frequencies (RF). Hence, these forces and moments resulting from sloshing needs to be controlled to avoid structural damage due to modes coupling.

Dou et al [11] investigated the significant of Tuned Liquid Damper (TLD) in damping non-linear vibration of elastic Supporting Structural Platform (SSP).It was observed that the amplitude of the roof plate reduced appreciably and a frequency shift after TLD on the SSP. Also, energy equilibrium between absorption and production was broken due to abrupt excitation which resulted in larger wave height.

Heng et al. [12] studied the effect of a horizontal perforated plate on slosh motion using rectangular tank. They designed horizontal perforated plate (HPP) to enhance the inherent damping of the tank that moves from side to side through experiments. In their study, a simple analytical model was proposed to analyse the sloshing problem, under swaying and rolling excitation. They use quadratic pressure loss conditions to achieve boundary effect based on the different porosities and submerged depths of the plate. The results gave more insight to sloshing characterises in ship tank.

Jing-Han et al [13] studied sloshing and the effect of vertical baffle attached to the bottom of a tank. Linear Velocity Potential Theory (VPT) was employed in the study. Their conclusion was that, motion of the baffle, both magnitude and phase can be adjusted simultaneously in reducing the free surface elevation and significant reduction of sloshing wave.

Chia Chu et al [14] employed both experimental and numerical simulation to investigate sloshing with embedded multiple baffles fixed at bottom of a rectangular tank containing water. Volume of Fluid (VOF) method was employed in solving free surface equation. Validation of the simulation results was performed with shaking-table experiment. Determination of the impact of baffle's height and the space between them on slosh suppression was the objective of the study. Simulation results showed that the Natural Frequency (NF) of the tank was affected significantly as a result of the presence of multiple baffles. The reduction of the Hydrodynamic Force (HF) by the multiple baffle is much more than for a single baffle.

Mi-AnXue et al [15] studied four types of baffles and its effectiveness in slosh suppression under a forcing frequencies of *0.4 ω1 to 1.4 ω1*.Effectiveness of the baffle of vertical geometry near the Free surface is significant in slosh suppression than the one fixed at the bottom of the container. Slosh suppression of perforated baffle of vertical geometry is more significant than surface-piercing counterpart of vertical geometry mounted at the bottom of the tank at broad band frequency region. It was observed that the tank-liquid system first-mode NF was changed with the presence of the vertical baffles. The result of the experiment showed that alteration of flow fields and NF may significantly damp HF on the tank walls. Compressible VOF was better in obtaining more precise predictions of sloshing.

Konstantinov et al [16] investigated nonlinear oscillations of a cylindrical tank partially filled with a fluid, subjected to a harmonic horizontal force. They analysed the free surface oscillation of the fluid with twelve different modes of oscillations that analyses both the motion of the tank and the contained liquid under external forces. Nonlinear dynamics of the system considered to be the effects of gravity-capillary and dissipative effects. The effect of the surface tension and dissipation on the near-resonance oscillations of the system is analysed and the result showed that, it was difficult achieve steady state which was validated experimentally.

Zhiqiang et al [17] in their numerical study showed that Floating Liquefied Natural Gas FLNG-tank motion affected the roll motion response significantly. They also, established that tank fill at moderate level does not reduce roll motion response significantly.

Santosh, et al [18] investigated the effect of baffles inside a rectangular container in altering the dynamic system characteristics of a liquid inside rectangular containers experimentally. Natural frequency and damping values were identified as major performance index. These objects of three different configurations were centrally positioned in three location within the container, namely. bottom-mounted vertical baffles, surface-piercing wall-mounted vertical baffles, and bottom-mounted submerged-blocks have been tried out as potential passive slosh damping devices. Experiments were conducted in a rigid rectangular tank attached to a shake table laterally excited harmonically. Frequency response of the liquid in various baffles arrangements were observed at the free surface of the liquid. Sloshing characteristics of the liquid (water) to harmonic sinusoidal loading for different baffle configurations are investigated. Sine sweep and Logarithmic decay method have been resorted to in the experimental discourse. The result showed that the surface-piercing wall mounted baffles are the most effective one in slosh suppression among the three configurations.

Gurinder et al [19] studied fluid structure interactions in an elliptical tank, with different baffle configurations. They calculated the pressure exerted by the fluid on the walls of tank over a certain period of time using computer simulation, validated by experiment. The pressure exerted on tank's wall by the fluid was calculated over a certain period of time. They observed the dynamic response of baffled storage tank and its effects on baffle locations and shapes. The results showed that the combination of horizontal and vertical baffles were found to be significant in slosh suppression.

Mi-An Xue et al [20] investigated sloshing characteristic using double-phase fluid to solve the governing Navier-Stokes equations. Horizontal, perforated-vertical and their combination excited harmonically were considered. The results showed that serious dynamic impact pressures often occurred at the neighbourhood of free surface. The result also showed that the normal combinatorial baffles possess better damping characteristics.

Adebayo and Osheku [21] investigated essential mathematical equations governing the structural vibration. Flexural modes determination of aerospace vehicles, subject to aero-acoustic pressure and aerodynamic pressure forces were presented. The elastic properties of a rocket structural element initiate vibrations in the neighbourhood of resonance frequency.

Rakheja et al [22] investigated impact of different baffle geometries on liquid sloshing. The result showed that the conventional lateral baffle perform better than oblique baffle in damping the slosh under longitudinal acceleration excitation but, oblique baffle minimised longitudinal, lateral forces and moment when the tank accelerated longitudinally and laterally.

Mohammad and Saeed [23] developed an analytical model to estimate the hydrodynamic damping ratio of liquid sloshing for wall bounded baffles using, velocity potential formulation and linear wave theory. They approached the problem analytically and experimentally, with vertical and horizontal baffles fixed inside partially filled rectangular liquid tanks exited harmonically. The study investigated damping efficiencies of both vertical and horizontal baffles with various dimensions and locations in the tank. The result showed that the hydrodynamic damping effectiveness is significantly affected by the size and location of baffles. They proposed a simple approach for estimating the damping ratios of the baffles during earthquake motions.

Bernhard et al [24] used near-resonant, sway-induced sloshing flow in a rectangular tank to compare a homogeneous and inhomogeneous multiphase approach using commercial CFD code. Using dimensional analysis of the relative motion between the phases, it was observed that the inhomogeneous multiphase model gave good result than the homogeneous approach. Comparison of both the computational and experimental results showed that the homogeneous model tends to underestimate the experimental peak pressures by up to 50%. The inhomogeneous multiphase model was in good agreement with the experimental pressure data. Examination of the relative velocity at the fluid interface confirms that the inhomogeneous model is more appropriate to be used as a model for simulation of turbulence slosh induced-flow.

Panigrahy [25] investigated sloshing experimentally in a rectangular tank with pressure as varying parameter with time. The result of the investigation showed that ring baffle is much more effective in reducing slosh.

Tehrani et al [26] studied sloshing of fuel in a partly filled cylindrical tank equipped with baffle. In this study, three dimensional transient analysis were performed under varying magnitude of constant longitudinal, lateral and combination of longitudinal and lateral acceleration of tank, and two different filled volume using FLUENT software. The result of the investigation showed that the amplification ratios of the resulting forces and moments could approach as high as 2 and presence of baffles suppressed the slosh forces and moments significantly; amplification factor was reduced significantly by the presence of baffle.

Henderson et al [27] calculated the natural frequencies and damping ratios for surface waves in a circular cylinder with the assumptions of a fixed contact line, Stokes boundary layers, and either a clean or a fully contaminated surface. These theoretical predictions were compared with the measurements for the first six modes in a brimfull, sharp-edged cylinder of radius 2.77 cm and depth 3.80 cm. The differences between the predicted and observed frequencies were less than 0.5% for all except the fundamental axisymmetric mode with a clean surface. The difference between the predicted and observed damping ratio for the dominant mode with a clean surface was 20%; this difference was significantly larger for the higher modes with a clean surface and for all of the modes with a contaminated surface.

Premasiri, [28] developed a hydrodynamic model to investigate the effectiveness of baffle to increase the hydrodynamic damping in a rectangular tank. Choun (1996) and Choun and Yun (1999) presented an analytical treatment of rectangular tanks with a submerged structure using potential formulation and small-amplitude water wave theory. They observed that the sloshing amplitude and hydrodynamic pressure are reduced by submerged structures using linear theory of water waves.

Ibrahim, [7] developed simple dynamic truck roll model while considering both suspension flexibility and nonlinear dynamics of the liquid cargo motion. Small-scale model of experiment with cylindrical tank, excited in the horizontal direction was designed and constructed for the measurement of the viscous damping and damping of the natural frequency of the liquid cargo. Natural damping characteristics of the tank was enhanced by partitioning the rectangular tank with slots and holes of different sizes, making the liquid behave like a dynamic absorber. Dimensional similarity technique was developed to make the measured data applicable for the full size vehicle. Roll responses of the vehicle was measured experimentally by calculating motion parameter of the slosh. The results obtained showed that, significant damping of the vehicle body roll motion was achieved; also a shift of the cargo centre of gravity was achieved due to the presence of anti-slosh damper in the tank.

Chen et al (1996) investigated sloshing of liquid in a storage, excited harmonically with large-amplitude. It was concluded that design of seismic-resistant tank should employ non-linear analysis. Also, cognisance must be taking of the real sloshing amplitudes which may exceed linear predictions for avoidance of potential damage to the tank roof due to hydrodynamic wave pounding.

Uras, [29] studied the effect of viscosity on the sloshing response of tanks containing viscous liquids, by employing in-house finite element computer code, FLUSTR-ANL. Two tank of different sizes, each filled at two levels were modeled. Their dynamic responses under harmonic and seismic ground motions were simulated. It was observed that, under harmonic excitation the dynamic response reaches the steady-state faster as the viscosity value becomes larger. The fundamental sloshing frequency for each study case was not affected by an increase in viscosity. For the small tank case, a 5% difference is observed in the fundamental frequency of the smallest in the other of ratio 1.1000 viscosity cases considered in this study.

Sakai et al [30] studied sloshing on a tank containing oil with floating roof analytically and with model testing. They employed theory of FSI to analyse the interaction and its effects between the between the roof and the contained liquid. Analytical results were validated experimentally with the aid of shaking-table, model of single and double deck roof. It was concluded that the presence of this device does not affect the NF but, subsequent modes are affected by the double deck type significantly in determination of stresses associated with it.

Su, [31] and Martel et al (1998), studied the effects of viscosity on the dynamic characteristics of tanks from various points of view. They concluded that damping factor and sloshing amplitude may be affected seriously by viscosity for small size tanks. In practice, the liquid’s viscosity has no significant effect on the dynamic characteristics of liquid storage tanks (Chiba 1995; Uras 1995). They suggested that some methods should be introduced to suppress sloshing loads such as annular ring tanks, floating plates and lid, these were studied and employed to reduce the sloshing effects (Eulitz 1961; Abramson and Ransleben 1961; Bauer 1966).

Cole, [32] investigated the effect of baffle thickness on slosh suppression experimentally in a cylindrical tank on the effectiveness of baffle with respect to amplitude to width ratio (η/w). In his conclusion, baffle effectiveness decreases by fifty percent (50%) with increase of baffle thickness at moderate amplitudes of oscillation.

3. COMPUTATIONAL MODELING

The concave baffle set up characteristics are listed below:

Baffle focal length: 0.0200 m and 0.0400 m
Tank is 75 % filled with water.

Baffle positions: 72%, 66%, 59 % respectively
Tank size: 0.6 m (height); 0.4 m (diameter).

3.1 Environmental Condition: Gravity

Figs. 1 to 3 show geometry creation using ANSYS CFX Workbench 15.0 [2], Solid Works [33] for Concave Rigid-ring Baffle (CARB1 and CARB2) of 0.1m of thickness. Fig. 4 shows geometrical representation of Flat Rigid-ring Baffle (FRB) used as the control. Fig. 5 illustrates a sample of finite element of the tank, baffle and the test fluid (water).

Continuity Equation while Fig. 7 shows algorithms for problem set-up.

3.2 Equation of Motion

The dynamic of fluid while in motion could be represented mathematically by equations derived from conservation of mass and Navier-Stokes equations [34]. These equations were solved to obtain pressure and velocity which were used to evaluate the forces at the walls of the tank. The basic differential equation that a velocity potential must satisfy everywhere in the liquid volume is given by:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (1)$$

This equation is also known as Continuity Equation. Eqn. (2) represents general differential and compressible form of this equation.

$$\frac{\partial\rho}{\partial t}+\vec{\nabla}.(p\vec{V})=0 \qquad (2)$$

Where $\vec{\nabla}$ is the component of velocity vector in *x, y, z* axes respectively.

Momentum Equation (incompressible Navier–Stokes equation in vector form) is given as

$$\rho\frac{D\vec{V}}{Dt}=-\vec{\nabla}p+\rho\vec{g}+\mu\nabla^{2}\overrightarrow{V} \qquad (3)$$

$$\nabla^{2}=\frac{\partial^{2}}{\partial x^{2}}+\frac{\partial^{2}}{\partial y^{2}}+\frac{\partial^{2}}{\partial z^{2}} \qquad (4)$$

Where, ∇^2 is the Laplacian operator, in Cartesian coordinate, $\vec{g}$ is acceleration due to gravity in vector form.

Integration of these governing equations yields non-steady version of Bernoulli's equation for a potential flow without vorticity as:

$$\frac{\partial\phi}{\partial t}+\frac{p}{\rho}+gz+\frac{1}{2}(u^{2}+v^{2}+w^{2})=f(t) \qquad (5)$$

where, *Φ. P, ρ* and *g* are the velocity potential, fluid pressure, fluid density and effective gravity acting in the negative *z* direction (this is equivalent to laboratory value but in opposite direction to the axial acceleration for a space vehicle) respectively. Small values of velocities *u, v, and w* were assumed, for the squared and higher power terms of these values to be negligible in comparison to those terms that are linear for linearization of the equation. Existence of the derivative of the velocity potential with physical meaning facilitates addition of time function to the definition of *Φ*. Hence, constant of integration *f (t)* in Eq. (5) is absorbed into the definition of *Φ*. The linearised form of the equation (5) as detailed by Franklin [35] is given as:

$$\frac{\partial\emptyset}{\partial x}+\frac{p}{\rho}+gz=0 \qquad (6)$$

3.3 Boundary Conditions (BC) at the Free Surface

The walls BC and FS of the tank could be satisfied by solution of any mathematical function that satisfy equation (1). Also, Equation (6) is used to derive one of the BC at the FS. There is a free movement of the surface hence, insignificant values of the gas density in comparison to the liquid pressure at the surface, makes it equal to gas static pressure p_0 at the FS. Nonsteady Bernoulli's equation at the FS is given by Franklin [35] in the form

$$\frac{\partial\phi(x,y,z,t)}{\partial t}+g\delta(x,y,t)=\frac{p_{0}}{\rho}, \quad \text{for } z=\frac{h}{2} \qquad (7)$$

FS small displacement is represented by *δ(x, y, and t)* and the height above FS is given in the form

$$z = h/2 \qquad (8)$$

Unlinearised Eq. (7) would be solved at the point of displacement, therefore

$$z = h/2 + \delta \qquad (9)$$

of the FS instead of equilibrium position

i.e. *z = h/2.* The difference between the two conditions *(z = h/2 and z = h/2 + δ)* results in higher order term of *δ,* which could be neglected. For small value of *g*, surface tension effect is significant to be considered in Equation (7). Gas pressure retains its value as p_0 but, pressures values of liquid and gas are not the same at the free surface and the adjacent side this difference is a function of surface curvature and tension. Equation (7) represents the dynamic state at the FS. Relationship between displacement at the surface *δ* and the component of the velocity along vertical axis of the liquid at the FS requires kinematic analysis. In a linearised form, this condition is simply.

$$\frac{\partial\delta}{\partial t}=w=\frac{\partial\varphi}{\partial z}\ , \quad \text{for} \quad \frac{h}{2} \qquad (10)$$

Combining Equations (7) and (10) and writing it in terms of $\varphi\ (or\ \delta)$ and differentiating with respect to *t* and z respectively $yields$ b

$$\frac{\partial^{2}\varphi}{\partial t^{2}}+\frac{\partial\varphi}{\partial z}=0 \text{ for } \frac{h}{2} \qquad (11)$$

Natural frequency of the sloshing is an integral part of the time derivative of φ in Eq. (11)

3.4 Boundary Conditions at the Tank Walls

Assumption of negligible values of viscosity and viscous stresses render these quantities unsuitable for defining boundary condition at the wall hence, the value of velocity perpendicular to the wall's plane of the tank, which is equal to V_n is more appropriate, (*n* stands for normal direction) and condition of "No-slip" is applied. For a stationary tank, the BC at the wall is the normal velocity component of the liquid to the wall and equals to zero.

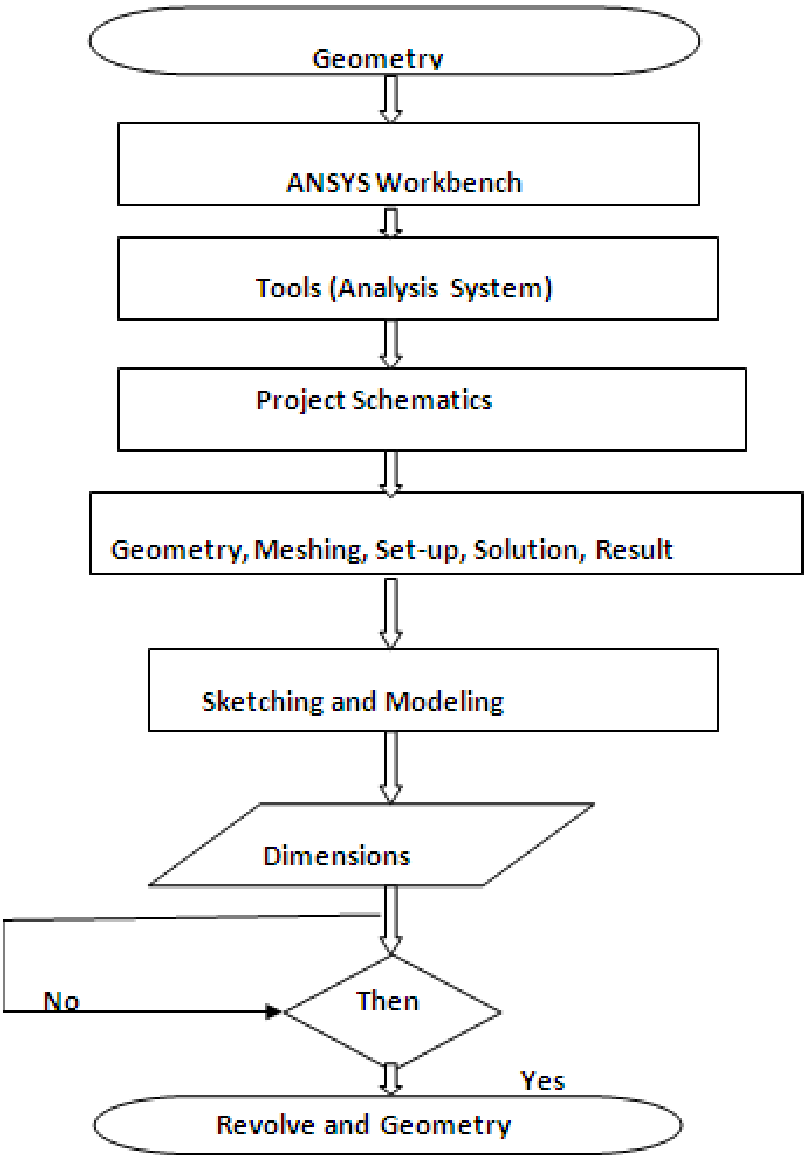

Fig. 1. Flow-chat illustration of geometry creation (ANSYS CFX Workbench 15.0 November, 2013) [2]

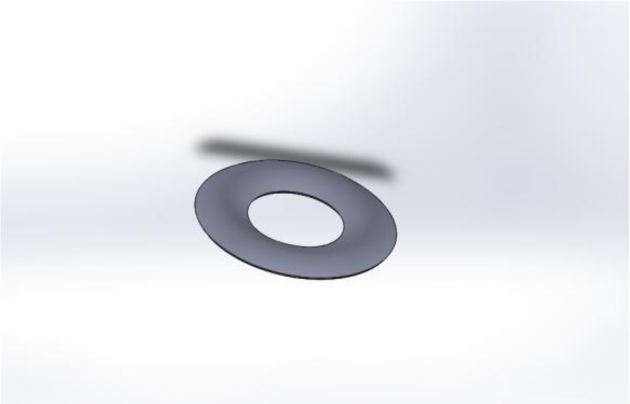

Fig. 2. SolidWorks 2014 illustration of Concave Rigid–ring Baffle with pitch of 0.0200 m [31]

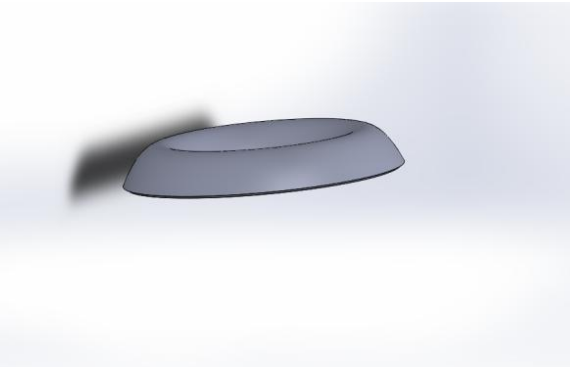

Fig. 3. SolidWorks 2014 illustration of Concave Rigid–ring Baffle with pitch of 0.0400 m [31]

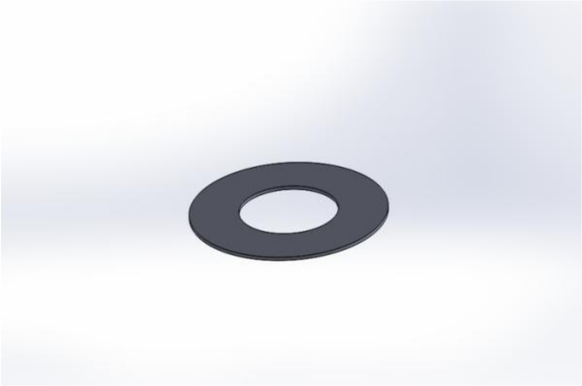

Fig. 4. SolidWorks 2014 illustration of Flat Rigid – ring Baffle of 0.1 m width [31]

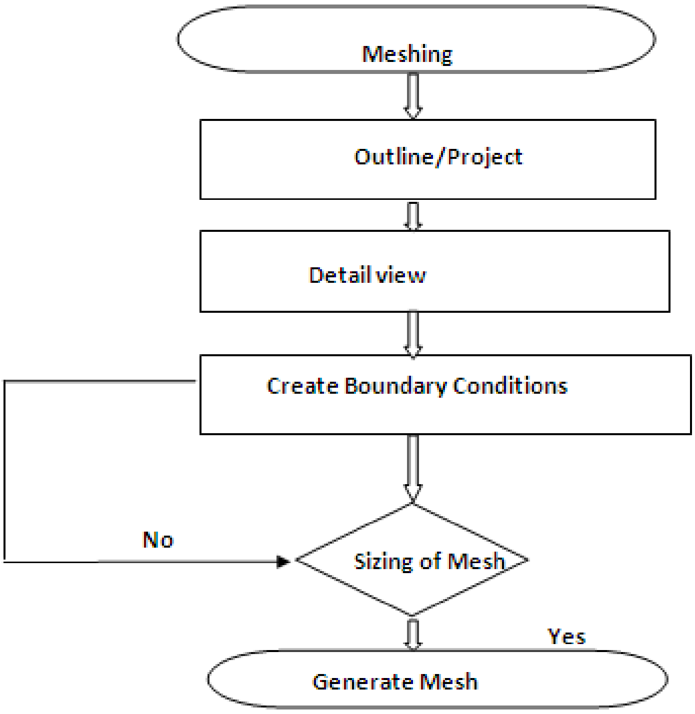

Fig. 5. Finite Element Mesh of the Computational Domain (ANSYS Modelling Meshing Guide, 15.0 November, 2013) [2]

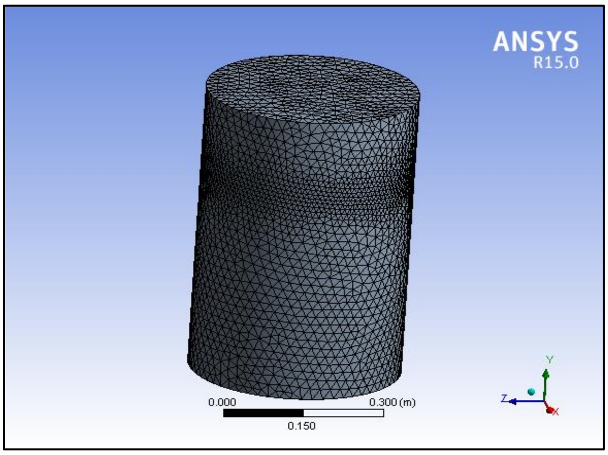

Fig. 6. Finite Element Mesh of the Computational Domain (ANSYS Modelling Meshing Guide, 15.0 November, 2013) [2]

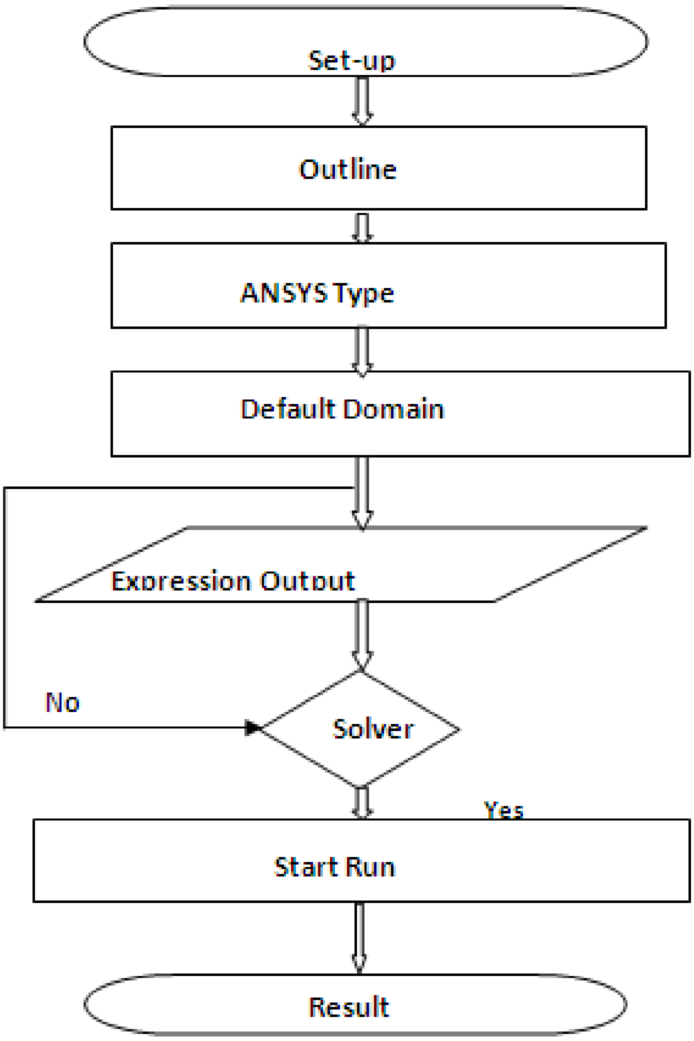

Fig. 7. Set-up Algorithm [36-40]

hence, BC for Φ at the wall of the tank's wall reduces to.

$$\frac{\partial \emptyset_c}{\partial n} = V_n \tag{12}$$

$$\frac{\partial \emptyset}{\partial n} = 0 \tag{13}$$

Where, V_n is the liquid velocity perpendicular to the plane of the wall, and *n* stands for the normal or perpendicular direction, $\emptyset_c$ and $\emptyset$ are the potential for the tank's rigid body motion and a motion of the liquid relative to the rigid body motion respectively**.** The force aggregate at the wall of the cylinder are given as.

$$\boldsymbol{F_x} = \sum_c^{wetted\ area}\left(\boldsymbol{p_c} * \vec{\boldsymbol{A}}_{\boldsymbol{cx}}\right) \tag{14}$$

$$\boldsymbol{F_y} = \sum_c^{wetted\ area}\left(\boldsymbol{p_c} * \vec{\boldsymbol{A}}_{\boldsymbol{cy}}\right) \tag{15}$$

$$\boldsymbol{F_z} = \sum_c^{wetted\ area}\left(\boldsymbol{p_c} * \vec{\boldsymbol{A}}_{\boldsymbol{cz}}\right) \tag{16}$$

3.5 Miles' Equation (Performance Evaluation Index)

For a flat rigid-ring baffle in a cylindrical tank, the damping ratio as a function of baffle depth d should be estimated from Miles' equation. The Damping Ratio (DR) which is a measure of the baffle performance is then estimated from:

$$\boldsymbol{\xi} = \frac{\boldsymbol{\delta}}{\boldsymbol{2\pi}} = \boldsymbol{2.83e}^{-4.60\frac{d}{R}\left[\frac{2W}{R}-\left(\frac{W}{R}\right)^2\right]^{\frac{2}{3}}}\left(\frac{\eta}{R}\right)^{\frac{1}{2}} \tag{17}$$

ξ, damping ratio; w, baffle width; η, maximum slosh-wave height at the wall and δ, the damping factor (or logarithmic decrement) and R, tank radius. The term in brackets is the fraction of the tank area covered by the baffle (Miles, 1958).

4. MODEL RESULTS

The model estimate of the damping ratio for cylindrical tank with concave baffle as well as flat ring baffle are hereby presented.

Comparison of the numerical results of the Concave baffles and the conventional Flat Rigid-ring Baffle.

Figs. 8 and 9 are the graphs showing the values of DRs for CARB1 and CARB2 respectively, obtained at three different positions along the tank's depth. Fig. 10 is the graph of Damping Ratio and Slosh Wave Amplitude of FRB obtained numerically in gravity environment. The numerical values of DRs are shown in Tables 1 and 2.

From the results, it is observed that the values of DRs for CARB1, CARB2 with pitch values of 0.0200 m, 0.0400 m and FRB, secured at 59, 66 and 72 % filled-position of the tank. At 72% baffle position, DRs were: 0.3133, 0.3214, 0.3165, for CARB1, CARB2, and FRB respectively. These values show clearly that the DR increased from 0.3133 to 0.3214 representing 2.6% increase in the initial value and 1.5% greater than the DR for FRB but, decreased at 66% baffle position (DRs were 0.6409, 0.6401, 0.6347 for CARB1, CARB2, FRB respectively) with 0.12%, despite the reduction concave baffle increased by 0.97% than its FRB counterpart. Increment of DR was observed from 0.6409 to 0.6401 at 59% baffle position (DRs were 0.9640, 0.9644, and 0.9481 for CARB1, CARB2, FRB respectively) from 0.964 to 0.9644 representing 0.04% of the initial value and 1.57% more than FRB.

Deductions that can be made from the above analysis and comparism are:

(1) Concave baffles will perform well in damping slosh dynamics near free surface of the tank upon increment of its pitch than its Flat Rigid-ring counterpart.

(2) Increment of the baffle does not really have significant effect on the damping effectiveness of the baffle as the depth increases.

(3) Concave baffle will suppress slosh dynamics near the bottom of the tank. Fluctuations of thrust in liquid rocket engine system leads to problem of pogo oscillation [41], this baffle will help in ameliorating this effect during power phase of the flight.

(4) Concave baffle has the advantage of suppressing slosh effectively at two positions of the tank i.e. free surface and near the bottom which are adjudged to be critical and significant in determining the stability of dynamic systems prone to sloshing.

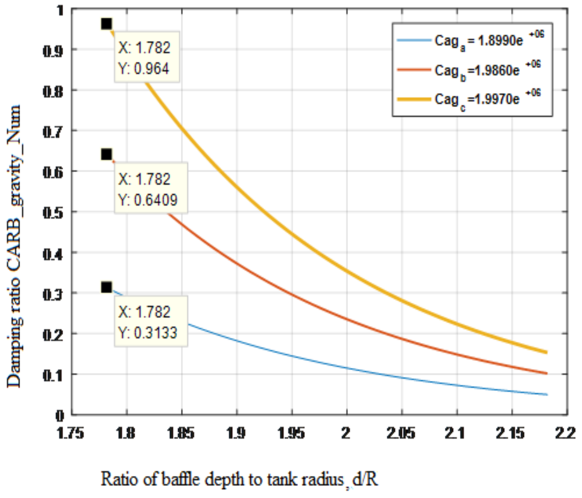

Fig. 8. CARB1 graphs showing DR values at different positions of the tank-water depth

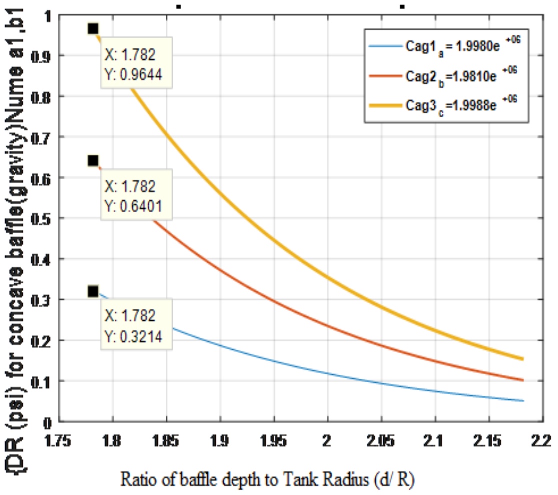

Fig. 9. CARB2 graphs showing DR at different positions of the tank-water

Table 1. Slosh Amplitude and Damping Ratio for Two Selected Concave Baffles

Baffle Configuration	Slosh-Wave Amplitude	Damping Ratio	Baffle position in the Tank (%)
CARB 1	1.8990e+06	0.3133	72
0.0200m	1.9860e+06	0.6409	66
	1.9970e+06	0.9640	59
CARB 2	1.9980e+06	0.3214	72
0.0400m	1.9810e+06	0.6401	66
	1.9988e+06	0.9644	59

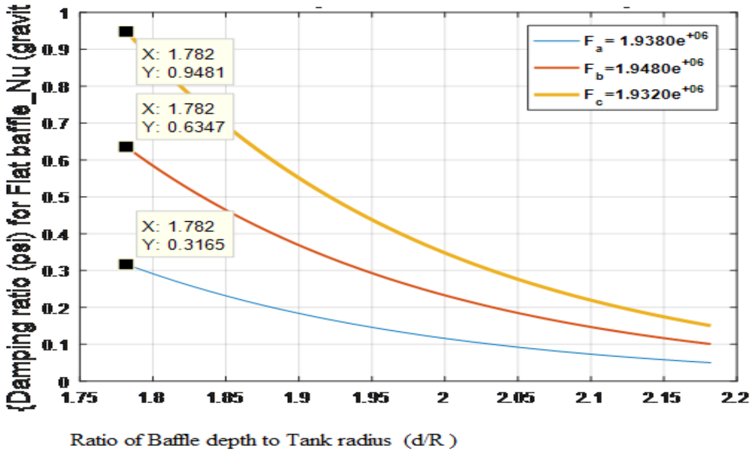

Fig. 10. The graph of Damping Ratio for FRB

Table 2. Values of Slosh Wave Amplitude and Damping Ratio for FRB

Baffle configurations	Slosh-Wave Amplitude Numerical	Damping Ratio	Baffle position in the Tank (%)
FRB	1.9380e+06	0.3165	72
Numerical	1.9480e+06	0.6347	66
	1.9320e+06	0.9481	59

5. CONCLUSION

Conclusively, it was found that concave baffle has better damping characteristics than Flat Rigid-ring Baffle from the free surface to the bottom of the tank.

The curve geometry of the concave baffle is an added advantage to its damping effectiveness as it enables it to curtail splashing and reduction of hydrodynamic pounding on the tank's wall, thereby reducing propensity of the tank to structural failure.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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