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Optimization and Reduction of Sloshing in the Fuel Tank

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Abstract: The sloshing effect has a major impact on the control and safety of moving vehicles, using liquid as fuel. It is necessary to predict and understand fluid slosh effect in liquid propellant vehicles for its safety and performance. Over the years, many research studies have been conducted to study sloshing in space vehicles. In space vehicles, it creates destabilizing effect and many techniques are employed to reduce the effect. Use of baffles is one among the technique. This study aimed at analysing the linear and nonlinear sloshing inside a partially filled hydrogen liquid in fuel tank is studied using computational fluid dynamics with volume of fluid along with k-epsilon turbulence model to determine the sloshing behavior in the tank with and without baffles of varying symmetry with help of Simulation software ANSYS. Comparison study of result are done to analyse the impact and for further improvement.
Keywords: sloshing, computational fluid dynamics, volume of fluid, baffles

I. INTRODUCTION

Every abrupt change in motion in a vehicle with a partially filled fluid tank causes sloshing, or the movement of the fluid's free surface within the tank. Sloshing glitches in liquid tank have to be considered for the design of fuel tank for rocket. When the tank is forced to move, free surface of the liquid in the tank distorts, fluid moves in large amplitudes, and resultant impact pressure is exerted on the tank walls which may damage the local structure or influence the stability of rocket. Thus, sloshing causes structural and stability problems in tanks or containers. When sloshing occurs, a container undergoes various type of liquid motion that subject the container to massive loads. For example hydrodynamic forces acting on tank walls may lead to fatigue damage or structural failure. Sloshing is an undesirable occurrence because it losses the vehicle's stability, and can lead to a crash and fire explosions if the tank includes combustible liquids. Sloshing is an unwanted effect that occurs in fuel carrying spacecrafts, Aircraft, and trucks transferring fuels. As a result, slosh forces or pressures have played a dangerous factor in the critical systems of Aerospace Industry, where stakes are higher and margin for fatalities are not allowed. To avoid serious consequences, tank configurations must be confined. Aerospace Industry was first introduced to sloshing in 1957 when NASA began testing the Jupiter Missiles. The later departures of the same Jupiter missiles launched Pioneer 4, the first successful American lunar probe. The first Jupiter rocket, the AM-1A, was launched from Cape Canaveral's Launch Complex-5 on 1st March 1957. After control crushed about the 50-second point, the vehicle blew up at T+73 seconds. The second Jupiter launch, which took place on April 26th, went off without a hitch before T+70 seconds then Due to instabilities caused by Propellant due to sloshing, the rocket broke.

Baffles are usually installed inside tank to control sloshing dynamics loads, increase the hydrodynamic damping ratio, and enhance the stability of container vehicles. Baffles are additional structural elements can provide passive control of the effects of liquid motion. The approach taken was to assess the reliability of the designs developed and computational fluid dynamics simulations of the design were compared in these traditional engineering approaches to tackle the major challenges.

II. THE PROBLEM STATEMENT

The problem statement is to develop a concept and a mechanism to handle the instabilities caused by the sloshing of water in a half-filled water tank being kept as the payload aboard a water rocket. This problem is directly analogous to the issue of sloshing of liquid propellants inside the tanks in a liquid propellant rocket or inside the tanks of a spacecraft or an aircraft. The sloshing of a propellant can be a serious engineering issue.

It can cause problems to the attitude control system of the spacecraft or to the guidance and navigation controls in a rocket or an airplane. In addition to this sloshing hinders with the fuel feed systems and propellant feed systems in both aircrafts and spacecrafts. These issues make it very important to dampen the effects of sloshing inside the tanks. Development of these methods can help students understand the importance of engineering skills in the real world.

III. BAFFLES DESIGN AND SHAPE

Baffles are usually installed inside tank to control sloshing dynamics loads, increase the hydrodynamic damping ratio, and enhance the stability of container vehicles. Baffles are additional structural elements can provide passive control of the effects of liquid motion. Baffles are the best passive way to reduce the sloshing effect inside the tank. It also has its own drawback such as it will increase the weight of the tank. While keeping this as our objective we have design the baffles in such a way the it should not increase that much weight which can affect the performance of the rocket.

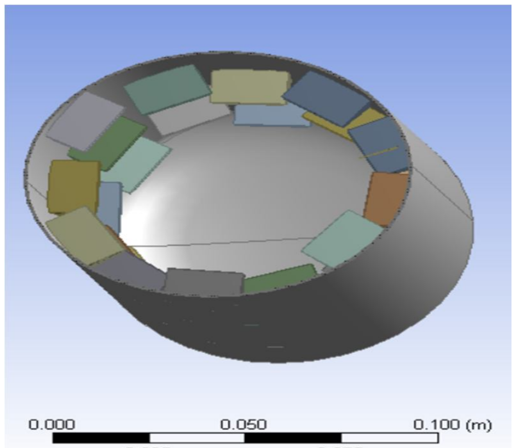

Fig.1 Internal view of sloshing tank with baffles

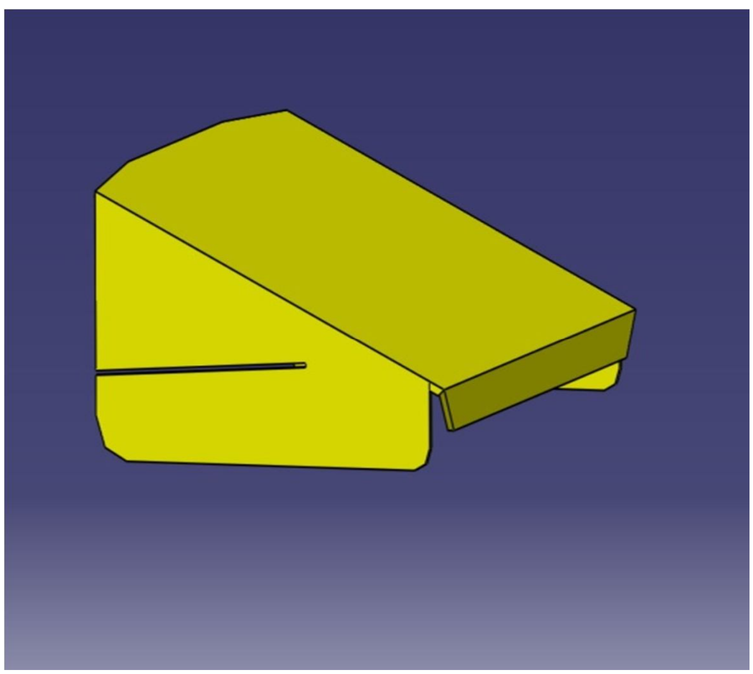

Fig.2 Baffles Design

We have design the above baffle with aim that it should increase the weight as compare to regular baffles use in tankers. And we can see in that design that baffle is cover from both side so that the water could be stop from escaping from the side after the impact, which will reduce the amount of water going up. With this it will transfer less amount of force to baffle above it. In the design we can see that slope has been provided to the baffle which will help the water to quickly come down & with less force/velocity.

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IV. SLOSHING EFFECTS

Sloshing is an important phenomenon in spacecraft, road vehicles, ships & in many aircrafts. Sloshing of propellant in spacecraft may introduce uncertainty in altitude of spacecraft which is called jitter. It can also cause pogo oscillation & may results in structural failure. Sloshing can define as movement of liquid or fuel within a tank or vessel during motion or travelling. Motion of liquid & its effects is called sloshing. Used of baffles is one of solution for avoiding sloshing effect. Baffled tank is widely used. Depending upon amplitudes & frequency of motion of container, responses of liquid free surface can be most bewildering in their complexity. Liquid sloshing involves problem of hydrodynamic pressure distribution, forces, moments & natural frequencies of free liquid surfaces. These parameters have direct effect on dynamic stability & performance. During sloshing breathing vibration of tank are radial, both flexure & stretching of wall occur, while longitudinal axis of tank remains straight. During oscillation of tank different sloshing waves can be generated, they can be standing wave, travelling wave, combination wave. Sloshing also introduce different types of loads inside container, & can be non-impulsive dynamic pressure, impulsive dynamic pressure, total dynamic forces & moments, drag & inertial forces, vortex induced pressure field. Sloshing disturbances can be caused by gust loads, control modes & structural loads. The stability of space vehicle can be increased by reducing force & moment resultants caused by oscillating propellant & increasing sloshing frequency. The easiest way to decrease slosh if it is too large is to slow down movement.

Problem faced by designer of optimizing a damping system into design requirements that follow:
1) Produce high damping effect
2) Pay a minimum weight penalty
3) Utilize minimum space
4) Absorb the liquid forces and moments or transfer them uniformly to the tank structure, thereby to avoid points of high stress concentration
5) Function throughout environmental changes, such as temperature
6) Not interfere with other operations, like as the emptying of the container or the measurement of the liquid level
7) Be easy to assemble
8) Not cause damage to the tank or other built-in equipment during transportation of the vehicle
9) Not interfere with cleaning operations

The expression for the natural frequencies for free liquid oscillations is as follows:

$$\omega^2 = \frac{g}{a}\, \varepsilon \tanh(\frac{h}{a}\varepsilon)$$

g = acceleration due to gravity
a = radius of tank
h = depth of liquid in tank
ε = roots of eigen value

It is observed that the eigen frequencies are proportional to the square root of the **g**. However, when the vehicle experiences a large acceleration normal to the mean free surface of the fluid, **g** becomes the effective longitudinal acceleration of the spacecraft. Therefore, the natural frequencies of the liquid remain a constant while the vehicle is at rest but vary when the spacecraft is in flight. It is also seen that the frequencies are inversely proportional to the square root of **a** and thereby decrease with a rise within cross-sectional area of the container. The influence of tank geometry upon frequencies of liquid is also exhibited by value of **ε**. The liquid height has relatively no effect on the frequencies for **h>a**.
Slosh mass is simply mass involved in sloshing. Fixed mass is that mass which does not take part in sloshing. Total fluid mass(m) is addition of fixed mass(mf) & slosh mass(ms). Some parameters of interest are slosh frequency(fs) & slosh mass(ms). These parameters are determined for different fill levels of fuel, & are in need to perform stability analysis.

The equations are:
Slosh frequency(fs):

$$fs = \frac{1}{2\pi}\left(1.641\frac{g}{R}\tanh\left(1.641\frac{h}{R}\right)\right)^{0.5}$$

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Slosh mass(ms):

$$\boldsymbol{ms = m\frac{R}{2.199h}\tanh(1.641\frac{h}{R})}$$

Dashpot damping(c):

$$\boldsymbol{c = 4\pi\, fs\, ms\, \xi}$$

h is the fill level, **R** is the radius, and **g** is the acceleration of gravity.

The damping ratio **ζ** is defined in terms of the damping factor **δ** as:

$$\boldsymbol{\xi = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}}}$$

In the equation, the damping factor **δ** is defined as:

$$\boldsymbol{\delta = \frac{1}{n}\ln(\frac{x0}{xn})}$$

V. METHODOLOGY

In this paper rocket fuel tanks (with baffles and without baffles) shapes are designed using CATIAV5 software. The commonly used tools to create a model in solid works are Extrude, extrude cut, Revolve, revolve cut Sweep, Swept cut, Fillet, Chamfer, Mirror. CFD Analysis is carried out in three steps i.e. (i) preprocessing, geometry, – Designing, meshing, boundary conditions and numerical method, (ii) Processing – Solving fluid flow governing equations by numerical method till the convergence is reached and (iii) Post processing – extracting results in terms of graphs, contours which explains the physics of flow and required results. The above three steps are carried out in ANSYS using fluid fluent CFD.

A. Computational Analysis

Fuel tank is a crucial part of rocket system and there is requirement of durability and performance of tank. CFD is used in developing fuel tank it helps in sloshing simulation which help us to get a proper insight of behaviour of liquid in fuel tank which means we can analyse pressure distribution and find critical region where it will fail. Computational analysis numerically solved by the set of governing mathematical equation.

B. Governing Equation

Navier-Strokes equations are the governing equation of CFD which is based on conservation of law of physical properties of fluid. The principle of conservational law is change of properties for example mass, energy and momentum in an object is decided by input and output.

C. Continuity Equation

$$\frac{D\rho}{Dt} + \rho\frac{\partial U_i}{\partial x_i} = 0$$

D. Momentum Equation

$$\rho\frac{\partial U_j}{\partial t} + \rho\, U_i\frac{\partial U_j}{\partial x_i} = -\frac{\partial P}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_i} + \rho g_j$$

where

$$\tau_{ij} = -\mu\left(\frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j}\right) + \frac{2}{3}\delta_{ij}\,\mu\frac{\partial U_k}{\partial x_k}$$

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E. *Energy Equation*

$$\rho\, c_\mu\, \frac{\partial T}{\partial t} + \rho\, c_\mu\, U_i\, \frac{\partial T}{\partial x_i} = -P \frac{\partial U_i}{\partial x_i} + \lambda \frac{\partial^2 T}{\partial x^2{}_i} - \tau_{ij}\, \frac{\partial U_j}{\partial x_i}$$

F. *VOF Method*

Volume of fluid method (VOF) is a free surface modelling technique which is use to locate the free surface or fluid – fluid interface. It belongs to class of Eulerian method which are characterized by a mesh that is either stationary or moving in prescribed manner to accommodate the evolving shape of interface. Numerical simulation of an fluid problem is performed by solving three equation continuity (mass conservation), Navier strokes (momentum conservation) and energy conservation. Effect of heat transfer are not required here so the energy conservation is neglected.

G. *Continuity Equation*

$$\frac{\partial U_i}{\partial x_i} = 0$$

H. *Navier Strokes Equation*

$$\rho\, \frac{\partial U_i}{\partial t} + \rho\, U_j \frac{\partial U_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \mu\, \frac{\partial^2 U_i}{\partial x_j\, \partial x_j} + \rho g_i$$

VOF model is used to analyse immiscible fluid with distinctly defined interface this model captures the interface and hence is very efficient in modelling flow problem where shape of interface is of interest. The volume fraction in particular cell which act as a phase indicator function.

The volume fraction ith phase in cell within a multiphase domain is given by equation below

$$\alpha_i = \frac{V_i}{V}$$

where,

V_i is the volume of ith phase in cell
V is the volume of cell

Domain with two phase the phase indicator is defined as follows: -

- α 1 =1 if cell is filled with phase-1
- α2 =0 if cell is filled with phase-2
- 0<α2>1 if cell contain the interface

I. *Operating Conditions*

Pressure based transient solver is used with explicit mode and gravity is enabled. Turbulent model is considered and multiphase VOF method is used. Hydrogen liquid and diesel Air are being used as primary and secondary phases respectively and aluminum as solid material for tank. Sinusoidal acceleration 3[m/s^2]*sin(8.98[rad/s]*t) function is given to fuel tank along with X-direction and hence fuel tank constant velocity 30m/s. Gravitational acceleration is given along Y-direction as -9.81m/s^2.

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J. Properties of the Fluid

Table1: properties of hydrogen liquid

Density (Kg/m^3)	Viscosity [Kg/(m s)]
70.85	1.332e-05

VI. RESULTS AND DISCUSSIONS

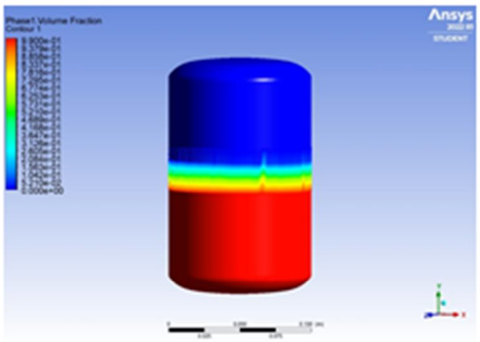

Fig3 Initial Timestep=0 without baffles

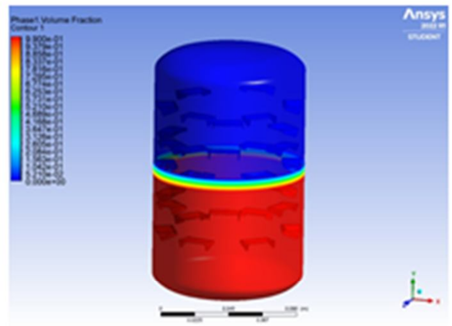

Fig4 Initial Timestep=0 with baffles

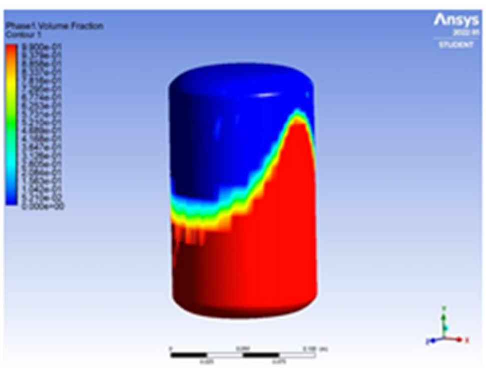

Fig5 At timestep=200 without baffles

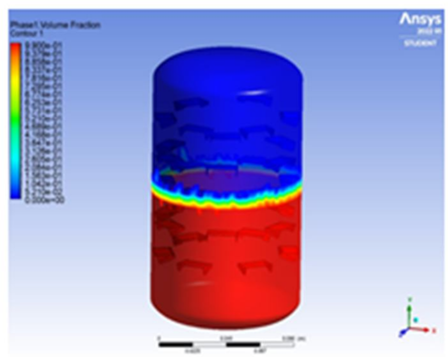

Fig6 At timestep=200 with baffles

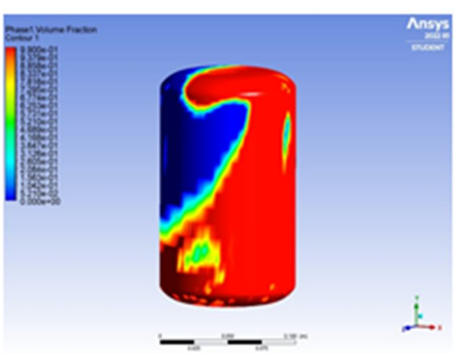

Fig7 At timestep=400 without baffles

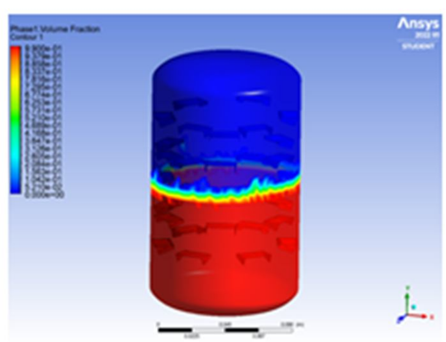

Fig8 At timestep=400 with baffles

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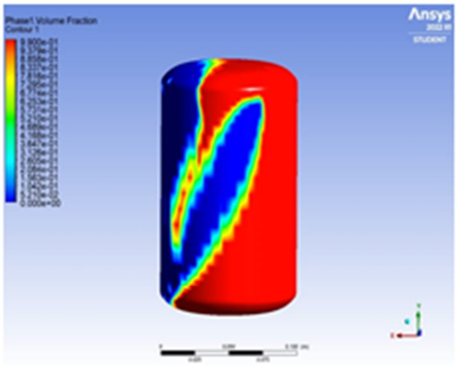

Fig 9 At timestep=600 without baffles

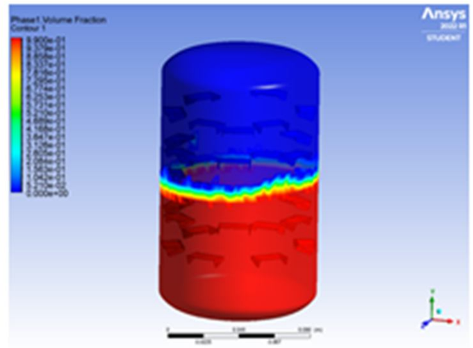

Fig 10 At timestep=600 with baffles

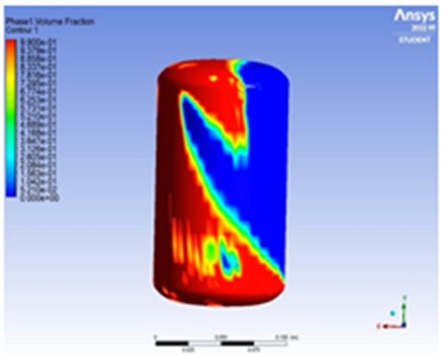

Fig 11 At timestep=800 without baffles

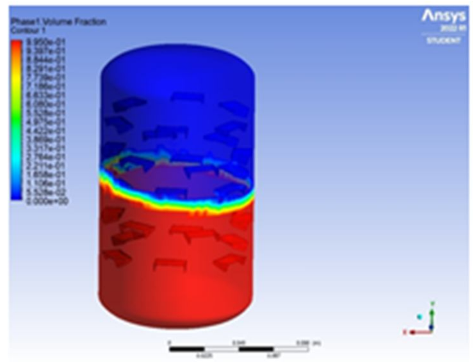

Fig 12 At timestep=800 with baffles

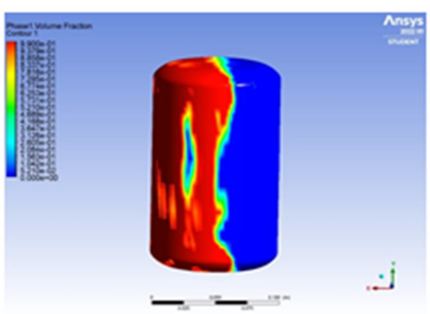

Fig 13 At timestep=1000 without baffles

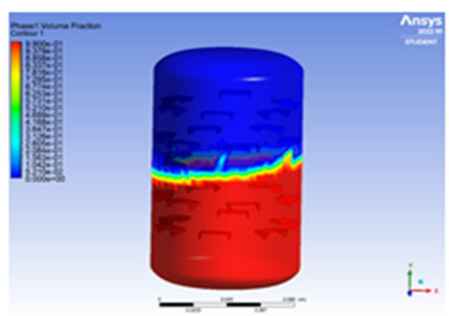

Fig 14 At timestep=1000 with baffles

In this study, the variation in sloshing forces is investigated by installing baffles inside a partially filled tank. The results acquired from transient fluid slosh analysis are reviewed to determine the variation in dynamic load forces. Initially, investigations were done on a tank without baffles, and then the same was conducted by installing baffles. Initial data were used as references.

Here as visible in figure, elevation of liquid free surface is stimulated from timestep 0 to timestep 1000 for both baffled and un-baffled tank. In the case of the un-baffled tank, the liquid was stable at timestep 0 as in fig 1. In fig 3, at time step 200 under excitation the liquid elevation is visible, in figure 5,7,9 the displacement of hydrogen liquid maximum. Whereas in the case of the baffled tank shown in figure the liquid-free surface elevation decreased and stabilized dynamic liquid slosh to an extent. It is clearly seen in the figures the hydrogen liquid amplitude is not getting higher than as compared to un-baffled tank. As seen the baffles are usually installed inside tank to control sloshing dynamics loads, increase the hydrodynamic damping ratio, and enhance the stability of container vehicles. Compared to the un-baffled tank the disturbance of fluid decreases that decreases the dynamic force impact on walls.

A slope surface is introduced in the baffle structure to stabilize the amplitude of movement of fluid. In the design, baffle is cover from both sides so that the water could be stop from escaping from the side after the impact, which will reduce the amount of water going up. We can conclude from the result that the baffles provided here are effective and can decrease the undesirable sloshing effects.

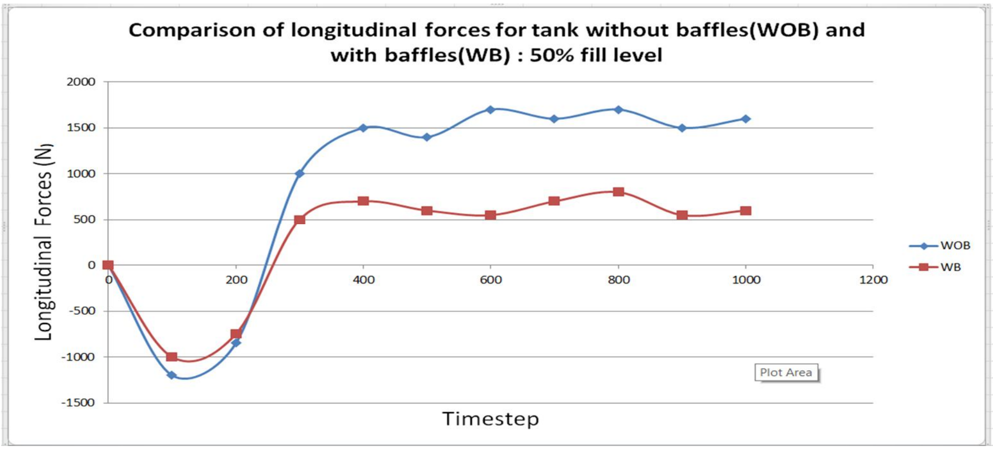

Fig.15 Comparison of longitudinal forces for tank without baffles and with baffles for 50% fill level

In this graph, we studied comparison of longitudinal forces for tank without baffles and with baffles where 50% fuel tank filled with hydrogen liquid. Longitudinal force is traced for the timestep for both tank conditions and the results are proof to effectiveness of the designed baffles. Accordingly, the magnitudes of forces plotted along y-axis have significant difference for both conditions. The reduction in the magnitude of force in baffled tank is visible in the graph which is a validation to the baffle's potential in subduing the sloshing loads.

VII. CONCLUSION

Many research and studies has done to investigate the sloshing anomaly and proposed different models and techniques to reduce the sloshing forces on the tank. The results are extracted from ANSYS software and CAD model of sloshing tanks (with baffles and without baffles) are designed in CATIAV5. In this study, sloshing phenomenon and longitudinal forces acting inside the tank for both cases of without baffles and with anti-slosh baffles are inspected using computational fluid analyses. The free surface elevation; dynamic loads were taken in account and studied. Graphs used to plot the longitudinal forces against timestep to study the comparison of longitudinal force in tanks with baffles and without baffles at 50% of hydrogen liquid inside the tank. The baffles considerably reduced the sloshing forces. The disturbances and magnitude of the sloshing and moment forces are excessive for the tank without baffles. The results analysis clearly proven that baffle design is effective and the magnitude of sloshing forces are significantly reduced.

VIII. FUTURE SCOPE

The sloshing impact on the vehicles is the main core for this study. More techniques can be tested and modification in baffles can be done for further experiment to reduce the impact of force even more. The future studies will search for optimizing the forces to marginal value.

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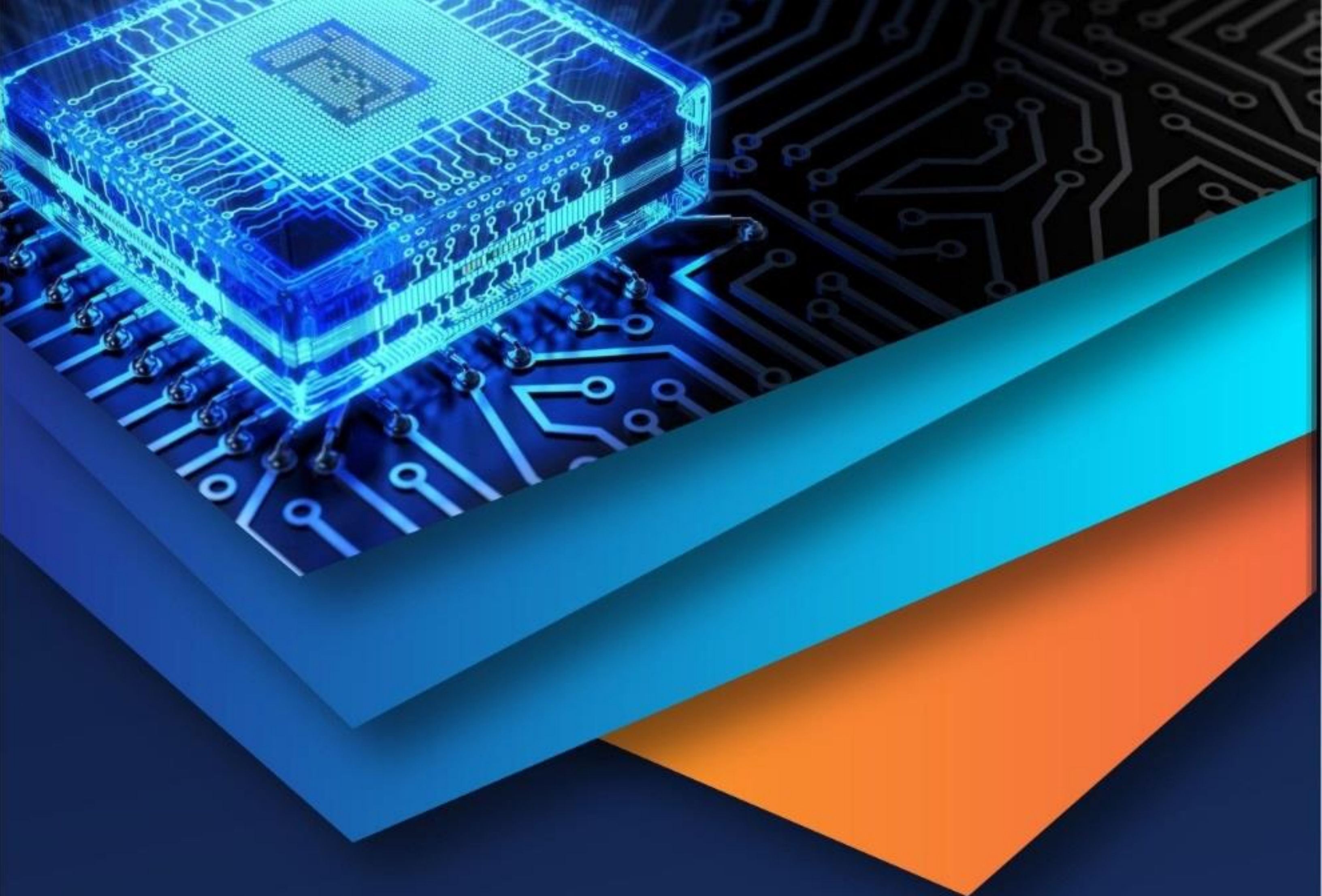

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