CFD ANALYSIS OF FUEL SLOSHING IN A CYLINDRICAL TANK WITH AND WITHOUT BAFFLES UNDER LINEAR ACCELERATION

Thesis Submitted to

National Institute of Technology, Rourkela

For the award of the degree

Of

Master of Technology

In Mechanical Engineering with Specialization

In “Thermal Engineering”

By

Rohit Suyal

(Roll No. 213ME3440)

Under the guidance of

Prof. A. K. Satapathy

DEPARTMENT OF MECHANICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

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ROURKELA

CERTIFICATE

*This is to certify that the thesis entitled "***CFD ANALYSIS OF FUEL SLOSHING IN A CYLINDRICAL TANK WITH AND WITHOUT BAFFLES UNDER LINEAR ACCELERATION***", submitted by* **Rohit Suyal (Roll Number: 213ME3440)** *to National Institute of Technology, Rourkela, is a record of bona fide research work under my supervision, to the best of my knowledge in partial fulfilment of the requirements for the degree of* **Master of Technology** *in the Department of Mechanical Engineering, National Institute of Technology Rourkela.*

To the best of my knowledge, this work has not been submitted to any other University/Institute for the award of any degree or diploma.

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DECLARATION

I certify that

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3. I have followed the guidelines provided by the Institute in writing the thesis.
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5. Whenever I have used materials (data, theoretical analysis, and text) from other sources, I have given due credit to them by citing them in the text of the thesis and giving their details in the references.
6. Whenever I have quoted written materials from other sources, I have put them under quotation marks and given due credit to the sources by citing them and giving required details in the references.

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Signature of the Student

ACKNOWLEDGEMENT

First & Foremost I would like to express my deepest gratitude to my project guide **Prof A. K. Satapathy** without whim this work would not be possible at all. I would like to thank him for his extensive support and inspirational guidance for my project topic. He continuously encouraged me and his invaluable suggestions helped me to complete the project successfully. Also I consider myself fortunate to work under him in such an exciting and challenging research project like "**CFD Analysis of Fuel Sloshing in a Cylindrical Tank with and without Baffles under Linear Acceleration**". The project gave me an opportunity to work in a new environment of ANSYS FLUENT.

I am also extremely thankful to my friend **Uday Raj** & colleagues especially **Sangram Kumar Samal** and **Alok Narayan Behera** for their help and precious suggestions in the execution of the project work.

I would also like to thank my Department for providing the facility of CFD lab, where I completed the maximum part of my project work.

Finally, I express my gratitude to my parents for giving their constant support and encouragement throughout my life.

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ABSTRACT

The phenomenon of sloshing can be understood as any motion of liquid surface. When any partially filled container is disturbed by any external forces, sloshing occurs for example a tank containing fluid put on a moving vehicle. But for occurrence of sloshing the container must have a free surface of liquid. The sloshing causes additional sloshing forces and moments which finally changes the system dynamics and stability. For a moving vehicle this may affect the steering and braking performance as the liquid interacts with the walls of the container. The sloshing phenomenon includes various fields such as propellant slosh in rockets and space crafts, cargo ships and also the trucks which carry different type of fluids. To suppress the sloshing and to limit the effects generated baffles are used. They change the fluid's natural frequency and thus omits the chances of occurrence of resonance. The present study aims towards the design of different types of transverse baffles and their effects in reducing the magnitudes and variation of forces and moments generated in a cylindrical tank partially filled with gasoline subjected to linear acceleration and deceleration. A 3-D transient analysis of the tank was carried out for 20 seconds using ANSYS-FLUENT software at two different fill levels. Volume of Fluid (VOF) method was used to track the surface. The study shows that baffles with more no of holes on their surface reduces the longitudinal forces most effectively but vertical force are reduced with baffles having a single central cavity. For controlling the moments also baffles with single cavity proved to be more effective.

Keywords: Sloshing, Variable time Step, baffles, multiphase, volume of fluid (VOF), ANSYS- FLUENT.

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NOMENCLATURE

English Symbols

a	Acceleration
b	depth
c	Courant number
$\vec{F}$	Force vector
g	Acceleration due to gravity
h	height
I	Unit tensor
$\vec{M}$	Moment vector
p,q	phases
t	Time
Δt	Time step
Δx_{cell}	Cell size
V	Volume of fluid
X,Y,Z	Co-ordinate axes

Greek Symbol

k	Turbulence kinetic energy
ε	Turbulence dissipation
α_q	qth fluid volume fraction
ρ	Density
μ	Viscosity

Chapter 1

Introduction

Introduction

1.1 Sloshing: General

The phenomenon of sloshing can be understood as any motion of liquid surface inside any object. When any partially filled container is disturbed by any external forces, sloshing occurs for example a tank containing fluid carried by a moving vehicle. But for occurrence of sloshing the container must have a free surface of liquid. The sloshing causes additional sloshing forces and moments which finally changes the system dynamics and stability. For a moving vehicle this may affect the steering and braking performance as the liquid interacts with the walls of the container. The sloshing phenomenon includes various fields such as propellant slosh in rockets and space crafts, cargo ships and also the trucks carrying tanks with different type of fluids.

Liquid sloshing on one side affects the flow dynamics, on other side it may be detrimental for the container also. Liquid carrying trucks have to face different road conditions and the unavoidable motion of the vehicle may cause sloshing in the liquid. The forces associated with the sloshing can cause violent movement of the interface.

Many engineering problems include sloshing such as ship instability, Propellant slosh in a spaceship or rockets, liquid storage tanks under earthquake, water reservoir and oceans and in pressure suppression pools.

When the fluid interacts with the wall, the energy exchange takes place between the two and the fluid can show different types of motions. The fluid can have motions like planar, rotational, chaotic etc depending upon the external excitation.

Thus to avoid the spilling of the fluid and the structural damage of the container, the partially filled container should be handled carefully. If we have a free surface, oscillations or liquid sloshing will be induced as the container is given excitations. The basic problem of liquid sloshing involves the estimation of hydrodynamic pressure distribution, moments, forces and natural frequencies of the free surfaces of the liquid. The above mentioned parameters directly affects the dynamic stability and performance of moving containers.

The lowest frequency among the infinite frequencies that a liquid motion can have is generally excited by the external excitation. Therefore most studies are done to investigate forced harmonic oscillations near the lowest natural frequencies.

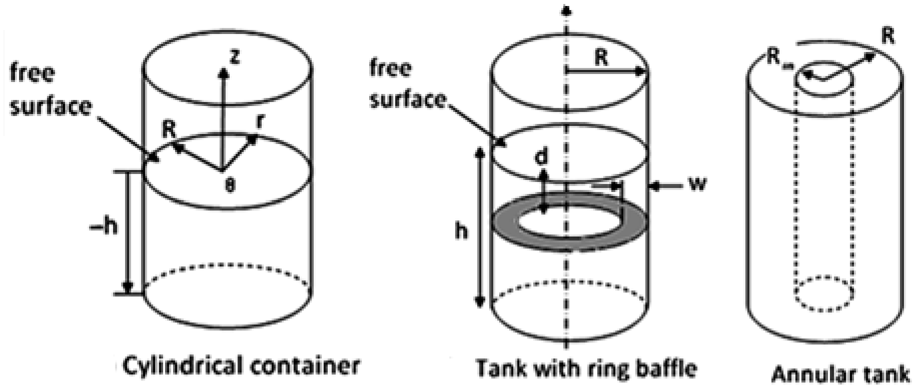
1.2 Sloshing in moving vehicles:

The sloshing phenomenon may occur either in the stationary container or in the moving tanks. For the first case it may include the liquid storage tanks, water reservoir or even the ocean especially in case of an earthquake. Thus from designing a ship to the space crafts and rockets sloshing has been an area of research for many engineers and scientists.

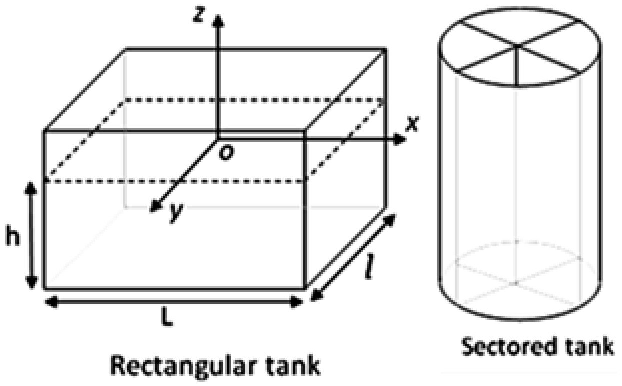
On the other side the sloshing in the moving vehicles have become an area of intensive research now a days. We find that millions of tons of fuels and other fluids are being transported from one place to another by using a truck per year. The fluid may be LNG o, kerosene or gasoline and sometimes even water in the draught hit areas. It has been found that trucks carrying liquids are 4.8 times more prone to the rollover accidents than the trucks carrying a rigid material. Thus it becomes quite important to study the sloshing behavior in a moving vehicle because of the following reasons:

1. Variations in the center of mass coordinates.
2. Dynamic motions of fluid in both the pitch and roll planes.
3. Addition of sloshing forces and moments.
4. Effects on Steering and Braking performance of the vehicle.
5. Likeliness to be involved in rollover accidents.
6. Analytical solution to this problem is a very difficult.

Different tank geometries which has been used for study of sloshing are shown in Figures 1.1



1.1 (a) 1.1 (b) 1.1 (c)



1.1 (d) 1.1 (e)

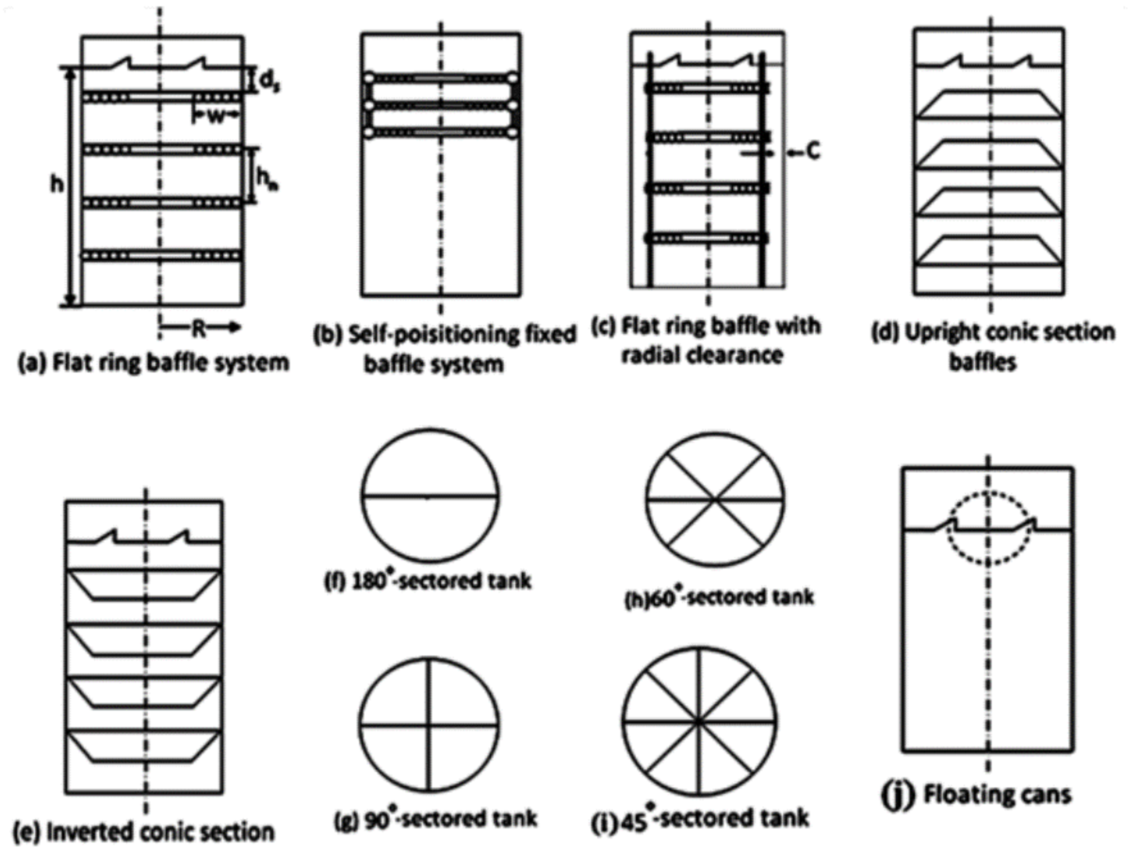
Fig 1.1: Different Tank Geometries

1.3 Suppression Devices:

With increase in the mass of the liquid inside the container the forces and moments developed due to the sloshing may be very high particularly in the vicinity of the resonance. Thus to save the container from structural failure it is necessary to reduce these forces and moments. Baffles are the general and conventional methods to reduce the dynamic loads. The liquid is trapped in between these baffles and energy is dissipated. These baffles change the natural frequencies of the fluid. The two important parameters in studying the sloshing behavior are: the tank geometry and the fill level. Thus the antisloshing baffles are designed to reduce the dynamic load for all possible fill levels and tank orientation and the external excitation.

Fig 1.2 shows the geometries of some baffles which are commonly used for reducing the slosh:

1. Horizontal baffle rings. Fig 1.2 (a)-(c).
2. Conical baffles as shown in Fig 1.2 (d) and (e)
3. Radial (sectored) baffles or cruciform in the form of complete sectored baffles as shown in Fig 1.2 (f)-(i). floating lid devices are also used Fig 1.2 (j).



(a) Flat ring baffle system
(b) Self-poisitioning fixed baffle system
(c) Flat ring baffle with radial clearance
(d) Upright conic section baffles
(e) Inverted conic section
(f) 180°-sectored tank
(g) 90°-sectored tank
(h)60°-sectored tank
(i)45°-sectored tank
(j) Floating cans

Fig 1.2: Anti-Sloshing Devices

1.4 Free Surface Representation

In the problem of study of the sloshing behavior we need to track the interface between two immiscible fluids. For this purpose three basic techniques are used which are as follows:

1. **Capturing (Moving grid or Lagrangian approach):** These methods include moving-mesh, particle-particle scheme, and boundary integral method.

2. **Tracking (Fixed grid or Eulerian approach):** Again this tracking method is divided into two approaches: surface tracking and volume tracking. These include front-tracking, volume-of–fluid (VOF), marker and cell (MAC) method, smoothed particle hydrodynamics etc.

3. A combination of both 1 and 2: Combined methods include the mesh free/particle method, Coupled Eulerian-Lagrangian and variants from the previously mentioned two methods. Amongst these, an indicator function known as volume fraction (color function) for Volume of Fluid (VOF) methods or a level set for level-set methods.

1.5 CFD Packages:

As sloshing includes the Navier-Stokes equations, the analytical solutions of which is very difficult. Thus numerical solutions are done which are validated by the experimental results. For numerical solutions different types of CFD packages are available now a days. Some of the popular packages are: ANSYS-FLUENT, CFX, PHONICS, FLOW-3D etc. Most of these softwares use the FVM (Finite Volume Method) for discretization purpose. In our present study we have used ANSYS-FLUENT v. 15.

1.6 Background of the Problem:

The analytical techniques developed for solving the sloshing problem re not applicable in the large amplitude sloshing problem occurring in the moving vehicles. Also most of the technology has been developed till now is for space applications where the external environment is completely different than the road. Also the excitation related to the space problems are very small as compared to the road applications. Also the study of sloshing in a rectangular tank may be considered as 2-D problem if the width is small but most of the times we use cylindrical tank where the 2-D assumption will not work. Thus we took a practical problem of sloshing behavior in a cylindrical tank subjected to longitudinal acceleration and deceleration.

1.7 Objective of the Present Work:

- Simulation of sloshing in gasoline in a cylindrical tank subjected to longitudinal acceleration/deceleration at two different fill levels by using ANSYS- FLUENT software with and without baffles.
- To study the sloshing forces and moments developed in different planes and their effect on the dynamic stability and the accelerating, braking and steering performance of the vehicles.
- To study the effectiveness of different shaped transverse baffles for minimizing the sloshing forces and moment.

1.8 Closure.

In this chapter we got some basic knowledge about sloshing behavior of the liquid and its effects. We also found that by introducing baffles we can reduce the sloshing dynamic loads. Today we have many commercial CFD packages so that we can easily handle such complex problems like sloshing than its previous analytical solution.

Chapter 2

Literature Review

Literature Review

2.1 Introduction

The present chapter includes the summary of the various literatures and works in the field of sloshing. The study provides the basic information of the sloshing and background of the problem. Thus it helps to define our objectives.

2.2 Areas of research in Sloshing:

After 1950 sloshing in tanks received much attention over the years. In the starting the study was confined to the aeronautics, where the sloshing of the fuel in the tank might affect the dynamic stability of the plane. Further it led to the study of propellant in the rockets with the development of space technology. Later the sloshing became an area of research in the cargo ship and marine applications and also for the liquid carrying trucks. The different fields of application of sloshing problem include:

- Dams.
- LNG carrier.
- railway compressors
- Automotive industry.
- Industrial packing machine.
- Storage tanks.
- Oil tanks.

2.3 Computational studies:

K.M.Tehrani et al. [1] did a 3-D transient analysis of the sloshing in a cylindrical tank. The tank was subjected to both longitudinal and lateral acceleration and sometimes the combination of accelerations in both directions. The fuel was filled in the tank at two different fill levels. The study was performed both with and without baffles in ANSYS FLUENT. The baffle was of conventional type having a central orifice. The result was described in terms of amplification factor which was the ratio of transient force to mean force. The study shows that where the amplification factor without baffles was around 2 , it is significantly reduced as we use baffles.

J.H. Jung et al. [2] took a 3-D rectangular tank and filled it with the water up to 70%. They studied the sloshing behavior with different heights of baffles. He made a parameter (h/B) where h is the height of the baffle and B is the liquid height in the start of the analysis. They found that as we increase the height the sloshing reduces and after a certain (h/B) value, also called the critical value the water doesn't touch the roof. The liquid surface also shows the linear behavior after this height. The VOF model was used to track the surface.

S. Rakheja et al. [3] checked the effectiveness of the baffles placed with different orientation inside a cylindrical tank. VOF (Volume of Fluid) multiphase model was used for tracking the interface of the two fluids. The baffles used include lateral, conventional, partial and oblique. The tank was subjected under combined acceleration with different fill levels. The study shows that the conventional baffle with a central orifice is useful in reducing the longitudinal sloshing forces while the oblique baffles are good in reducing the sloshing forces and moments in both lateral and longitudinal directions and in other planes.

Bernhard Godderidge et al. [4] took a rectangular tank subjected to sway induced sloshing. They conducted the study both experimentally and computationally using CFD analysis. For the density and viscosity of the fluid, they took both homogeneous and inhomogeneous multiphase approach and then compared the computational and experimental results. The results after comparison show that the homogeneous approach gives 50 % less accurate results for peak pressures with respect to the inhomogeneous multiphase model.

Kingsley et al. [5] A multidisciplinary design and optimization (MDO) method is presented. They basically focused on the design prospect of the liquid containers. For that they used a rectangular tank and both numerical simulation and experiments have been done. The numerical results were validated with the experimental ones. VOF model for multiphase interface tracking, $k - \varepsilon$ model for turbulence has been used.

D.Takabatake et al. [6] studied the damage caued to the liquid storage tanks during earthquake in Tokachi-oki, Japan in 2003. Earthquakes generally occur in Japan. They observed that sloshing causes the structural damages to the petroleum tanks. To reduce this they used a splitting wall as a new anti-sloshing device. Experiments were done and then numerical simulation was done. The results were almost same The new proposed anti- sloshing devices reduced the sloshing effectively. Based on the numerical simulation, the proposed device can be also effective against earthquake ground motion.

Eswaran et al. [7] used a cubic tank to study the effects of baffles on sloshing fileed partially. VOF model along with ADINA software was used for the numerical analysis.

Vaibhav singal et al. [8] a partially filled kerosene tank was used for the sloshing analysis. Computational study was done in the tank both with and without baffles. VOF as multiphase model and ANSYS FLUENT software for finite volume method were used. The baffles reduce the sloshing effectively.

2.4 Numerical and Experimental studies

Sakai et al. [9] took a floating-roofed oil storage tanks for studying the sloshing behavior through theoretical analysis and model testing. The analysis studied the interaction happened between the roof and the fluid contained by the tank for which fluid-elastic vibration theory was used.

Biswal et al. [10] they used thin annular circular shaped baffle to reduce the sloshing in a partially filled cylindrical tank. They studied the influence of the annular baffles on the dynamic response of the tank.

.

M. H. Djavareshkian et al. [11] opened a new method for simulation of sloshing problem by using VOF (volume of fluid) method. This method is used to track the interface inside the containers.

Pal et al. [12] in place of Finite volume method, they used the finite element technique to study the sloshing behavior of an inviscid, incompressible liquid filled inside a thin cylindrical tank. The composite cylindrical tanks were given small displacements. The formulation of finite element equations were done for both thin cylindrical wall and the fluid domain. The tank system was analyzed both rigid and flexible in the study. The effect of structural response and flexibility of the tank on the sloshing behavior was discussed. An experimental set-up was made to study sloshing frequencies, sloshing displacements and hydrodynamic pressure.

Abramson et al. [13] used ring and circular sectored cylindrical and spherical tanks to analyze the liquid motion. They applied linear theories, based on the potential formulation of velocity field, Tests were conducted experimentally for the validating the mathematical models.

Wei Chen et al. [14] studied the high amplitude liquid motion caused due to the sloshing inside a container subjected to harmonic and earthquake base excitations. It was found that the liner assumption of the liquid flow may prove to be detrimental under seismic excitation and thus non –linear sloshing should be considered while designing the seismic-resistant tanks. The linear theory was good in predicting the hydrodynamic forces but inaccurate in finding the sloshing amplitude.

Hasheminejad et al. [15] used linear theory to predict the sloshing frequencies. They analysed the sloshing behavior inside a half filled cylindrical tank placed horizontally having elliptical cross section by a 2-D hydrodynamic analysis. They also studied the effect of baffles placed on the free surface.

Celebi et al. [16] used a rectangular tank with vertical baffle partially filled with water .They solved Navier-Stokes equations by using FDM assumptions. VOF method was used to demonstrate the surface. The result shows that the vertical baffle proved to be useful in reducing the sloshing.

Rebouillat et al. [17] describes the problem of modeling the solid-fuel interaction. The study describes the sloshing phenomenon in partially filled cylinders in terms of sloshing wave amplitudes, frequency and pressure exerted on the walls of the container. The problem is of importance for naval, space and road transportations. Numerical results are compared with the experimental results if available.

2.5 Closure:

The research and work described in the chapter includes both numerical and experimental analysis of sloshing forces and moments in different types of geometries. Most of the sloshing problem behaves non-linearly and hence it becomes challenging. Numerical approach towards solving a sloshing problem needs experimental validation. Thus it requires to analyze the sloshing problems scientifically.

Chapter 3

Physical Model

Physical Model

3.1 Physical Model

The present problem consists of a cylindrical tank of a moving vehicle as shown in the figure 3.1. The length and diameter of the cylinder are 8m and 2m respectively. The tank is partially filled with gasoline (ρ =850 kg/m^3, μ = 0.0687 kg/m-s) at two different fill levels of 40% and 80% respectively. Remaining part is the air. As the vehicle is subjected to acceleration or deceleration, the fuel shows sloshing. We will consider the sloshing only in the accelerating and decelerating phase and not because of the other disturbing forces during the uniform motion. To reduce the sloshing different types of baffles have been introduced inside the cylinder discussed in the later section of this chapter.

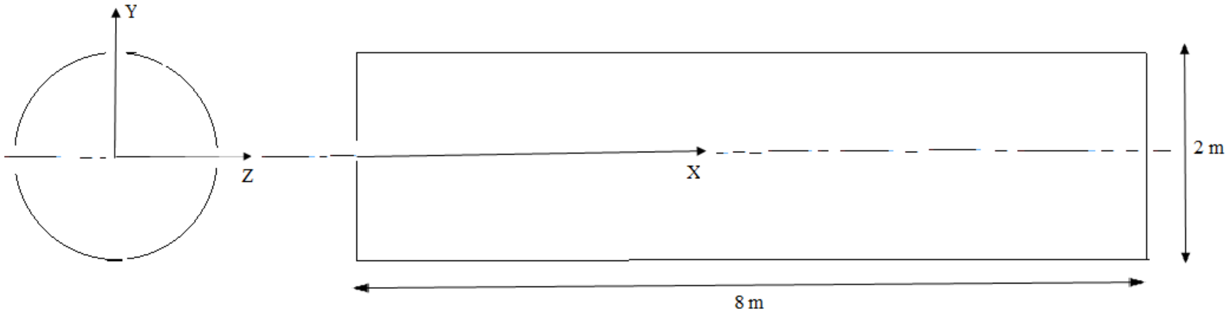


Fig 3.1 The fuel tank

3.2 Motion of the tank

The fuel tank is subjected to a constant acceleration of magnitude 2.77m/s . As we want to solve the problem for extreme conditions, we accelerate the vehicle for first 8 seconds. The velocity goes up to 80 km/h. Then we keep the vehicle moving in this speed for next 4 seconds i.e. up to 12 seconds. For last 8 seconds we decelerate the vehicle from 12 sec to 20 sec. Thus simulation is done for all the cases are solved for 20 seconds at least as described above.

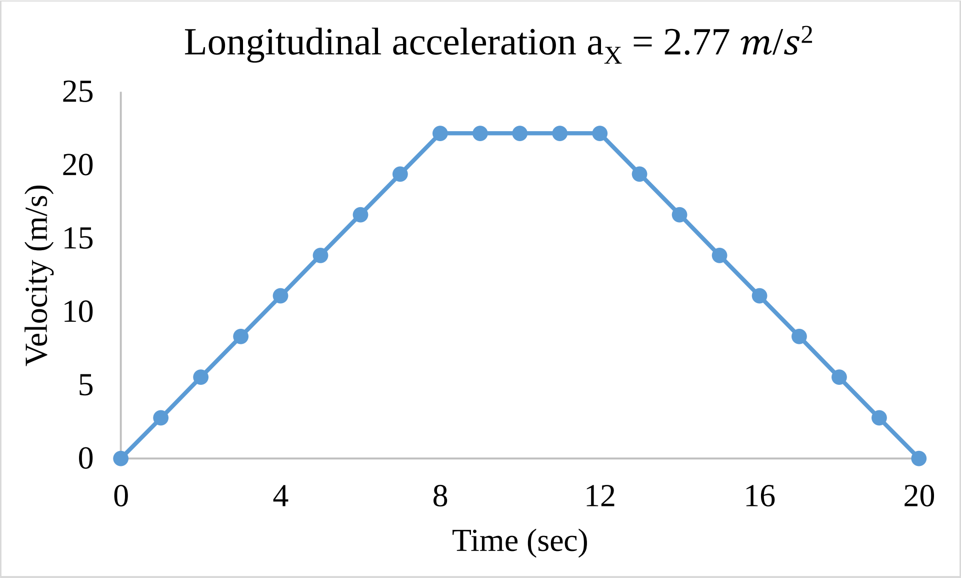


Fig 3.2 Motion of the Tank

3.3 Types of baffle used

Due to the acceleration imposed on the tank filled with gasoline partially, sloshing occurs. In attempt to reduce the sloshing and the forces and moments produced by it, baffles are placed inside the tank. Simulation is carried for the tank both with and without baffles. The different configurations of the transverse baffles are analyzed with respect to their effectiveness in reducing the sloshing forces and moment. The baffles are equi-spaced and the distance between any two of them is kept 2m as shown in the fig 3.3.The baffles are concentric with the cylinder.

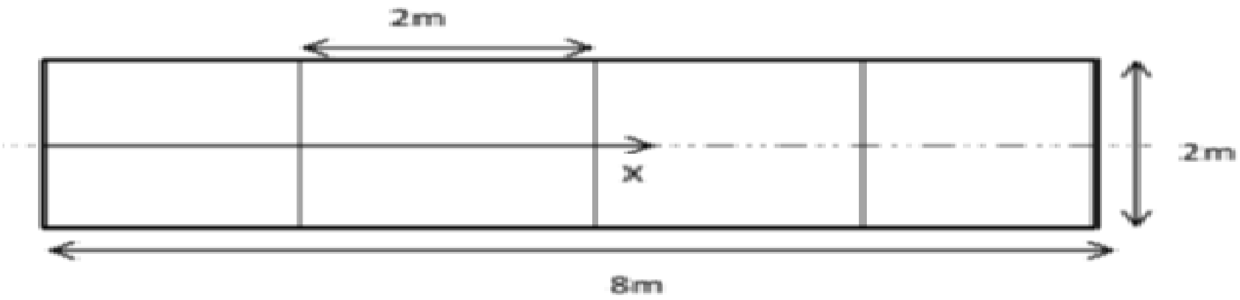


Fig 3.3 Cylinder with transverse baffles

Different types of Baffles Used: All baffles are circular and are kept in transverse direction and are concentric with the tank. Baffles have been configured such that after introducing the baffles the remaining solid material in the baffle’s cross sectional area is almost same in all the cases which is around 75 %. Fig 3.4 shows different types of baffles:

Fig 3.4.a

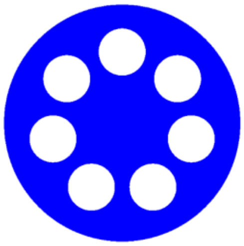


Fig 3.4.b

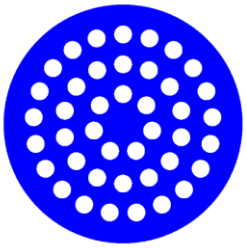


Fig 3.4.c

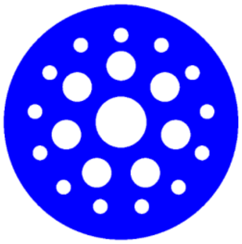


Fig 3.4.d

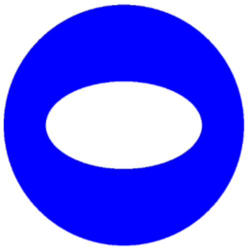


Fig 3.4.e

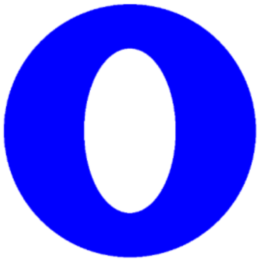


Fig 3.4.f

Fig 3.4 Different Configurations of Transverse Baffle

3.4 Closure:

Physical model of the present study, motion of tank and different configurations of the baffles with their geometry have been explained in this chapter.

Chapter 4

Mathematical Formulation

Mathematical Formulation

In mathematical model we describe the system in the language of mathematics. In this way we try to represent the fluid flow during sloshing in the form of mathematical equations called as governing equations. These equations give an exact representation of the real event. Once the equations are formed CFD techniques are used to solve the governing equation. The governing equations relevant to the study are: Continuity equation, Navier-Stokes equation, and VOF. This chapter presents an explanation to these governing equations and the VOF technique to track the free surface. Sloshing is a time dependent process, hence time dependent form of the equations is used.

4.1 Governing Equations:

4.1.1 Continuity Equation:

This equation represents that mass is conserved in a flow. For cylindrical coordinates,3-D, incompressible, unsteady, continuity equations is:

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\,(\rho r u_r) + \frac{1}{r}\frac{\partial}{\partial \phi}(\rho u_\varphi) + \frac{\partial}{\partial z}(\rho u_z) = 0 \qquad \text{...... } \mathbf{4.1}$$

u_r, u_φ and u_z are components of velocity in r, ϕ and z direction and ρ is the density.

4.1.2 Navier-Stokes equation (Momentum equation):

These equations are the results of applying Newton's law of motion to a fluid element and hence also called as momentum equations. The equation can be applied for both laminar and turbulent flow.

r- momentum equation:

$$\rho\left(\frac{\partial u_r}{\partial t} + u_r\frac{\partial u_r}{\partial r} + \frac{u_\varphi}{r}\frac{\partial u_r}{\partial \varphi} + u_z\frac{\partial u_r}{\partial z} - \frac{u_\varphi^2}{r}\right) = -\frac{\partial p}{\partial r} + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_r}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 u_r}{\partial \varphi^2} + \frac{\partial^2 u_r}{\partial z^2} - \frac{u_r}{r^2} - \frac{2}{r^2}\frac{\partial u_\varphi}{\partial \varphi}\right] + \rho g_r \qquad \text{......} \mathbf{4.2}$$

ϕ- momentum equation:

$$\rho\left(\frac{\partial u_\varphi}{\partial t}+u_r\frac{\partial u_\varphi}{\partial r}+\frac{u_\varphi}{r}\frac{\partial u_\varphi}{\partial \varphi}+u_z\frac{\partial u_\varphi}{\partial z}+\frac{u_r u_\varphi}{r}\right)$$
$$=-\frac{1}{r}\frac{\partial p}{\partial \varphi}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_\varphi}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 u_\varphi}{\partial \varphi^2}+\frac{\partial^2 u_\varphi}{\partial z^2}+\frac{2}{r^2}\frac{\partial u_r}{\partial \varphi}-\frac{u_\varphi}{r^2}\right]$$
$$+\rho g_\varphi$$

…… **4.3**

z- momentum equation:

$$\rho\left(\frac{\partial u_z}{\partial t}+u_r\frac{\partial u_z}{\partial r}+\frac{u_\varphi}{r}\frac{\partial u_z}{\partial \varphi}+u_z\frac{\partial u_z}{\partial z}\right)$$
$$=-\frac{\partial p}{\partial z}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 u_z}{\partial \varphi^2}+\frac{\partial^2 u_z}{\partial z^2}\right]+\rho g_z$$

…...**4.4**

Where p is the static pressure, u_r, u_φ and u_z are the velocity components in r, φ , and z direction. μ is the dynamic viscosity, ρ is density and ρg_r , ρg_φ and ρg_z are body forces due to gravity. For our problem we will add an extra force term in the direction of z for the acceleration in longitudinal direction.

4.2 Multiphase governing equations: As the present problem constitutes more than two phases i.e. gasoline and air, some equations related to the multiphase problems are as follows:

4.2.1 Conservation of momentum

A single momentum equation is solved for the domain, which gives the resulting velocity field shared among the phases.

$$\frac{\partial}{\partial t}\left(\rho\,\vec{V}\right)+\nabla.\left(\rho\vec{V}\vec{V}\right)=\ -\nabla p+\nabla.(\tau)+\rho g+F \qquad \textbf{….4.5}$$

Where p is the static pressure, $\vec{\tau}$ is the stress tensor and $\rho\vec{g}$, $\vec{F}$ are the gravitational body force and external body force (which arises from interaction with the dispersed phase), respectively. $\vec{F}$ represents the external body force can also be given as user defined source terms, which is momentum source here for the present problem. Momentum source is defined as the multiple of the density of a given specific mesh cell and the instantaneous acceleration. It has the units of Kg/ m^2s^2.

4.2.2 Volume of fluid model

The present problem consists of two phases i.e. water and air. For tracking the free surface of the gasoline multiphase volume of fluid (VOF) model has been used. This model permits the simulation of large amplitude slosh, which also includes the separation of the free surface. This technique was developed by Hirt, et al.. VOF is a numerical technique in CFD for tracking and locating the free surface (or fluid-fluid interface). The VOF method is based on earlier Marker-and-cell (MAC) methods which is now known as VOF given by Noh & Woodward (1976). In the VOF model, a single set of momentum equations is shared by the fluids, and the volume fraction of each of the fluid in each computational cell is tracked throughout the domain. VOF model solves phase and the total continuity equation and the result is pressure and volume fraction which points out where the interface is.

4.2.3 Volume Fraction

The VOF formulation works when two or more fluids (or phases) don't penetrate each other. If we add an extra phase to our model, a new variable is introduced to represent the volume fraction of that phase in the cell. For every control volume,

$$\sum_{p=1}^{n} \alpha_p = 1 \qquad \textbf{......4.6}$$

Where α_p represents the volume fraction for a particular phase p and n is the no of phases present in the computational cell. The value of α_p ranges between 0 to 1. 0 represents the cell is empty, 1 represents the cell is full with the particular phase p. An intermediate value between 0 to 1 shows that there is an interface of one or more fluids.

VOF model can be understood from (Figure 4.1). The figure is a result of simulation of 2-D sloshing problem in a rectangular tank and shows the phase contours of water. The red color represents the water phase and the rest portion represents air. From equation 4.5

$$\alpha_{water} + \alpha_{air} = 1$$

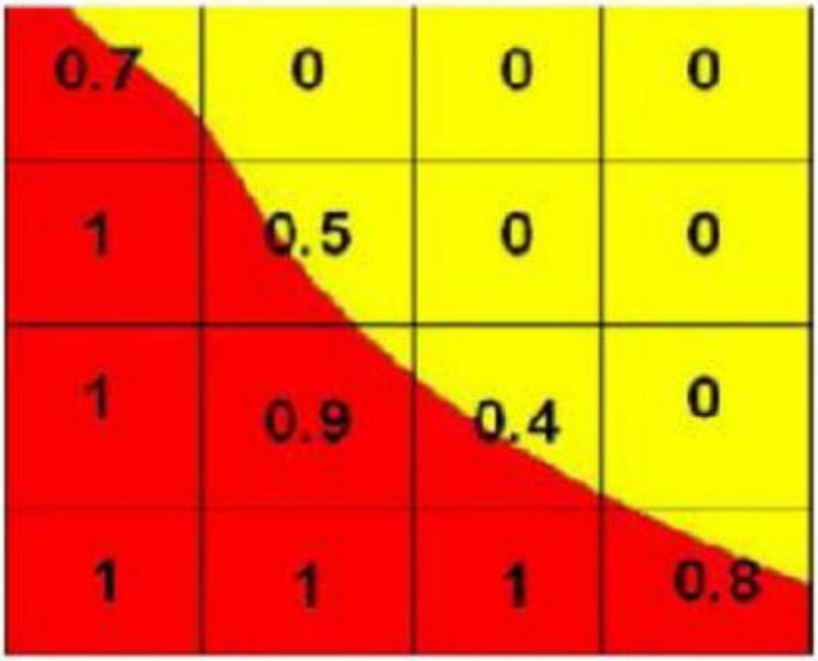


Fig 4.1 Illustration of VOF Model

4.2.4 Dynamic sloshing forces:

The sloshing forces are derived from the distributed pressure through integration over the wetted area of the wall cell,

$$F_x = \sum_c^{wetarea} P_c \overrightarrow{A_c} . \vec{\imath} \quad \text{....}\mathbf{4.7}$$

$$F_y = \sum_c^{wetarea} P_c \overrightarrow{A_c} . \vec{\jmath} \quad \text{....}\mathbf{4.8}$$

$$F_z = \sum_c^{wetarea} P_c \overrightarrow{A_c} . \vec{k} \quad \text{..}\mathbf{4.9}$$

where F_x , F_y, F_z , are the resultant slosh forces acting on the tank wall along the fixed x, y and z axes due to pressure P_c acting on cell "c" with area vector $\overrightarrow{A_c}.\vec{\imath},\vec{\jmath},\vec{k}$ are the unit vectors in the x, y and z direction respectively.

4.2.5 Sloshing moment

Along with the sloshing forces the sloshing moment also affects the stability and needs to be calculated. The moment is caused because of the variation in the cg coordinate. They significantly affect the directional response of the vehicle. The roll, yaw and pitch moments about a point "o" are obtained upon integrating the moment corresponding to each cell over the wetted area:

$$\vec{M} = \sum_c^{wet\ area} \overline{r_c} \times F_c \qquad \text{.....}\mathbf{4.10}$$

where $\vec{F_c}$ is the force vector caused by a cell "c" on the boundary, $\vec{r_c}$ is the position vector of cell "c" with respect to "o" and $\vec{M}$ is the moment vector about point "o". The coordinate of this point "o" are (0,-R, 0), where R is the tank radius. [1]

4.2.6 Turbulence Modelling

The standard k-ε model is a semi-empirical model and is based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate (ε). The k-ε model has been used in our study.

Although the form of the momentum equations remains the same, the viscosity term becomes an effective viscosity μ_{eff}, and is determined by the sum of the molecular viscosity μ and a turbulent viscosity μ_t .The turbulent (or eddy) viscosity μ_t is :

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

Where $C\mu$ is an empirically derived proportionality constant.

4.3 Closure

This chapter explains the different equations which govern the flow in sloshing. These equations are solved by CFD codes. Equations like continuity, Navier- stokes and VOF technique has been discussed. Also the equations for calculating forces and moments developed due to sloshing are explained.

Chapter 5

Computational Analysis

Computational Analysis

5.1 Introduction & Background: This chapter gives a brief description of discretization technique and flow process of CFD simulation. The ANSYS FLUENT setup for the present study has also been explained.

The equations governing the fluid motion in a fluid flow or heat transfer problems are generally partial differential equations which are non-linear in nature. There are different approaches for predicting the behavior of flow field. Some of them are as follows:

- Experimental Approach: In an experimental approach a prototype is prepared and analysis is done on it experimentally. This gives the most reliable result of any process as actual measurement is done. Then the results are predicted for the full- scale measurement for the same environment. But this process proves to be costly and expensive and sometimes it is impossible to use this approach. Moreover, experimental measurements also includes errors associated with measurement and measuring instruments. Despite all of these this process gives the most realistic and reliable result.
- Analytical Approach: The different governing equations of the model are solved mathematically by using boundary conditions. But because of the difficulties involved in solving the partial differential equation. A general information about the process can be obtained but the complexity of governing equation and complexity of the geometry puts limitations on this process.
- CFD or Numerical Approach: In this approach the non-linear partial differential equations are discretized into linear algebraic form of equation over a control volume by using any of the finite difference, finite volume and finite element methods. After that the set of linear algebraic equation are solved iteratively by using numerical technique such as gauss sidle method and TDMA method. CFD analysis reduces total effort and cost required for experimentation and data acquisition and thus removes the drawbacks of previous two approaches.

5.2 Computational Fluid Dynamics

During the past few decades, CFD has been used as an important element in professional engineering practice, and being used in several branches of engineering. Computational fluid dynamics (CFD) includes basically heat transfer and fluid mechanics that uses algorithm code and numerical method to analyze problem involving fluid flow by means of computer based simulation. CFD predicts the nature of fluid flow, chemical reactions, heat transfer, and phenomena related to them. CFD predicts all of them by solving the set of following governing mathematical equations numerically:

- Conservation of mass
- Conservation of momentum
- Conservation of energy
- Conservation of species
- Effect of body forces

CFD solves the non- linear Partial Differential Equations (P.D.E.). Complex physical problems can be solved and ideal conditions can be simulated. But there may be some error in the solutions of CFD like the truncation error. The non- linear equations are discretized into linear algebraic equations for each cell or grid. Then these linear equations are solved easily. There are three basic methods of discretization:

- **Finite Difference Method:** The domain is discretized into series of grid point i.e. Structured i, j, k, grid is required. After that the non-linear partial differential equations are discretized using Taylor series of expansion into linear algebraic equation. These algebraic equations are easy to solve.
- **Finite Element Method:** Basically used for structural problems, sometimes FEM can also be applied to fluid flow. The domain is divided into many elements and for each domain a particular equation comes.
- **Finite Volume Method:** In Finite volume method (FVM), First of all we discretize the domain into many control volumes and then we use gauss divergence theorem to discretize

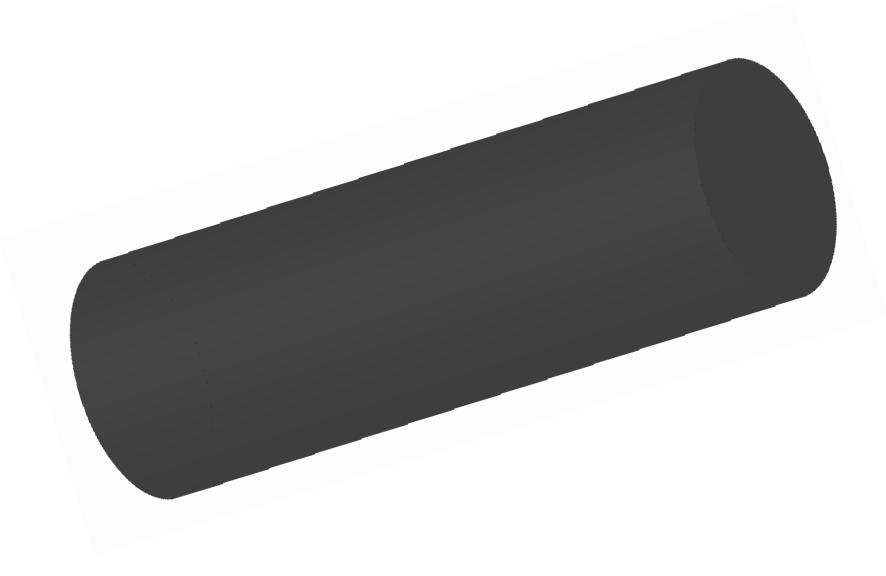
the partial differential equations over a control volume. This process gives algebraic equations which is solved by iteration method.

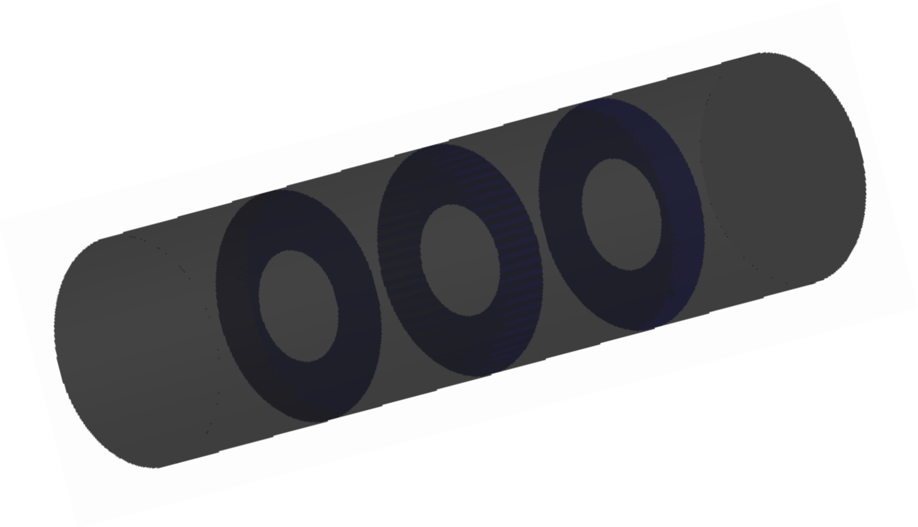
5.3 ANSYS-FLUENT SETUP

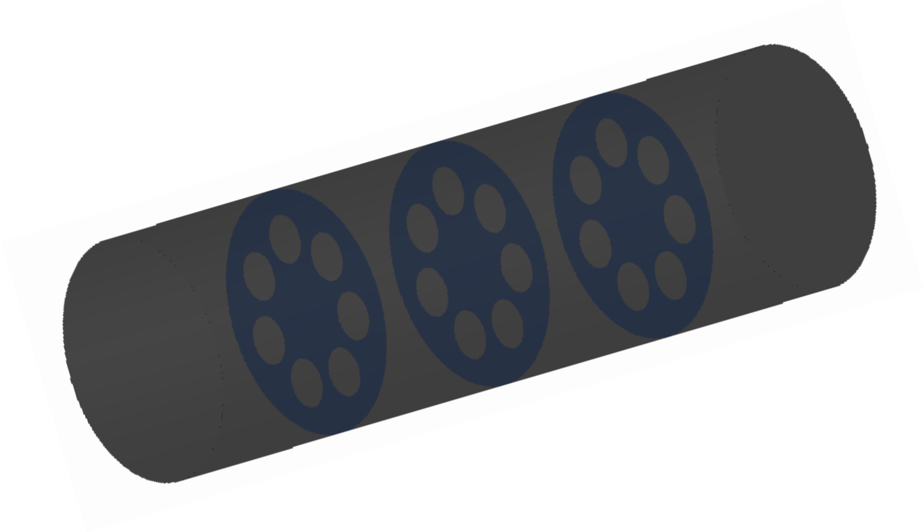
In the present study, simulation of fuel sloshing in a cylindrical tank is done by using ANSYS FLUENT. In ANSYS, ICEM CFD has been used for modeling geometry and meshing. Then the mesh file was exported to a FLUENT solver and Post-processing is done. The sequence of problem set-up is as follows:

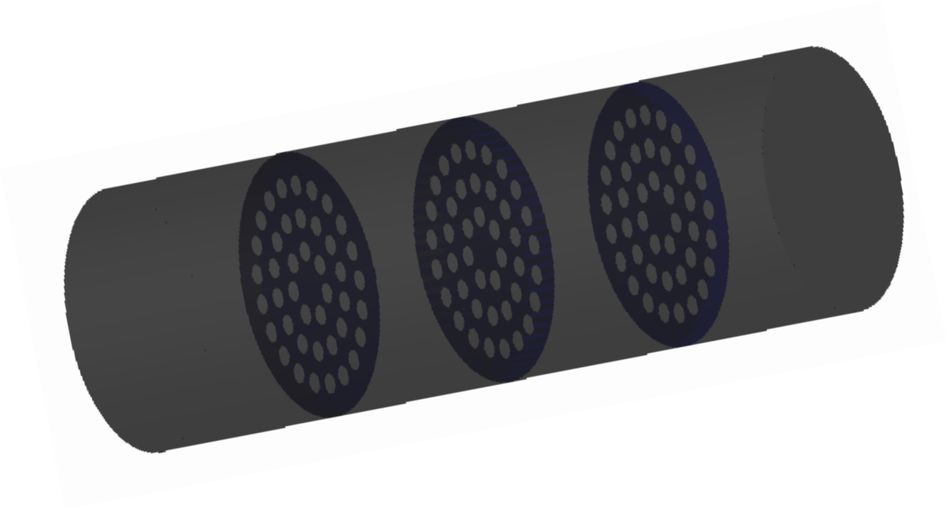
5.3.1 Geometric Modeling:

Geometric Modeling: Geometric modeling consists of drawing the geometry in a suitable software for our analysis. A 3D cylinder as described in chapter 3 is modeled in ANSYS ICEM CFD tool. Cylindrical geometry of without baffle and with 6 different kind of transverse baffles as discussed in chapter 3 are drawn as shown in fig. 5.1. The geometries for the present study for different cases are shown below:









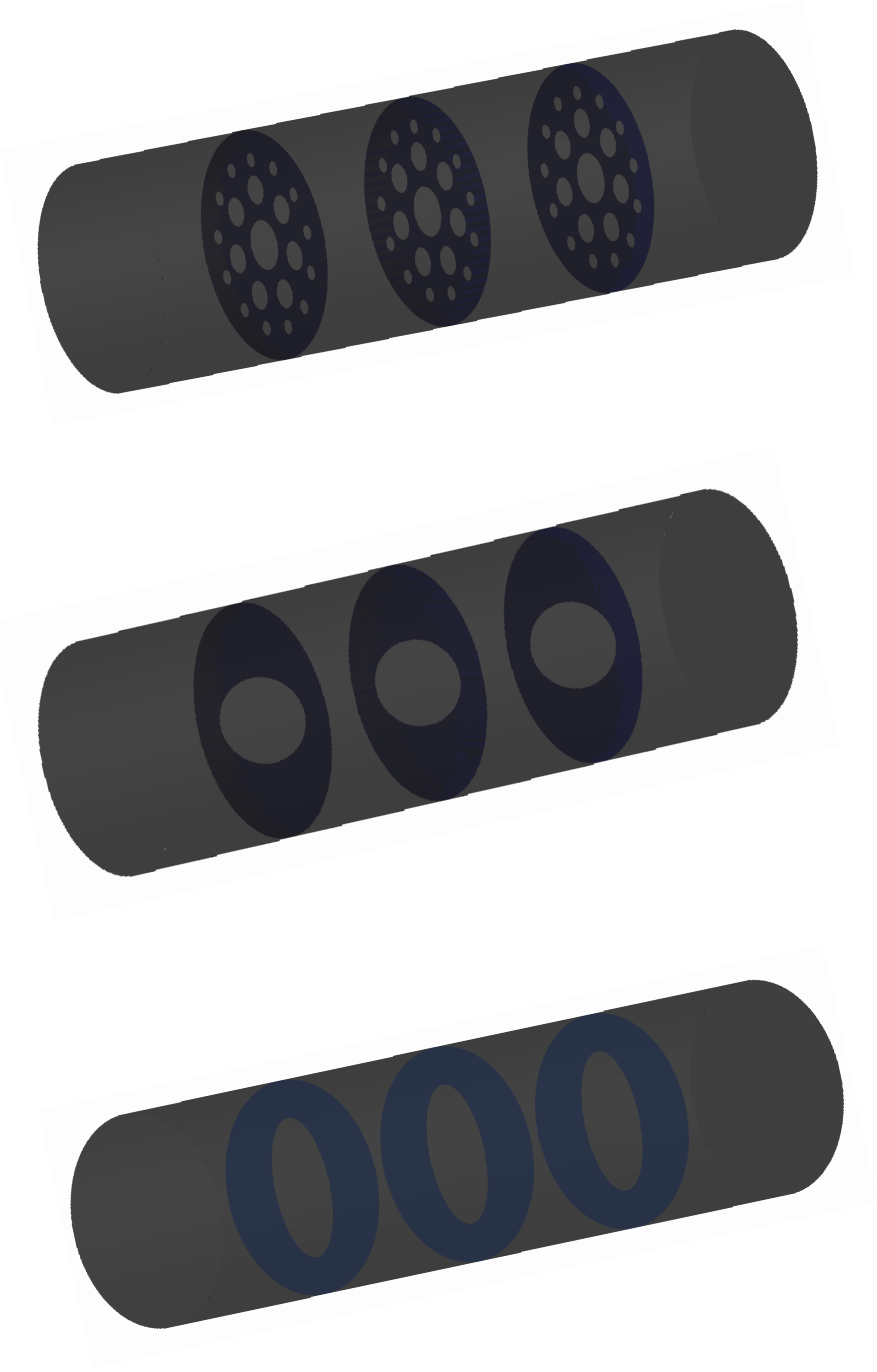


Fig 5.1: Modeling of different baffle configurations in tank using ICEM CFD

5.3.2 Mesh generation: Once the geometry is modeled, we need to discretize it into control volumes. This process is known as meshing. After modeling the geometry in ICEM CFD tool, we did meshing in ICEM CFD tool itself. For our problem we used tetrahedron mesh for all cases. Meshing is an important process as the courant number c depends upon it which is given as:

$$c = \frac{\Delta t}{\Delta x_{cell}/v_{fluid}}$$

Where, Δt is time step, Δx_{cell} is the cell distance and v_{fluid} is velocity fluid at cell. Δx_{cell} depends upon the quality of meshing. As we want our formulations to be conditionally stable the value of c should not go beyond 250 while iteration. If stability conditions are not fulfilled the simulation will diverge and we won't get a solution. As the courant number depends upon Δx_{cell} and which ultimately depends upon meshing, thus to avoid this we should have good quality mesh.

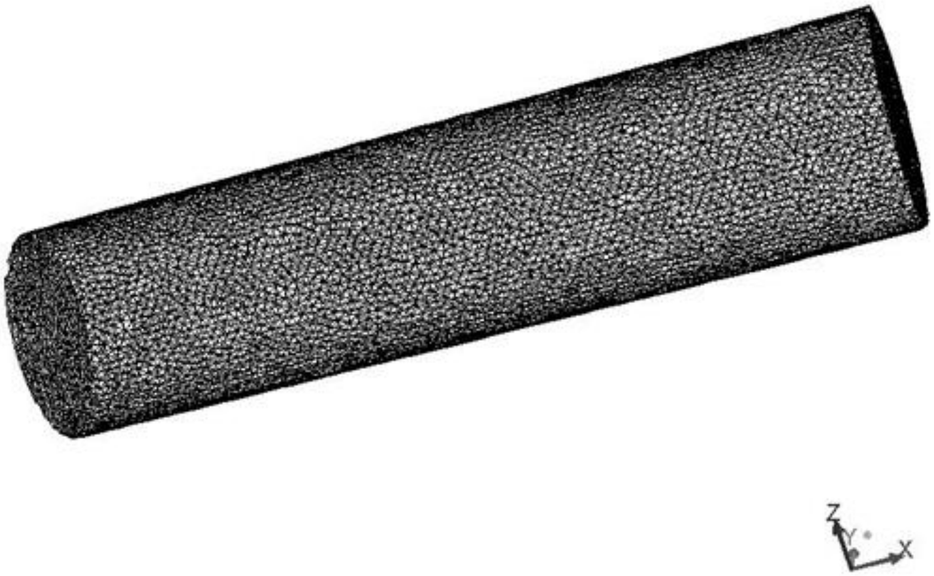


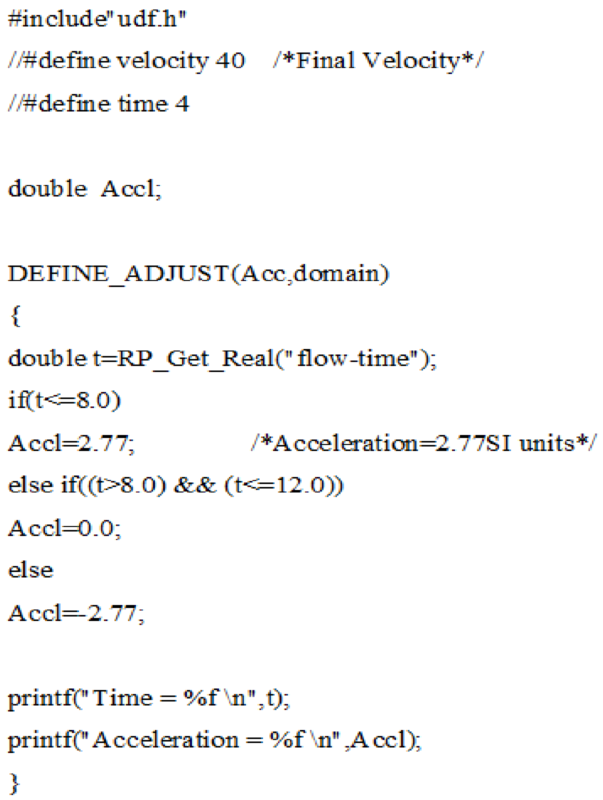
Figure 5.2: Cylinder after Meshing.

5.3.3 FLUENT SETUP: As mesh is generated in the ICEM CFD, it is saved as a mesh file and then imported into FLUENT. 3-dimensional double precision fluent solvers with parallel processing is used for our problem.

1. After reading the mesh file we should first scale it into proper unit if required. After checking the quality of mesh we get
   a. Orthogonal quality 0.443 .This value ranges from 0 to 1. If it is zero it is worst, and if one, the mesh quality is best. 0.443 shows the mesh quality is sufficiently good.
   b. Maximum Aspect ratio as 9.76.
2. Pressure based transient solver is used with explicit formulation with gravitation enabled in the vertical direction.
3. The two immiscible fluids used are air and gasoline, hence multiphase model is selected with the volume of fluid (VOF) formulation, scheme used is explicit. The fluid is turbulent and k-ε model is used.

4. Primary phase is kept as air and secondary is gasoline. Cell zone condition type is taken as fluid.

5. Linear motion acceleration as described in fig 3.2 in the form of in the form of a momentum source term is imposed on the model. There are no inlet and outlet boundary conditions. A user-defined code (UDF c-code) is written for momentum source. The code is given below:



```
#include"udf.h"
//#define velocity 40    /*Final Velocity*/
//#define time 4

double  Accl;

DEFINE_ADJUST(Acc,domain)
{
double t=RP_Get_Real("flow-time");
if(t<=8.0)
Accl=2.77;              /*Acceleration=2.77SI units*/
else if((t>8.0) && (t<=12.0))
Accl=0.0;
else
Accl=-2.77;

printf("Time = %f \n",t);
printf("Acceleration = %f \n",Accl);
}
```

Fig 5.3 UDF c- Code.

6. Operating conditions:

- Pressure: 101325 Pa.
- Gravitational acceleration : X=0 m/s^2,Y= -9.81 m/s^2, Z=0 m/s^2
- Density: 1.225 kg/m^3

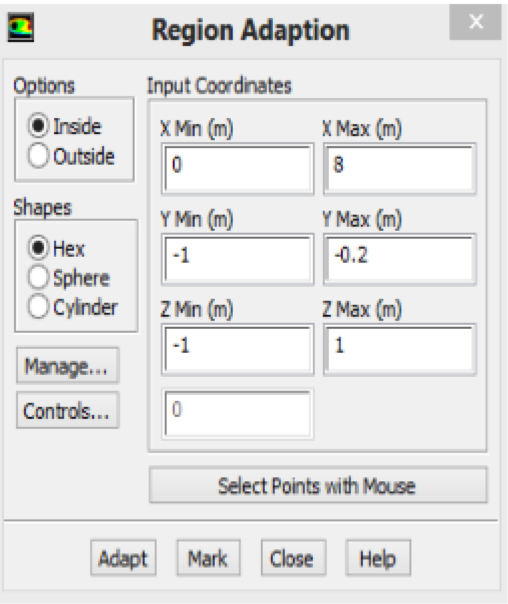
7. Solution Method is used in the present study is as follow:

- Gradient : least square cell based
- Pressure-velocity coupling : Fractional step
- Pressure : Body force weighted
- Momentum : Power law
- Volume fraction : Geo-Reconstruct
- Turbulent Kinetic energy: First Order Upwind
- Transient formulation : First order implicit with Non-iterative time advancement

8. Non-iterative relaxation factor:

- Pressure: 0.8
- Momentum: 0.6
- Turbulent kinetic energy: 1
- Turbulent Dissipation rate:1

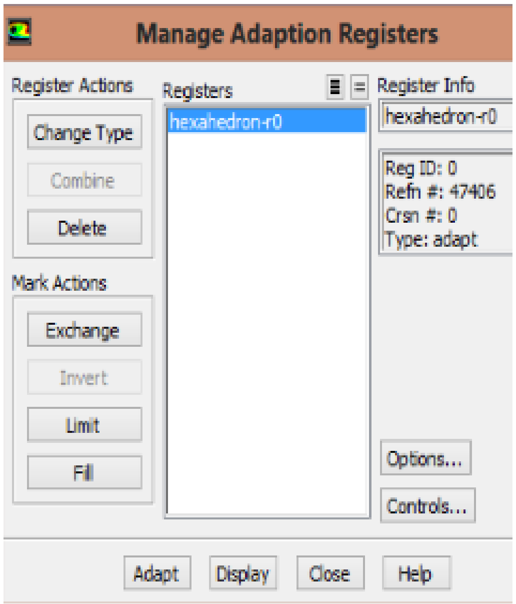
9. For filling the gasoline in the cylinder region is adapted and then patched by gasoline.



Options: ● Inside ○ Outside

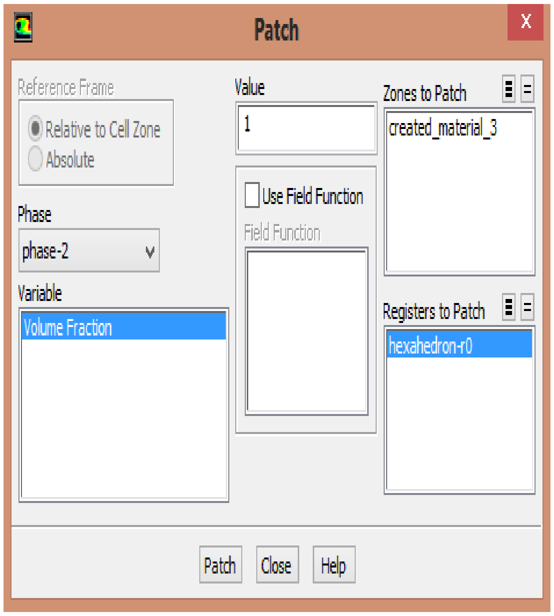
Shapes: ● Hex ○ Sphere ○ Cylinder

X Min (m): 0
X Max (m): 8
Y Min (m): -1
Y Max (m): -0.2
Z Min (m): -1
Z Max (m): 1
0



Registers: hexahedron-r0

Register Info: hexahedron-r0
Reg ID: 0
Refn #: 47406
Crsn #: 0
Type: adapt



Patch

Reference Frame

● Relative to Cell Zone
○ Absolute

Phase: phase-2

Variable: Volume Fraction

Value: 1

☐ Use Field Function

Field Function

Zones to Patch: created_material_3

Registers to Patch: hexahedron-r0

Fig 5.4 Patching process in ANSYS

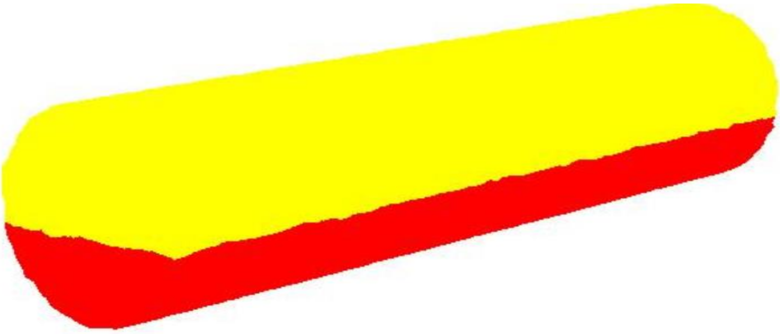
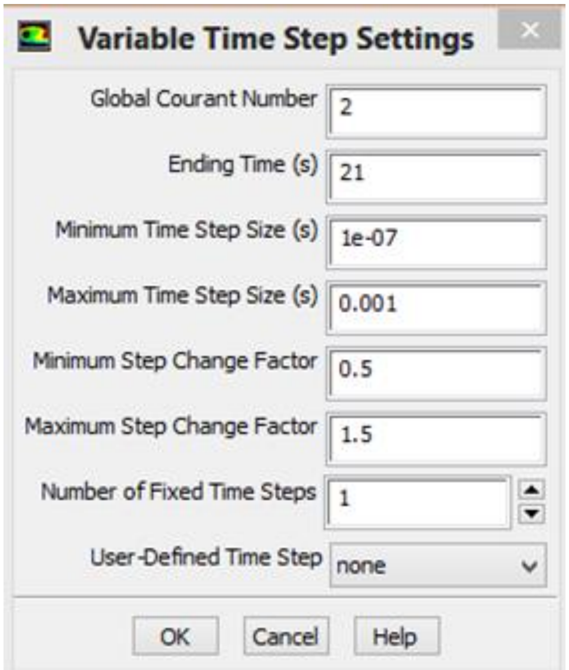


Fig 5.5 Gasoline (Red color) in the tank after patching

11. FLUENT creates surfaces for all boundary zones automatically with iso-surface option where data will be displayed. Iso- surface is used for tracing the points on free surface.

12. Time stepping method: Simulation of sloshing is explicit formulation and it is conditionally stable. Variable time stepping method has been used to limit the value of courant number beyond 250 and hence to avoid divergence.



Global Courant Number 2

Ending Time (s) 21

Minimum Time Step Size (s) 1e-07

Maximum Time Step Size (s) 0.001

Minimum Step Change Factor 0.5

Maximum Step Change Factor 1.5

Number of Fixed Time Steps 1

User-Defined Time Step none

Fig 5.6 Variable Time Stepping Method

5.4 Closure:

We discussed about the different approaches for predicting the flow behavior like experimental, analytical and CFD approach and discussed their advantages and disadvantages. we also discussed CFD and its various applications in industry. The three basic discretization scheme like FDM, FVM and FEA used in CFD are also given. The focus was given to ANSYS FLUENT solver theory as we are using this in the present problem. Also various steps while modeling the geometry, meshing and solving the problem in ANSYS are also given.

Chapter 6

Results & Discussion

Results and Discussion

The present chapter discusses various results obtained after the analysis of sloshing in a 3-D tank. The tank is subjected to a longitudinal acceleration of 2.77m/s^2. The results are presented in the form of graphs between forces, moments vs. time. The sloshing forces and moments are developed due to the accelerating motion developed in a tank which affects the stability of tank. The effect of sloshing forces and moments on stability is explained. Simulation is carried out for a tank without baffle and with differently configured transverse baffles for 20 seconds.

The sloshing analysis has been done for following 7 cases:

Case 1. Tank without baffles.

The other 6 cases with following types of different transverse baffles are used for the sloshing analysis. The baffles are already shown in chapter 3 (Fig 3.4)

Case 2. Ring Type Baffles fig. 3.4 (a) (Type I)

Case 3. Baffles with seven same sized holes fig. 3.4 (b) (Type II)

Case 4 Baffles with seven same sized holes fig. 3.4 (c) (Type III)

Case 5. Baffles with 2 set of different sized holes fig. 3.4 (d) (Type IV)

Case 6. Baffles having elliptical hole with major axis in horizontal direction fig. 3.4 (e) (Type V)

Case 7. Baffles having elliptical hole with major axis in vertical direction fig. 3.4 (f) (Type VI)

The following abbreviations are used for forces and moments in different planes:

F_X = Longitudinal Force.

F_Y = Vertical Force.

M_X = Rolling Moment.

M_Y = Yawing Moment.

M_Z = Pitching Moment.

The forces in the z direction are negligible and not taken for the analysis.

6.1 Case I: When fuel tank is subjected to longitudinal acceleration without baffle.

Following figure shows the graph between F_X and F_Y vs. time for 40% fill and 80% fill condition for a longitudinal acceleration of $2.77 m/s^2$.

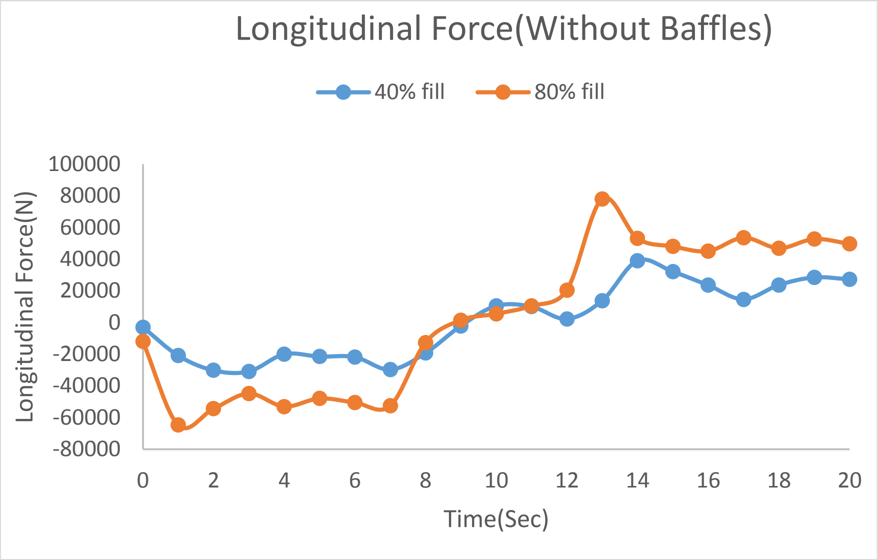


Fig. 6.1 F_X at 40% and 80% fill

From above Fig 6.1 it is clear that variation of longitudinal forces is more when the tank fill level is low but the magnitude of force is high in case of high fill condition.

Fig 6.2 shows the vertical forces without the use of baffles for two different fill levels. It also shows that the variation of sloshing forces is high at low fill level because of the large mass of fuel at 80% which does not slosh heavily. The magnitude of forces is high for larger mass of fuel i. e. for 80% fill. The variation in vertical force is very low in both fill level. This is because the tank is subjected to only longitudinal acceleration and this will not much affect vertical force amplification.

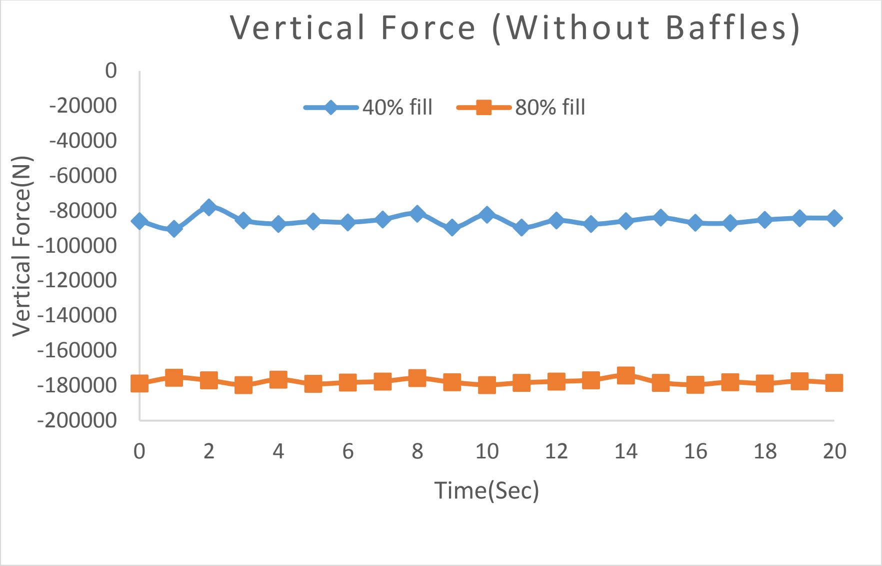


Fig. 6.2: F_Y at 40% and 80% fill without baffles

6.2 Comparison of longitudinal forces for tank without baffles (WoB) and with baffles (WB):

6.2.1 40 % fill level

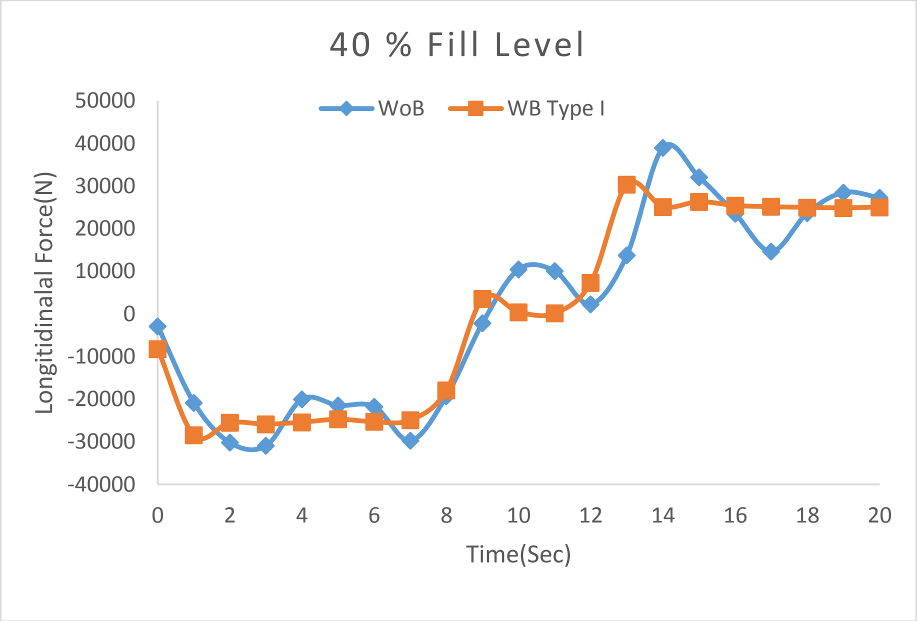


Fig 6.3

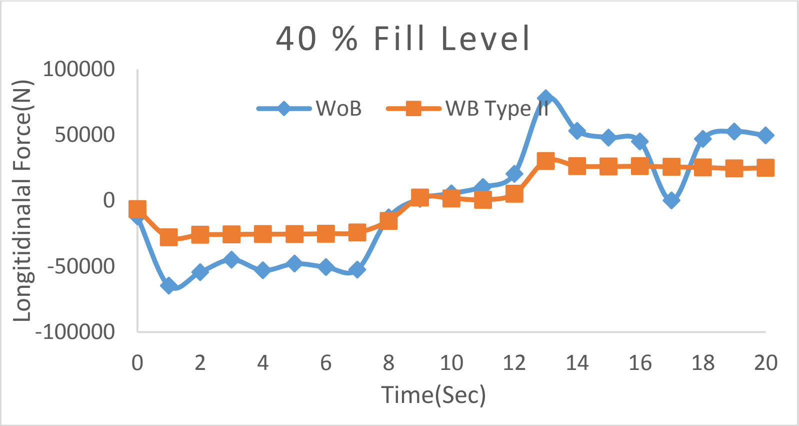


Fig 6.4

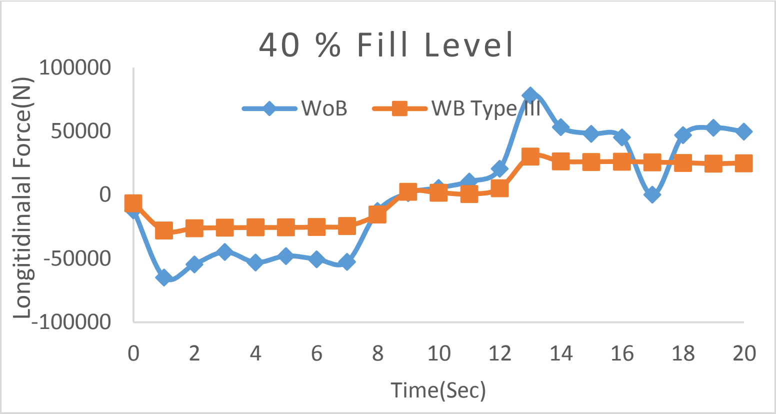


Fig 6.5

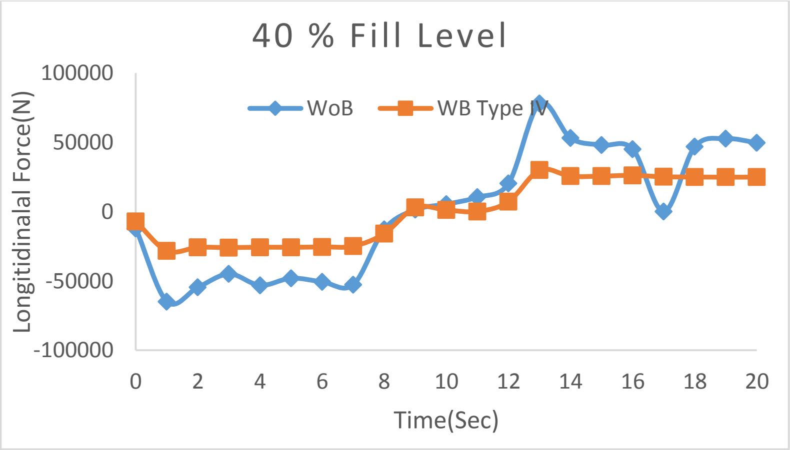


Fig 6.6

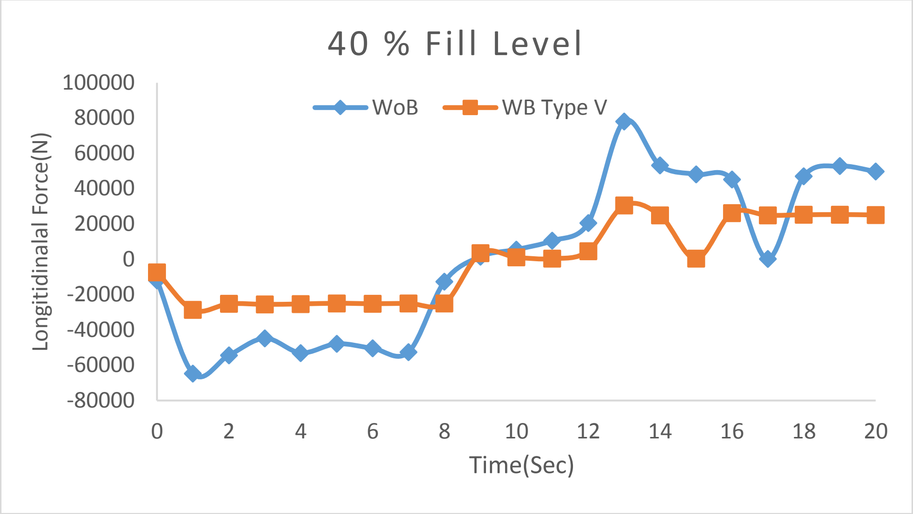


Fig 6.7

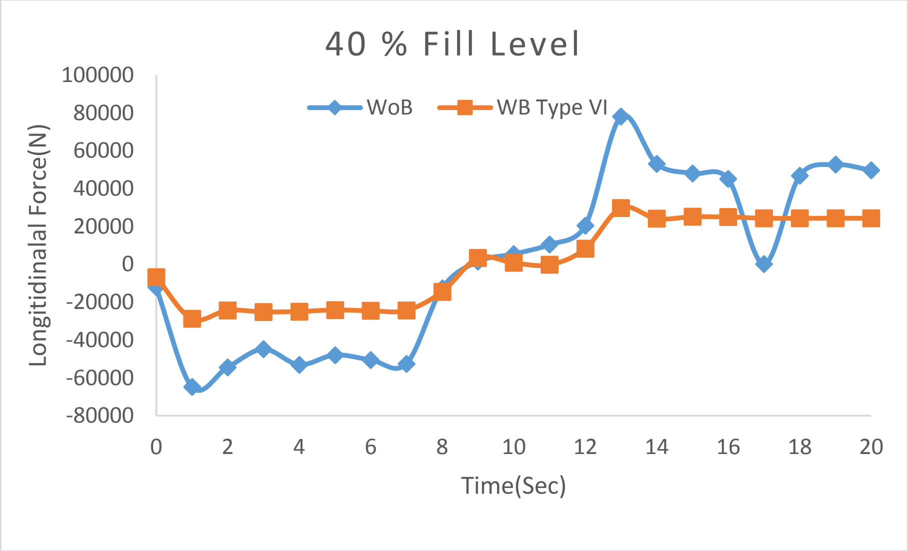


Fig 6.8

Above figures from Fig. 6.3 to Fig. 6.8 show the individual comparison of longitudinal sloshing forces produced in tank without baffle (WoB) and tank with a particular type of transverse baffles (WB). It is evident from the results that all type of baffles reduce the sloshing forces. Thus, it can be concluded that baffles are the effective means to reduce the sloshing forces. The reduction in forces is however different in different cases. The following figure (Fig. 6.9) shows the longitudinal forces collectively for all the cases together so that it would be easy to compare the relative reduction in the forces and to check the effectiveness of any particular type of baffle.

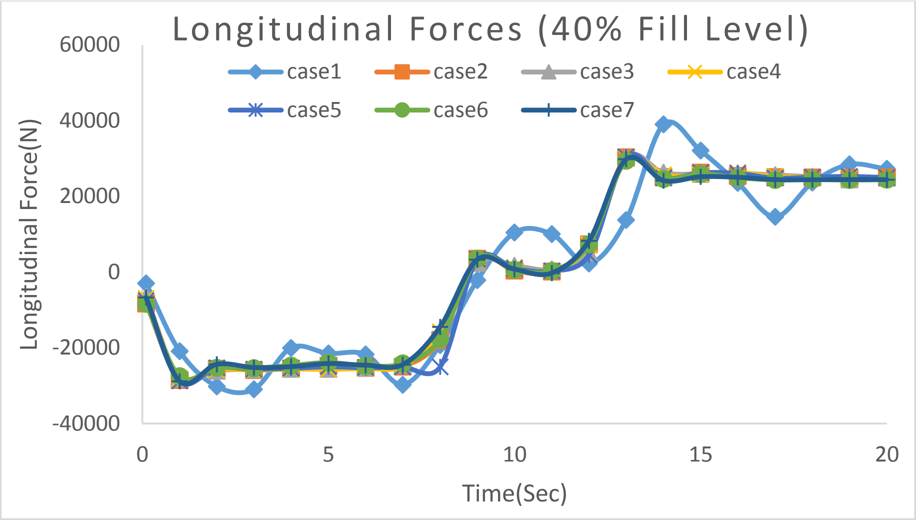


Fig 6.9

Fig 6.9 shows variation in longitudinal forces for all the 7 cases. The forces are highest in the tank without baffles. The variation of forces is of similar kind for all the cases. Two best cases are discussed below.

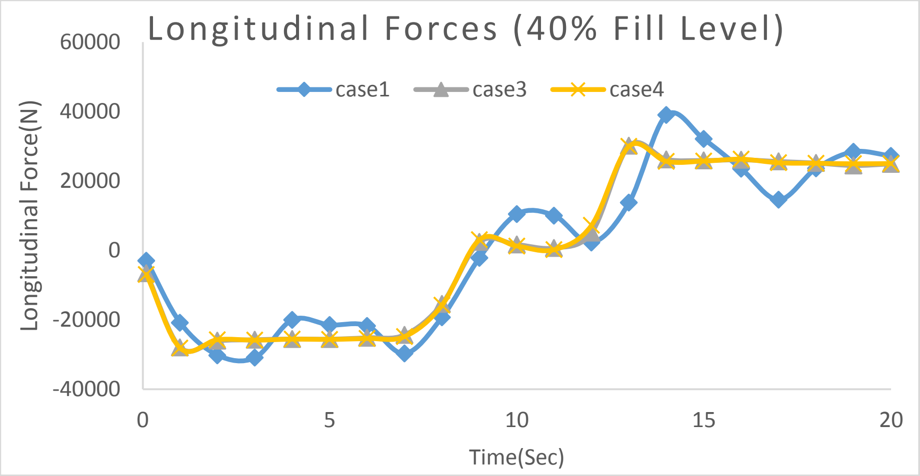


Fig 6.10

Figure 6.10 shows that the variation of longitudinal forces is least for type II baffle with seven same sized holes and type III baffle with 41 same sized holes give the best result and least variation in longitudinal forces. Thus as we provide holes in the baffle it leads to both reduction in magnitude and variation of the forces.

6.2.2 80% fill level:

Following figures show the variation in the longitudinal forces produced in the tank without baffle and with baffles for 80 % fill.

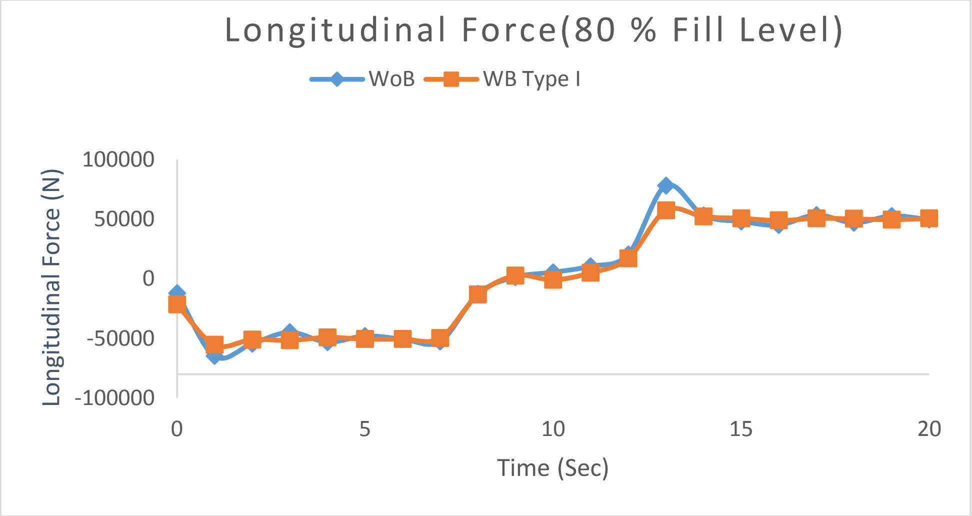


Fig 6.11

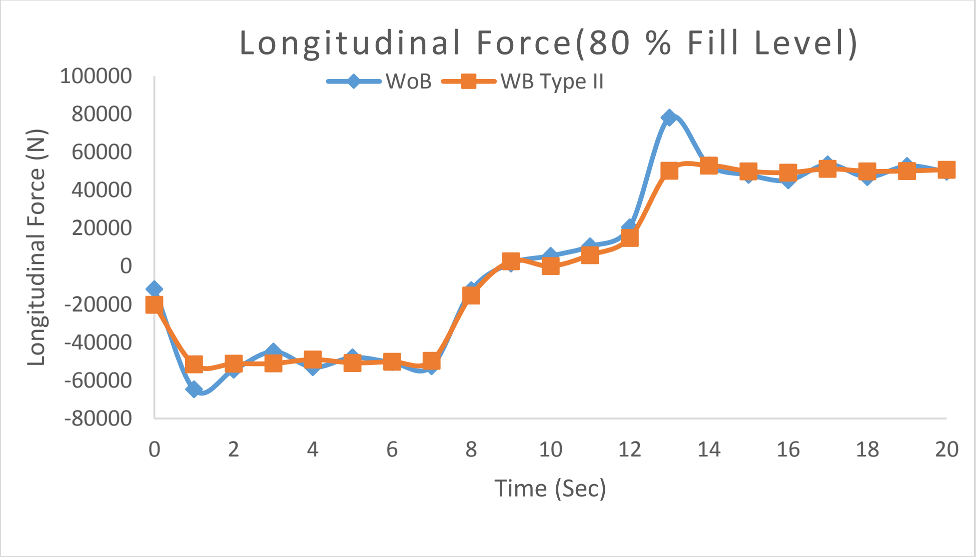


Fig 6.12

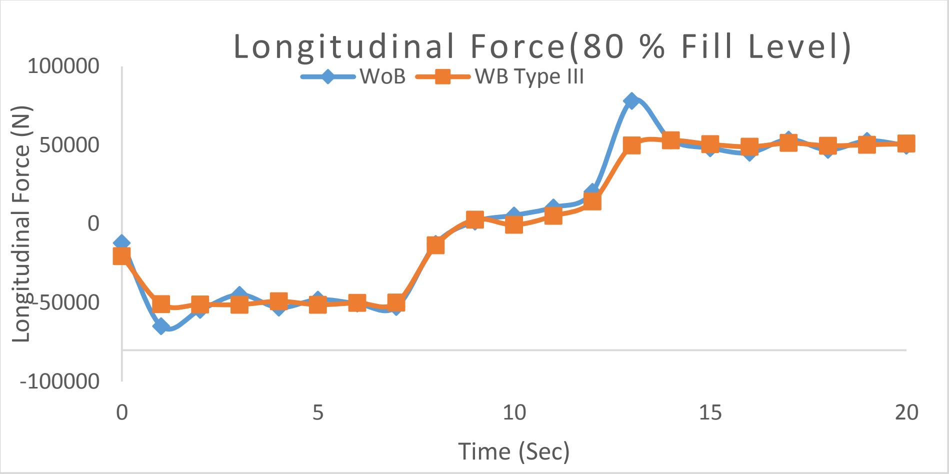


Fig 6.13

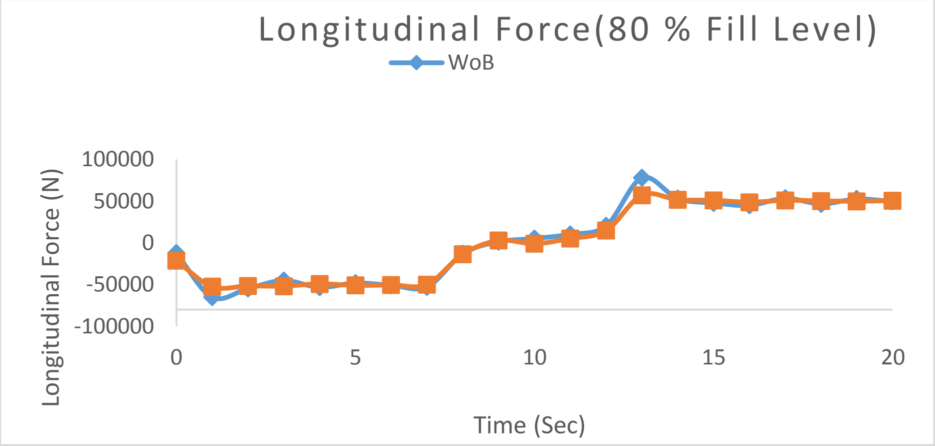


Fig 6.14

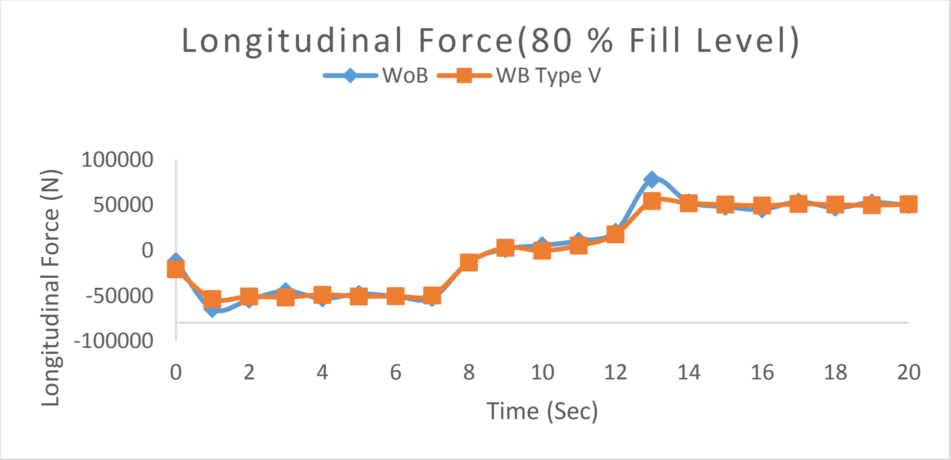


Fig 6.15

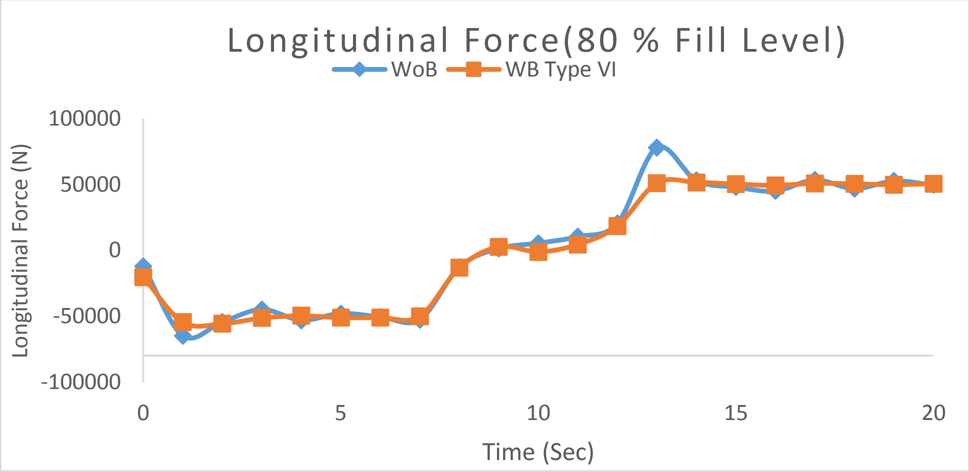


Fig 6.16

From above graphs, Fig 6.11 to Fig 6.16, we can easily see that as the fill level increases magnitude of the forces increases but variation becomes less as higher fill leads to less sloshing. Also, all type of baffles reduce the sloshing forces in some way or the other. But to check the most effective baffle we will represent the variation in the forces for all the cases in one single graph as shown below:

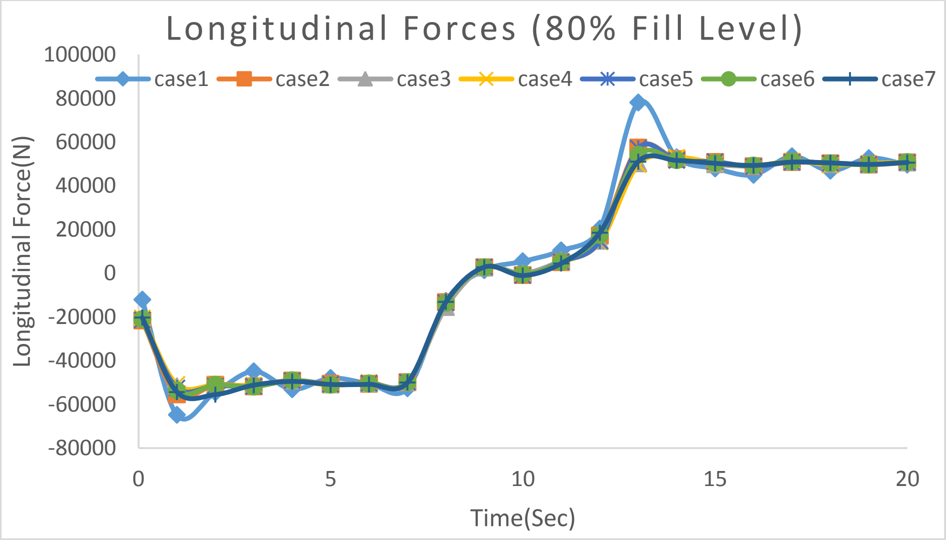


Fig 6.17

Fig 6.18 takes all the cases together. The sloshing forces are higher for tank without baffles. The baffles reduce the variation of forces. The two most effective cases with the case of tank without baffles are shown below.

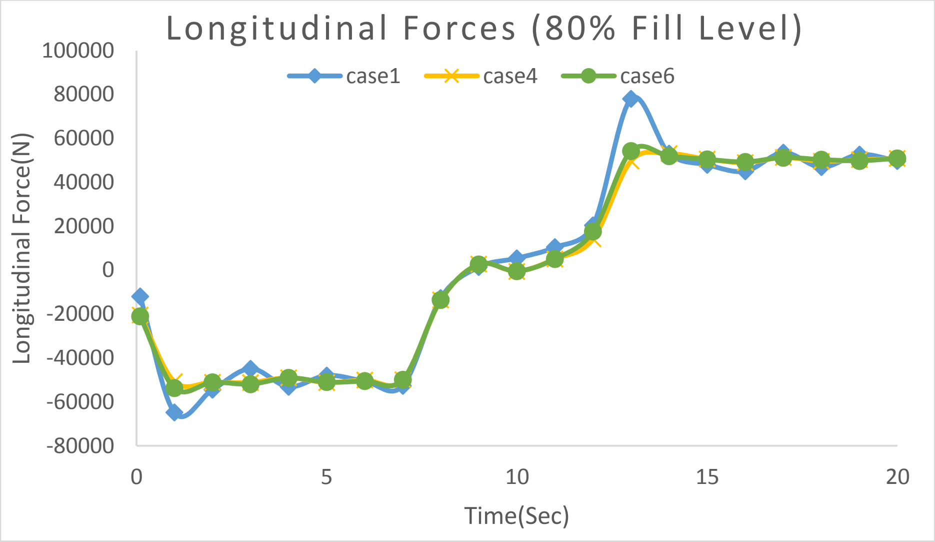


Fig 6.18

With 80% fill type V baffle along with type III shows good reduction as more area of the baffle is encountered with the fuel as major axis is in horizontal direction. It is better to use baffle with elliptical cavity than just a ring type baffle.

So it is concluded that the decreasing fill level of fuel affects the stability of the vehicle. In the present study it affects the braking performance of the vehicle when tank subjected to longitudinal acceleration. Baffles with holes reduce the longitudinal forces most effectively.

6.3 Comparison of Vertical forces for tank without baffles and with baffles:

Taking all the previous cases we can also find the variations in the vertical forces. But as longitudinal acceleration does not affect much the vertical forces the comparison between the sloshing forces in lateral direction with respect to time has been given in following two figures for all the 7 previously dscribed cases.

6.3.1. 40% Fill level: Fig 6.17 shows variation of vertical forces for 40 % fill level in the tank without baffle. Variation is only up to a certain range which is as expected because the longitudinal force does not affect vertical forces much.

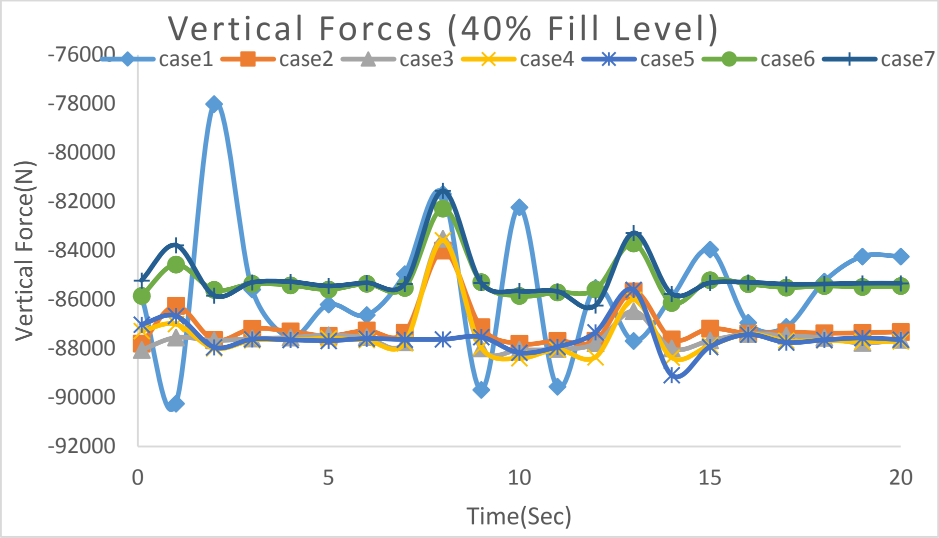


Fig 6.19

Fig 6.19 takes all the cases together. We find that all type of baffles reduce both mgnitude and variation in vertical forces. The two most favourable cases are discussed below.

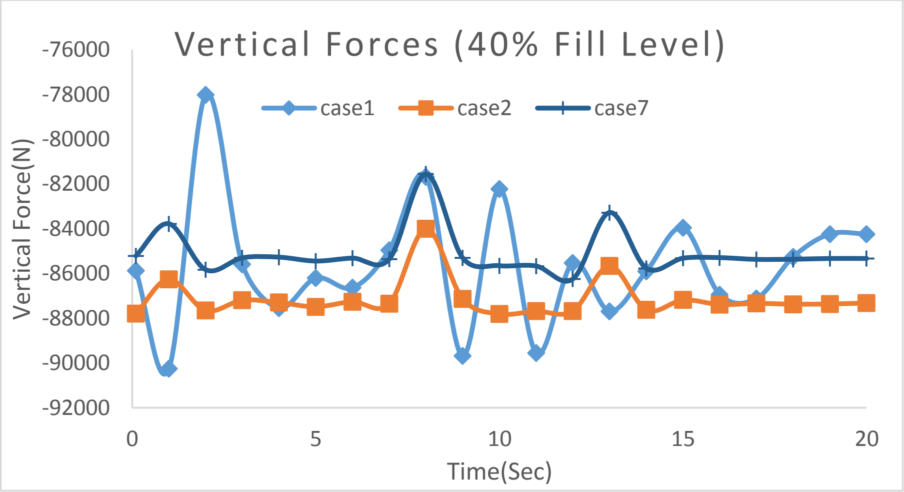


Fig 6.20

Fig 6.20 shows that Transverse baffles are not much effective while deceleration..At lower fill level baffle having elliptical cavity with major axis in vertical direction (Type VI) is most effective because of the less area of the cavity in the center.

6.3.2. 80% Fill Level:

Fig 6.21 shows that the magnitude of vertical forces are high in 80% fill level with less variation.

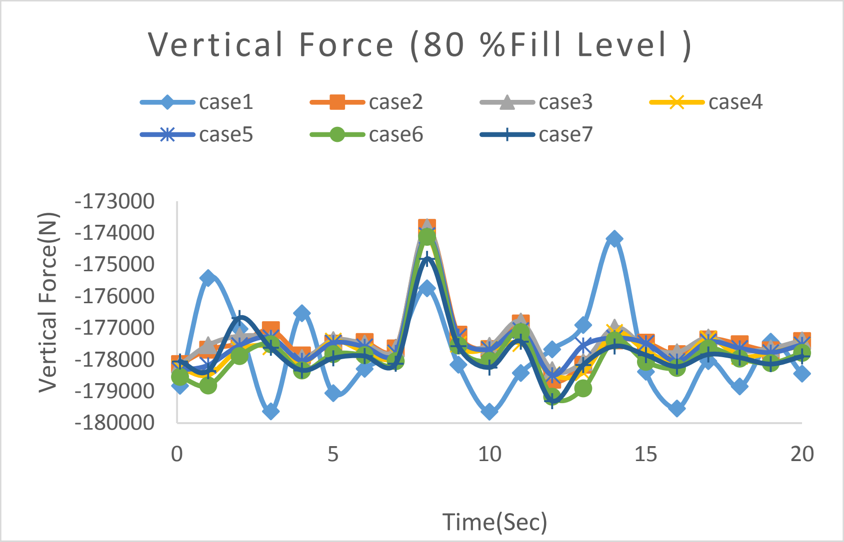


Fig 6.21

Above figure shows the comparison between sloshing forces for all the cases. It is found that baffles are not as much effective while reducing the vertical forces at higer fill level. The two suitable cases are shown below.

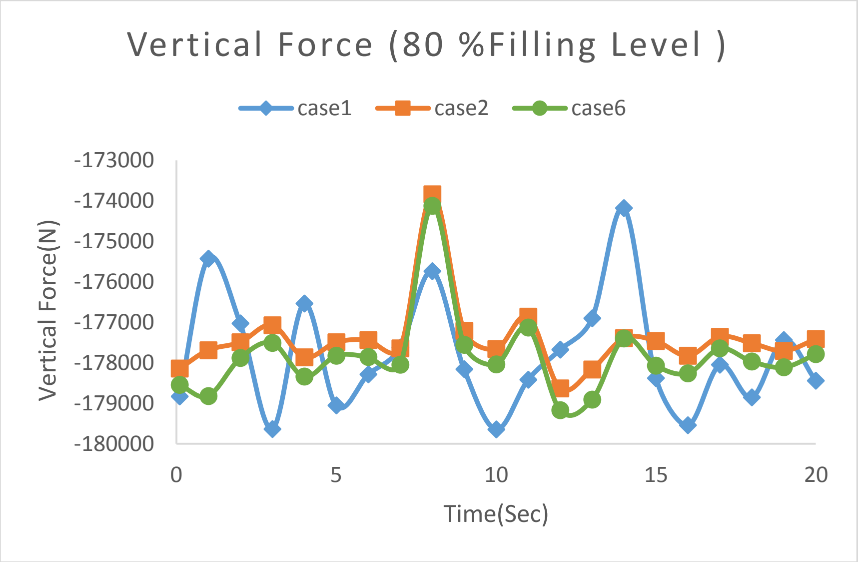


Fig 6.22

From fig 6.22 we can see that while type I baffle reduce the variation, the type V baffle reduce the magnitude.

So to reduce the sloshing in a moving tank and to improve braking and steering performance, three transverse baffles are placed in the tank and they effectively reduce the magnitude of sloshing for all fill levels. Different configured baffles are useful for different fill levels.

6.4 Sloshing Moments: As the tank is subjected to steering and braking acceleration, the movement of fluid within a partially filled tank leads to additional forces and moments which affects the braking and steering performance. The additional moment in roll, pitch and yaw plane affect the directional stability of vehicles. These moments significantly affect lower the roll stability limit and braking performance. Hence the moments also need to be discussed. Following discussion compares different moments in all cases:

6.5 Comparison of Yawing Moment for tank without baffles and with baffles:

Following two figures show the variations in the yaw moment for two different levels of the tank for all the cases together.

6.5.1. 40% Fill Level:

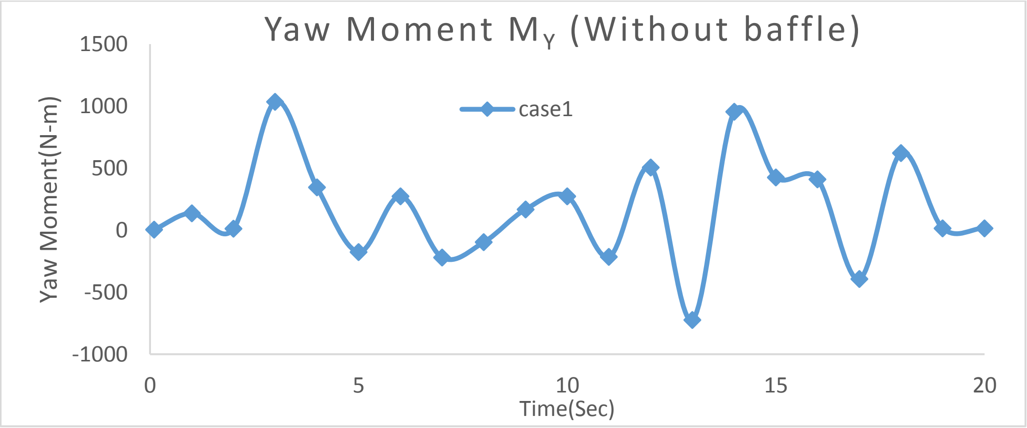


Fig 6.23

Fig 6.23 shows the variation of yawing moment in the tank without baffles. The magnitude of the yawing moment is less as compared to the pitching moment because the tank is subjected to the longitudinal acceleration.

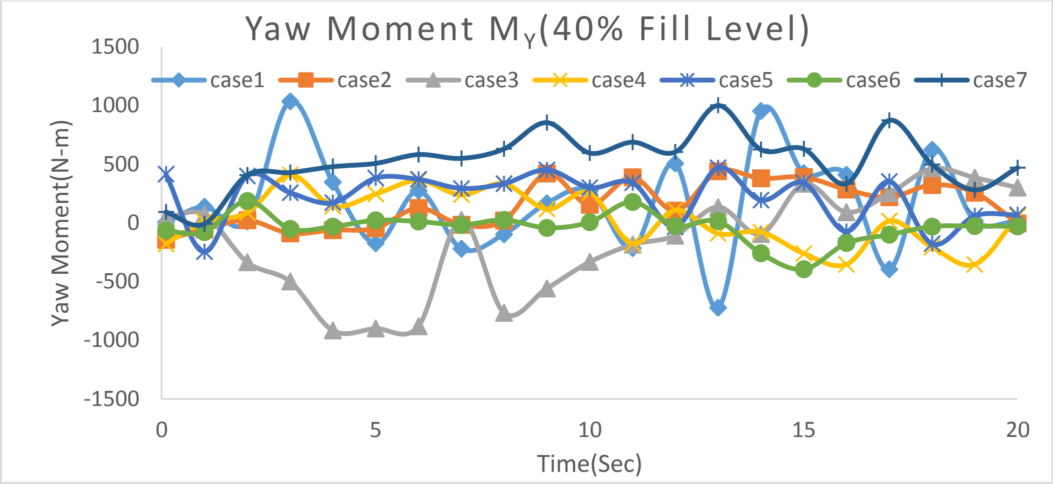


Fig 6.24

Fig 6.24 gives the variation of the yawing moment for all seven cases taken together. The most uneven distribution is found in case 3 with type II baffles. Otherwise all the baffles reduce the magnitude and other variation of moment.

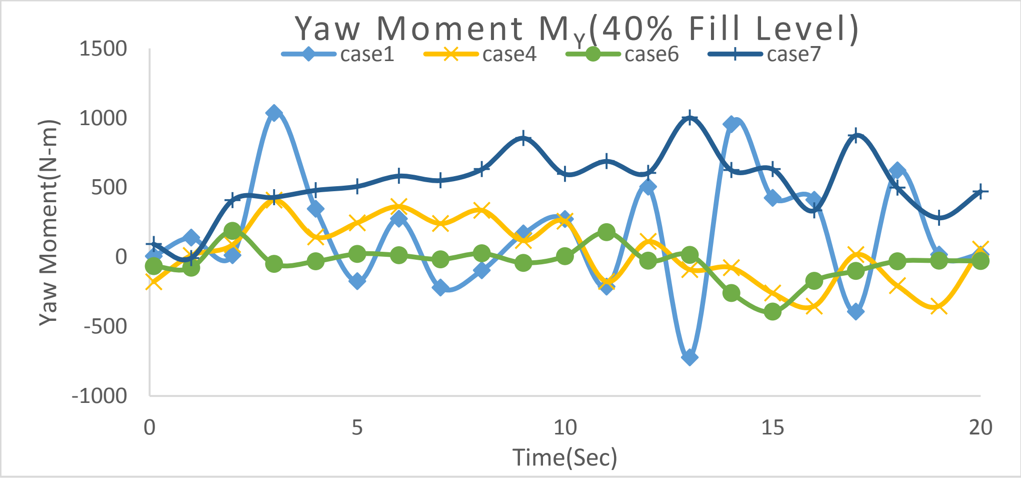


Fig 6.25

Figure 6.25 takes three cases one without baffle and other two with baffles. We come to know that all baffles reduce the yawing moment up to some extent. But most favorable results are obtained with type III & type V baffles (elliptical baffles with major axis in horizontal direction). Worst result are obtained with type VI baffles (elliptical baffles with major axis in vertical direction) which gives the highest magnitude of the moment.

6.5.2. 80% Fill Level

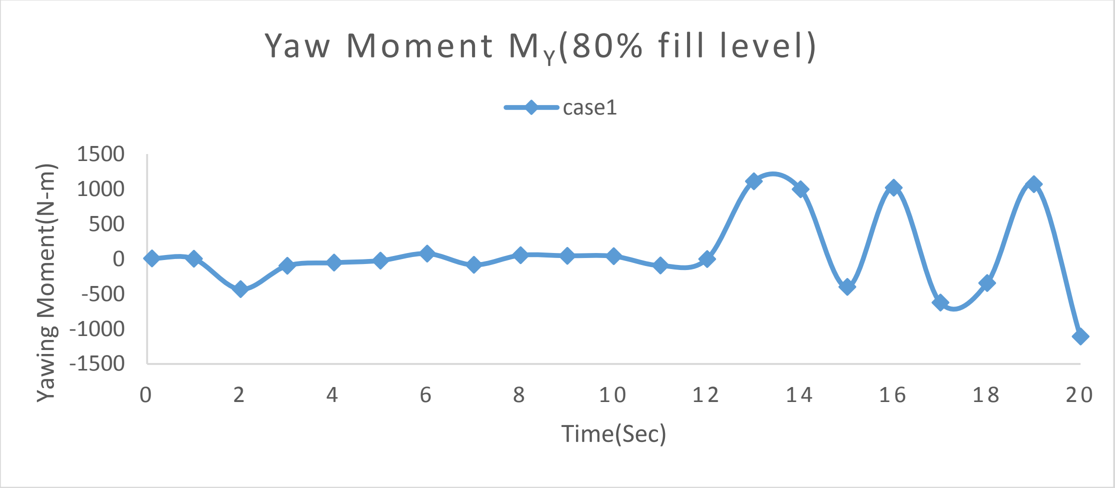


Fig 6.26

From Fig. 6.26 we come to know that the variation in the moment is less in 80% fill level although the magnitude is high. All the cases and their corresponding variation is shown in the figure 6.27

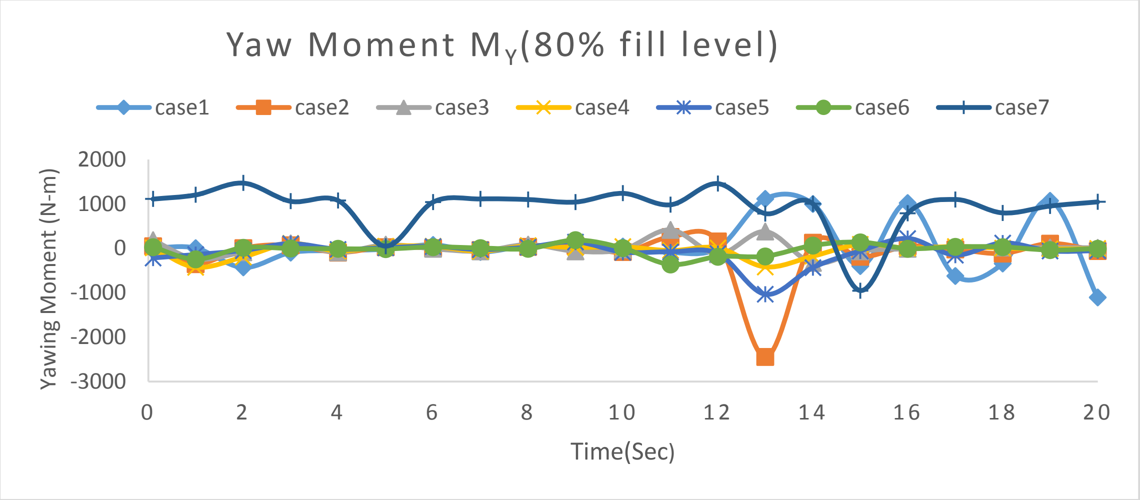


Fig 6.27

Fig 6.27 shows the different behavior of the different kind of baffles. Although the baffles with holes reduce the magnitude and variation at higher fill level the reduction is not as significant as in case of lower fill level. The few important cases are discussed below.

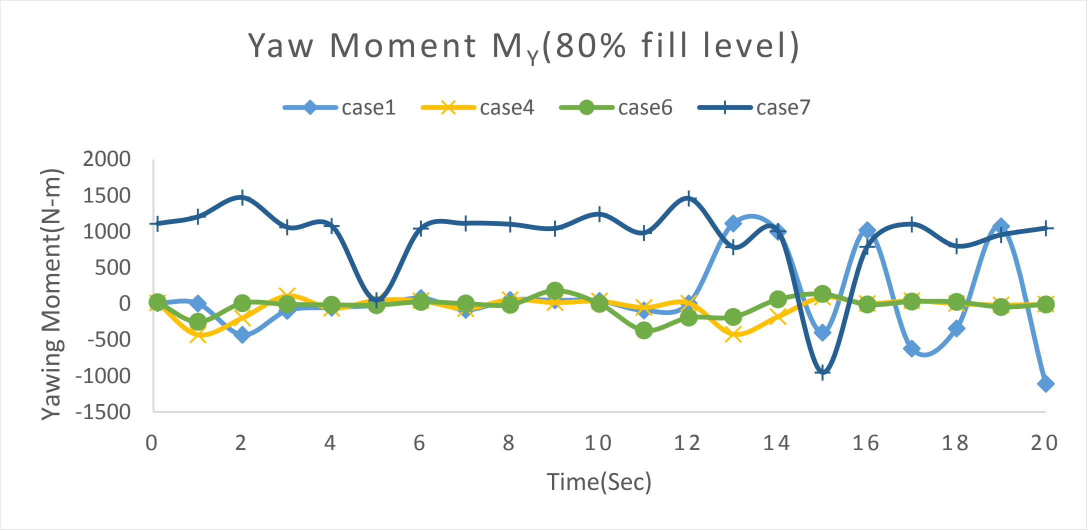


Fig 6.28

For 80% fill level also the minimum variation in the yaw moment is found with type V baffles (elliptical baffles with major axis in horizontal direction) and worst results are obtained with type VI baffles (elliptical baffles with major axis in vertical direction) which increase the moment rather more as shown in the figure 6.28.

6.6 Comparison of Pitching Moment for tank without baffles and with baffles:

Following two figures show the variations in the Pitch moment for two different levels of the tank for all the cases put together. Pitch moment affects the braking performance and in the present problem it is the most critical with respect to both magnitude and variation.

6.6.1. 40 % Fill Level:

Fig 6.29 shows the variation in the pitching moment for 40% fill condition. The variation as shown in graph is very large which clearly shows that it will affect the steering and braking stability.

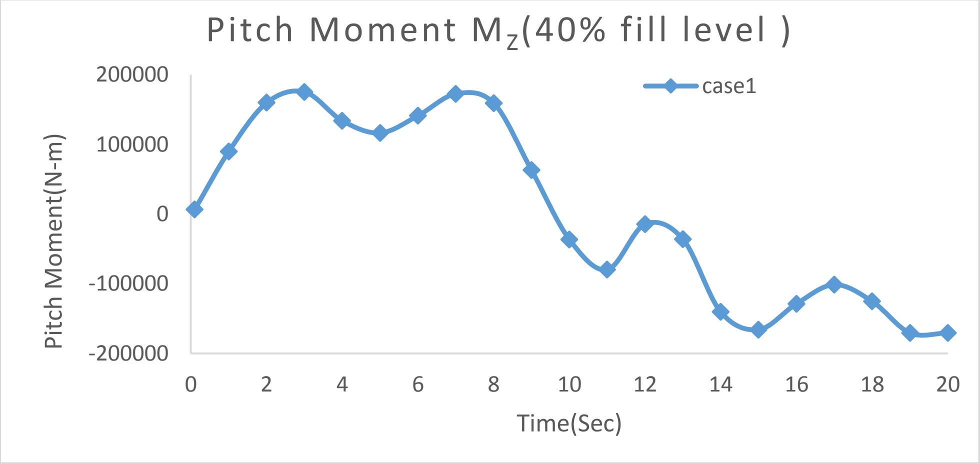


Fig 6.29

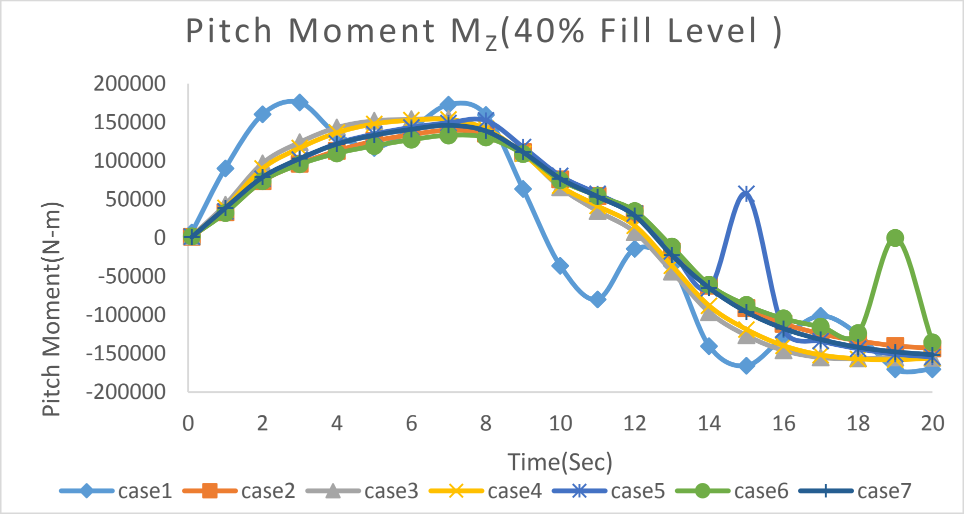


Fig 6.30

All baffles reduce the variation as shown in fig 6.30. Type IV and Type V baffles give sudden variation in the moment in the last stage of the applied acceleration. Thus, the variation is least in case of pitching moment by using the transverse baffles because of their orientation and placement. A few important cases are shown below separately for more clear description.

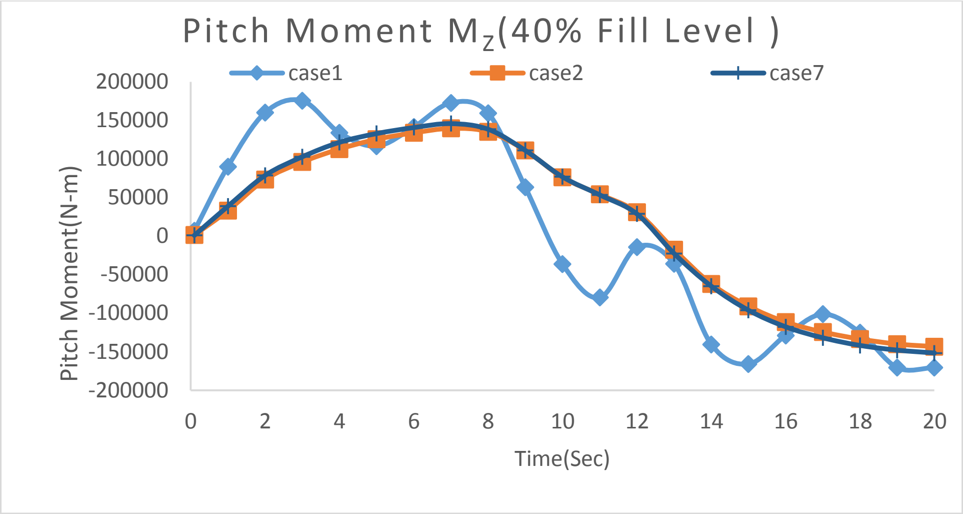


Fig 6.31

Fig 6.31 shows two cases with type I and type VI baffles which give the best results.

6.6.2. 80% Fill Level:

Fig 6.32 is shown below for the tank at fill level of 80%. It is clear that variation in the moment is less as compared to the lower fill level as expected.

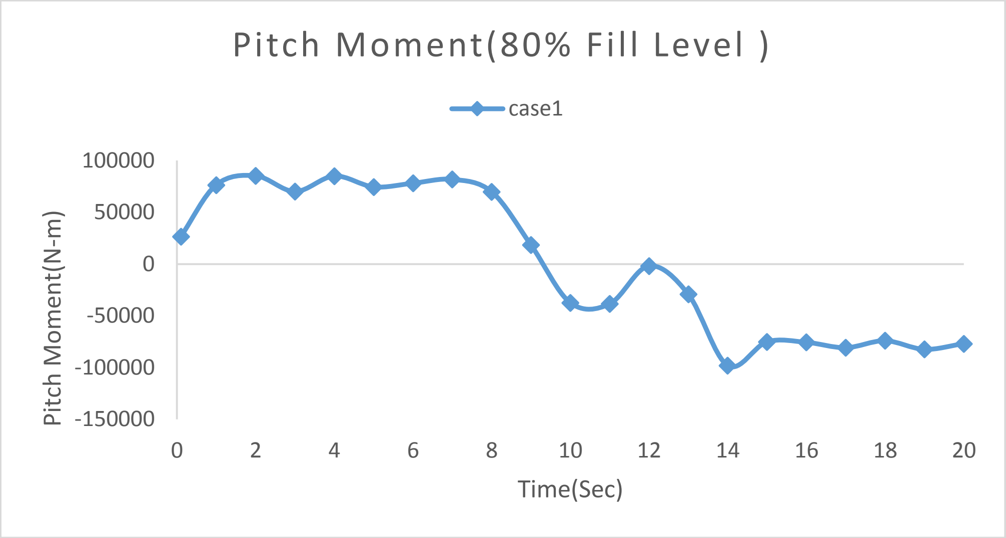


Fig 6.32

Fig 6.33 gives comparison between all cases.

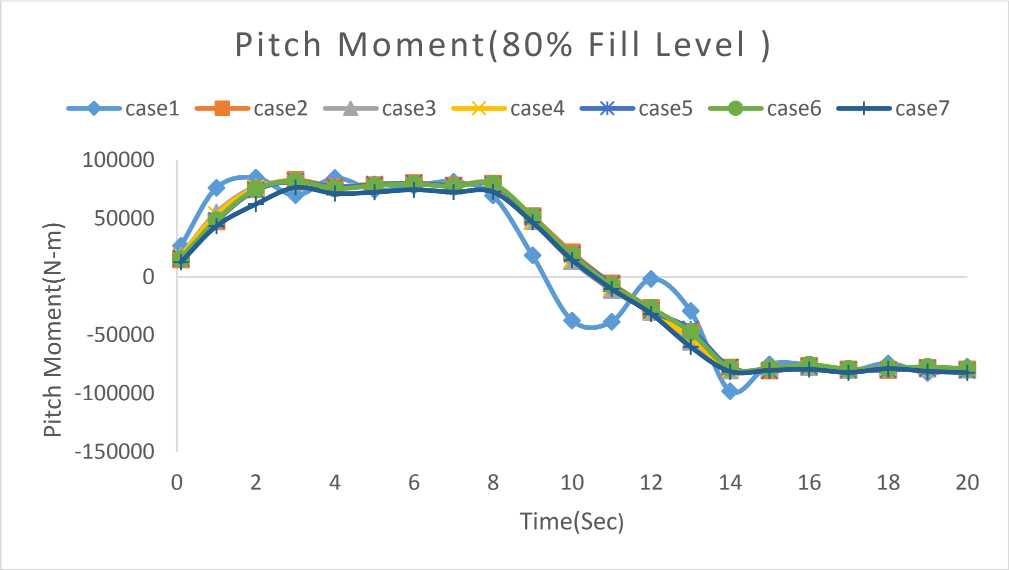


Fig 6.33

In fig 6.33 also we find that transverse baffles are very significantly reducing the pitching moment variation because of their orientation and placement. Also all types of baffles show similar kind of variation. Few cases are shown distinctly to have more clear vision as shown in the figure below:

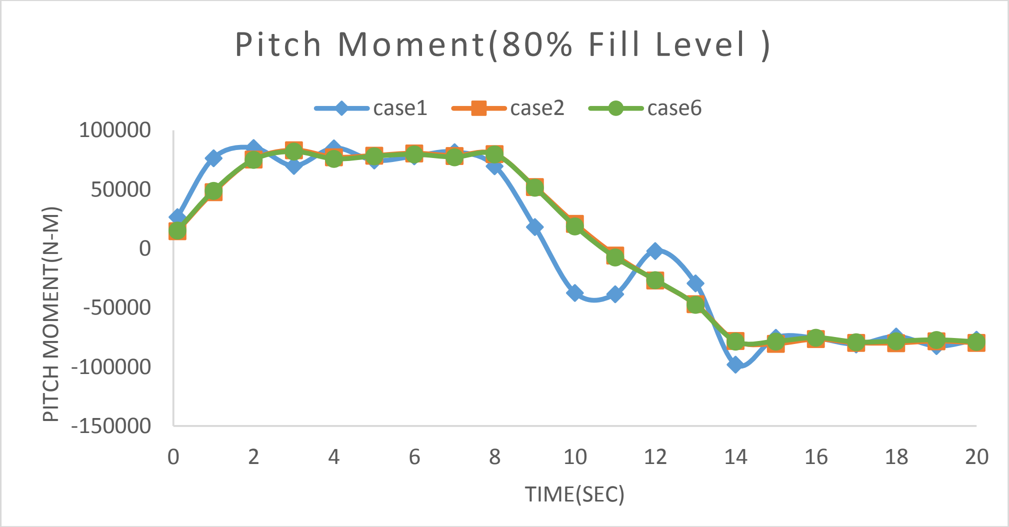


Fig 6.34

All above cases show similar type of variation and reduction in the moment. Although type I and type V give the best results. Thus it can be concluded for reduction of pitching moment the transverse baffles are very suitable and there is not much sudden variation in the pitching moment.

6.7 Comparison of Rolling Moment for tank without baffles and with baffles: Although the rolling moment is very insignificant as compared to the moments in other two directions in the present problem but for analysis purpose we took the two fill level conditions and compared the rolling moments produced in all seven cases with and without baffles.

Fig 6.35 shows the rolling moment variation of the tank for two different fill conditions. It is clear from the figure that variation is high in 40% fill condition because in lower fill level less fuel is trapped in between the two baffles.

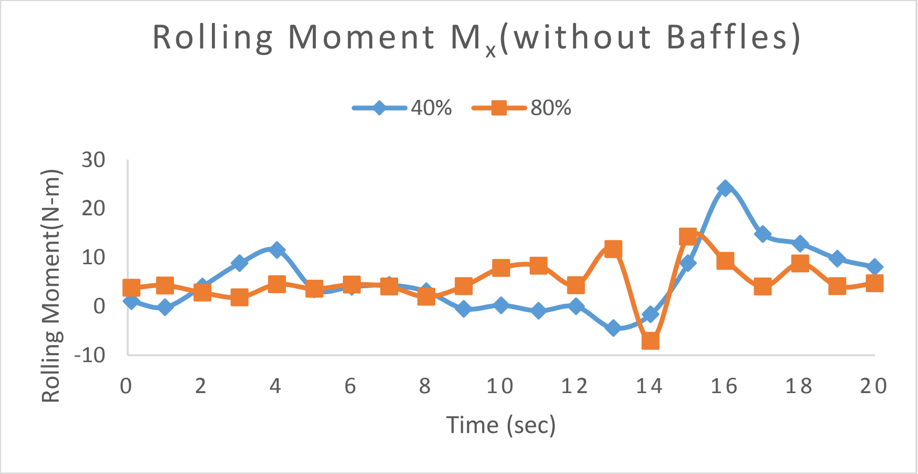


Fig 6.35

6.7.1. 40% Fill Level:

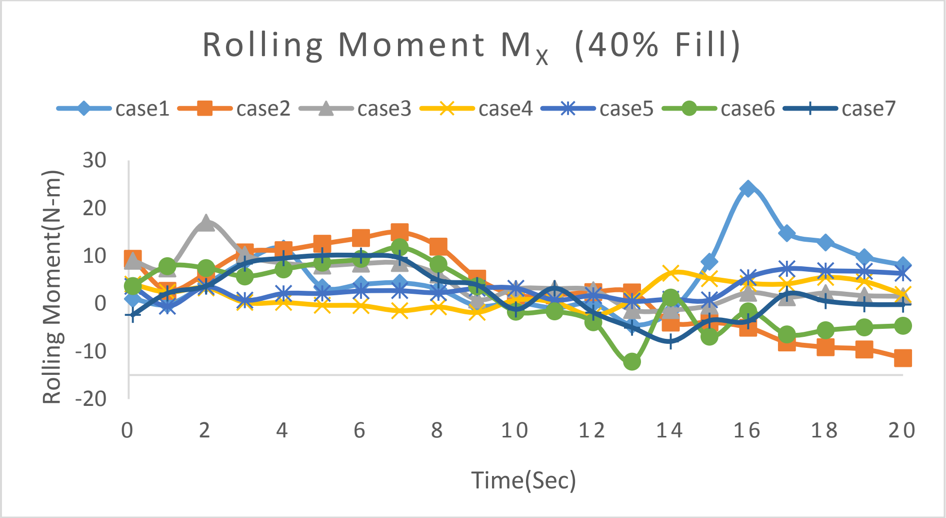


Fig 6.36

Fig 6.36 shows all seven cases compared together for 40% fill condition.

The magnitude of rolling moment is very less as shown in above graph. Also we find that type III baffles with 41 same sized holes and type IV baffles (Baffles with 2 set of different sized holes) give the least variation in the rolling moment as shown separately in the graph below fig 6.37:

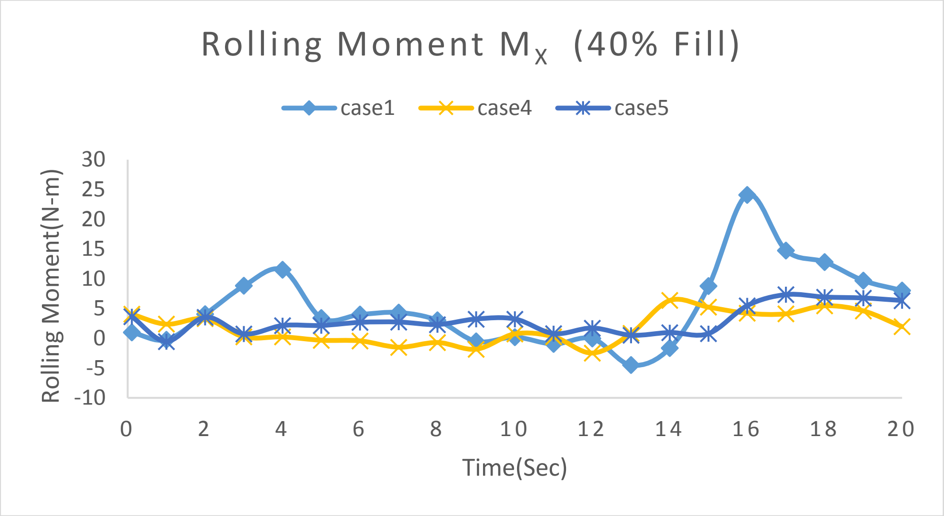


Fig 6.37

6.7.2. 80% Fill Level: Fig 6.38 and 6.39 show the graphs related to 80% fill level.

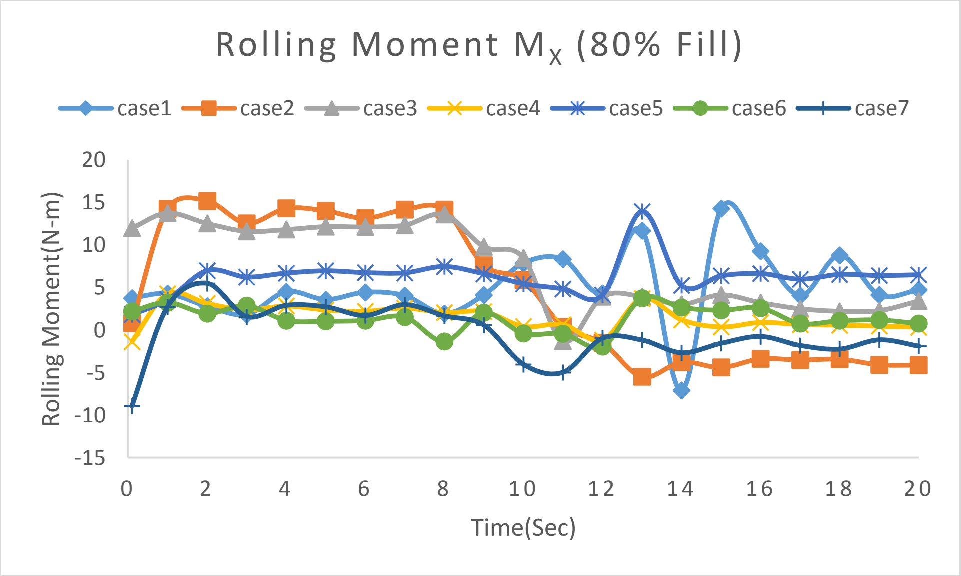


Fig 6.38

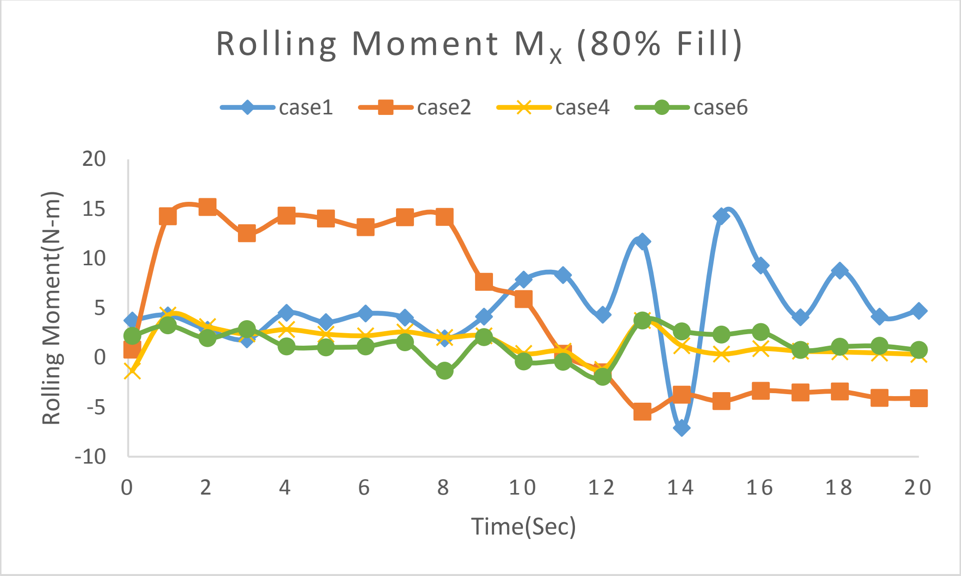


Fig 6.39

From above two graphs, in 80 % fill level type III baffle give the best results. Also type V baffles give lese variation in the rolling moment. The worst results are obtained with type I baffles.

The all above four graphs shows that variation in pitch moment is reduced by placing three transverse baffles. This pitch moment affects the pitch plane stability of the vehicle. The above graph also shows that variation in pitch moment is higher at the lower fill level and reduction in pitch moment is higher at lower fill level.. By introducing three transverse baffle slosh forces and moment reduces significantly at the lower fill level.

The above results can be summarized in following table:

Force/Moment	**40% fill**	**80% fill**	**Effectiveness of transverse baffles**
Longitudinal force	Type III	Type III	Very much effective with more no of holes.
Vertical Force	Type VI	Type I	Baffles more effective with single cavity

Yawing Moment	Type V	Type V	Least effective
Pitching Moment	Type VI	Type V	Very effective with single cavity
Rolling moment	Type III	Type V	Less effective

Table 6.1 Comparison of effectiveness of different baffles

6.8 Closure:

In this chapter, result for various cases are discussed with graphs. The result shows that as the no of holes increases on transverse baffle sloshing forces and moments are very much reduced in the longitudinal direction and pitch plane. For forces and moments in other plane baffles with single central cavity of different shapes are more effective.

Chapter 7

Conclusions

Conclusions

This chapter presents the conclusion derived from the above results and scope for work that can be done in the future:

7.1 Conclusion

For a partially filled tank with gasoline sloshing forces and moments are developed as it is subjected to linear acceleration/ deceleration. After simulating the problem in the ANSYS and analyzing the results we can conclude that:

- The fluctuation in sloshing forces and moments are more at the lower fill level.
- The magnitude of the forces and moment are high for higher fill as it includes larger mass of fuel but the variation is less.
- As the no of holes are increased in the transverse baffles slosh forces and moments are reduced more specially in the pitch plane which improves the braking performance of the vehicle.
- For forces and moments in other planes, the transverse baffles are not much effective.
- For other than pitch planes, if used, transverse baffles with single central cavity proves to be more effective. While for lower fill level Type VI baffle is more useful, for higher fill Type V is better.

7.2 Scope for future work

There are many scopes of working in the problem like sloshing in a cylinder with baffles. Some of them are:

- The study can be performed by taking baffles of other types like helical baffles with holes, porous baffle, perforated baffles etc.
- The problem can be solved by placing the above discussed baffles in other orientations such as in oblique positions instead of transverse.

- The problem can be solved for combined linear and lateral acceleration.
- The problem can also be extended for sinusoidal acceleration case.
- The problem can also be solved for storage tanks excited under earthquake.

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