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Analysis of a Baffle Plate in Cylindrical Vessel to Reduce the Pressure Effect During Sloshing

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Abstract

In this article, major focus is on the design, analysis, and modification of baffle plates which will help in slowing down the sloshing effects. Half-filled fluid which causes sloshing is a major concern. It affects the structure of the tanks moreover it reduces the braking efficiency of the truck carrying tank. With a capacity of 4900 liters, it is capable of impacting the tank walls with high forces. So it becomes necessary to reinforce the baffle plates in such tank, with the help of Solid works, CFD (Computational fluid dynamics). With the introduction of porous plate inside the tank it is seen the pressure has considerably reduced during sloshing when compared with the existing tank.

Keywords: Fluid Sloshing, Baffle plate, CFD

1. Introduction

Fluid sloshing is a source of major concern when it comes to designing of heavy-duty trucks. The main cause of fluid sloshing is due to the free surface motion of fuel in a partially filled containers. With the huge capacity of 4900 liters, this phenomenon is capable of impacting the container tank with high forces and some parts become vulnerable due to heavy dynamic loads. This is non-linear phenomena and can be simulated using computational fluid dynamics i.e CFD. This problem can be solved by using volume of fluid (VOF) interface capturing approach. If we observe the thin-walled structures of the tank, it becomes tedious to tackle this effects of fluid structure.

Interaction (FSI). It is done by using those material which aim for reduction of weight which are feasible.Analysis of fluid sloshing is an interesting challenge in computational mechanics due to its underlying complex physics. Simulation plays an important role here, which involves an accurate modelling of two phase flow problems as well as considering the sloshing effect on solid structure through coupled fluid solid interaction. Such simulations have found their place in industrial applications. Simulations can help in a collection of important information on structure and design of Tanks at an early stage by reducing the lead time in the manufacturing process. Also, the advent of novel materials like plastics and composites, aimed at overall weight reduction, has made such analysis procedure an absolute necessity.
Heavy-duty volvo fuel tanks are made of aluminum usually. There is a D-shaped body which is reinforced with baffles which is included in the tank structure. The baffles provide structural

rigidity and reduces the effect of sloshing waves. During test runs, cracks and leakages have been observed due to the sloshing impacts leading to eventual failure of the tank.

2. Literature review

The nonlinear nature of sloshing is the greatest hindrance in solving such a problem analytically and even computationally. Further, a number of assumptions are to be made, in which the solutions may deviate from the actual values. Experimental studies have been the most popular approach for liquid sloshing and have provided valuable insights into the physics

Abbreviations and Acronyms

CFD - Computational Fluid Dynamics
VOF - Volume of fluid
FEM - Finite element method
a - Acceleration
b - Depth
c - Courant Number
$F^{\rightarrow}$ - Force Vector
g - Acceleration due to gravity
h - Height
i - Unit tensor
$M^{\rightarrow}$ - Moment vector
p,q - Phases
t - Time
Δt - Time step
Δx_cell - Cell size
V - Volume of fluid
X,Y,Z - Co-ordinates axes
Greek Symbol

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

Continuity Equations:

This Equation represents that mass is conserved in a flow. For cylindrical coordinates, the incompressible, unsteady, continuity equation is:

$$\frac{\partial \rho}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(\rho r u_r) + \frac{1}{r}\frac{\partial}{\partial \varphi}(\rho u_\varphi) + \frac{\partial}{\partial z}(\rho u_z) = 0$$

u_r,u_φ,u_(z)are components of velocity in r, Φ and z direction and ρ is the density.

Navier-Stokes Equation:

This equation is also called as Momentum equation because these are the results of applying Newton's law of motion. The equation can be applied for both laminar and turbulent flow.

R - momentum equation:

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

ϕ-momentum equation:

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

Z -momentum equation:

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

Where P is the static pressure, u_r,u_φ,u_(z)are the velocity components in r, , Φ and z direction. μ is the dynamic viscosity, ρ is the density and ρg_r,ρg_φ,ρg_z are body forces due to gravity. For our problem we had add extra force term in the direction of z for the acceleration in the longitudinal direction.

Physical Model of Container

The problem consists of an elliptical tank with a moving vehicle. The length and major axis, the minor axis of the outer and inner tank are 5706 mm and 2200 mm, 1400 mm and 1900 mm and 1100 mm respectively. The tank is partially filled with Water (, μ=0.001003 kg/m-s) and the remaining part is air. As the vehicle is under the influence of acceleration and deceleration, the fluid inside the container shows sloshing.

To reduce the sloshing effect, different types of baffles plates are introduced inside the cylindrical container.

Reasons why to use so many holes

The perforated baffle plates with suitable smalls numbers of holes is considered to be an effective baffle arrangement in tanks on reducing the sloshing amplitude at higher excitation frequency due to the potential advantage of the perforated baffles on enabling the tanker payload to be increased without comprising safety.

The vertical baffle and the perforated baffle can obstruct fluids' movement and change the velocity fields, making the sloshing amplitude remarkably reduced due to the buffering effects of the baffles.

Mesh Generation

Once the geometry is modeled, we need to discretize it into control-based volumes and this process is known as meshing. In the CFD tool after modeling the geometry of baffles as well as cylinder, we will mesh it in the same tool. In project analysis, we will do tetrahedron mesh in all conditions. It is important because the courant number c depends on it.

Once meshing is being done, the mesh file is exported to CFD code SOLIDWORKS. In the present study 3-D, double precision fluent solvers with serial processing is used. The following procedure is followed in Solid works: 1) In setup, it is scaled to proper units if required and mesh quality is checked. 2) Pressure based transient solver is used with explicit formulation and a gravitational field is enabled. 3) Multiphase model with a volume of fluid (VOF) method is used, and turbulent model is considered.

Global Mesh Settings

Automatic initial mesh: Off

Basic Mesh Dimensions

Number of cells in X	26
Number of cells in Y	4
Number of cells in Z	8

Control Planes

Control planes in X direction

Name	Minimum	Maximum	Number of cells	Ratio
X1	-3.058	3.058	-	1.0000000

Control planes in Y direction

Name	Minimum	Maximum	Number of cells	Ratio
Y1	-0.580	0.593	-	1.0000000

Control planes in Z direction

Name	Minimum	Maximum	Number of cells	Ratio
Z1	-1.022	1.022	-	1.0000000

Solid/Fluid Interface

Small Solid Feature Refinement Level	1
Curvature Level	0
Curvature Criterion	0.390 rad
Tolerance Level	1
Tolerance Criterion	0.139 m

Refining cells

Refine fluid cells	Off
Refine partial cells	Off
Refine solid cells	Off

Narrow Channels

Advanced narrow channel refinement	On
Characteristic number of cells across a narrow channel	5
Maximum Channel Refinement Level	2
Minimum Height of Channel to Refine	Off

Maximum Height of Channel to Refine	Off

Computational Domain Size

X min	-3.058 m
X max	3.058 m
Y min	-0.580 m
Y max	0.593 m
Z min	-1.022 m
Z max	1.022 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features
Heat conduction in solids: On
Heat conduction in solids only: Off
Radiation: Off
Time-dependent: On
Gravitational effects: On
Rotation: Off
Flow type: Laminar and turbulent

Global Mesh Settings
Automatic initial mesh: Off
Basic Mesh Dimensions

Number of cells in X	26
Number of cells in Y	4
Number of cells in Z	8

Control Planes
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At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: On

Heat conduction in solids only: Off

Radiation: Off

Time dependent: On

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Gravitational effects: On
Rotation: Off
Flow type: Laminar and turbulent
High Mach number flow: Off
Default roughness: 0 micrometer
Gravitational Settings

X component	Table from time
Y component	-9.81 m/s^2
Z component	0 m/s^2

Default outer wall condition: Adiabatic wall
Initial Conditions

Thermodynamic parameters	Static Pressure: 101325.00 Pa
	Temperature: 20.05 °C
Velocity parameters	Velocity vector
	Velocity in X direction: 0 m/s
	Velocity in Y direction: 0 m/s
	Velocity in Z direction: 0 m/s
Solid parameters	Default material: Aluminum 6061
	Initial solid temperature: 20.05 °C
Concentrations	Substance fraction by mass
Turbulence parameters	

Global Mesh Settings
Automatic initial mesh: Off
Basic Mesh Dimensions

Number of cells in X	26
Number of cells in Y	4
Number of cells in Z	8

Control Planes
Control planes in X direction

Name	Minimum	Maximum	Number of cells	Ratio
X1	-3.058	3.058	-	1.0000000

Control planes in Y direction

Name	Minimum	Maximum	Number of cells	Ratio

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Y1	-0.580	0.593	-	1.0000000

Control planes in Z direction

Name	Minimum	Maximum	Number of cells	Ratio
Z1	-1.022	1.022	-	1.0000000

Solid/Fluid Interface

Small Solid Feature Refinement Level	1
Curvature Level	0
Curvature Criterion	0.390 rad
Tolerance Level	1
Tolerance Criterion	0.139 m

Refining cells

Refine fluid cells	Off
Refine partial cells	Off
Refine solid cells	Off

Narrow Channels

Advanced narrow channel refinement	On
Characteristic number of cells across a narrow channel	5
Maximum Channel Refinement Level	2
Minimum Height of Channel to Refine	Off
Maximum Height of Channel to Refine	Off

Computational Domain Size

X min	-3.058 m
X max	3.058 m
Y min	-0.580 m
Y max	0.593 m
Z min	-1.022 m
Z max	1.022 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features
Heat conduction in solids: On
Heat conduction in solids only: Off
Radiation: Off
Time dependent: On
Gravitational effects: On
Rotation: Off
Flow type: Laminar and turbulent
High Mach number flow: Off
Default roughness: 0 micrometer
Gravitational Settings

X component	Table from time
Y component	-9.81 m/s^2
Z component	0 m/s^2

Default outer wall condition: Adiabatic wall
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Thermodynamic parameters	Static Pressure: 101325.00 Pa
	Temperature: 20.05 °C
Velocity parameters	Velocity vector
	Velocity in X direction: 0 m/s
	Velocity in Y direction: 0 m/s
	Velocity in Z direction: 0 m/s
Solid parameters	Default material: Aluminum 6061
	Initial solid temperature: 20.05 °C
Concentrations	Substance fraction by mass
Turbulence parameters	

Fluids
Air
Water
Solids
Aluminum 6061
Local Initial Conditions
Initial Condition 1

Components	cylinder hollow_Case1.STEP[3]
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic Parameters	Static Pressure: 101325.00 Pa
	Pressure potential: On
	Temperature: 20.05 °C
Velocity Parameters	Velocity in X direction: 0 m/s
	Velocity in Y direction: 0 m/s
	Velocity in Z direction: 0 m/s
Turbulence parameters type:	Turbulence intensity and length
Intensity	2.00 %

Length	0.020 m
Concentrations	Substance fraction by mass

Goals

Global Goals

GG Av Dynamic Pressure 1

Type	Global Goal
Goal type	Dynamic Pressure
Calculate	Average value
Coordinate system	Global coordinate system
Use in convergence	On

GG Av Velocity (Y) 1

Type	Global Goal
Goal type	Velocity (Y)
Calculate	Average value
Coordinate system	Global coordinate system
Use in convergence	On

GG Av Turbulent Energy 1

Type	Global Goal
Goal type	Turbulent Energy
Calculate	Average value
Coordinate system	Global coordinate system
Use in convergence	On

Material Settings

Fluids

Air

Water

Solids

Aluminum 6061

Local Initial Conditions

Initial Condition 1

Components	cylinder hollow_Case1.STEP[3]
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic Parameters	Static Pressure: 101325.00 Pa
	Pressure potential: On
	Temperature: 20.05 °C
Velocity Parameters	Velocity in X direction: 0 m/s
	Velocity in Y direction: 0 m/s
	Velocity in Z direction: 0 m/s
Turbulence parameters type:	Turbulence intensity and length

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Intensity	2.00 %
Length	0.020 m
Concentrations	Substance fraction by mass
Use in convergence	On

Goals

Global Goals

GG Av Dynamic Pressure 1

Type	Global Goal
Goal type	Dynamic Pressure
Calculate	Average value
Coordinate system	Global coordinate system
Use in convergence	On

GG Force (Y) 1

Type	Global Goal
Goal type	Force (Y)
Coordinate system	Global coordinate system
Use in convergence	On

GG Torque (Y) 1

Type	Global Goal
Goal type	Torque (Y)
Coordinate system	Global coordinate system
Use in convergence	On

Calculation Control Options

Finish Conditions

Finish Conditions	If one is satisfied
Maximum physical time	10.000 s

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On
Periodic Saving	Units: Physical time
	Period: 0.010 s

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

GG Av Velocity (Y) 1

Type	Global Goal

Goal type	Velocity (Y)
Calculate	Average value
Coordinate system	Global coordinate system
Use in convergence	On

G Av Turbulent Energy 1

Type	Global Goal
Goal type	Turbulent Energy
Calculate	Average value
Coordinate system	Global coordinate system
Use in convergence	On

GG Force (Y) 1

Type	Global Goal
Goal type	Force (Y)
Coordinate system	Global coordinate system
Use in convergence	On

GG Torque (Y) 1

Type	Global Goal
Goal type	Torque (Y)
Coordinate system	Global coordinate system
Use in convergence	On

Calculation Control Options
Finish Conditions

Finish Conditions	If one is satisfied
Maximum physical time	10.000 s

Solver Refinement
Refinement: Disabled
Results Saving

Save before refinement	On
Periodic Saving	Units: Physical time
	Period: 0.010 s

3. Results and Discussion

Before presenting the results of our project, it is important to highlight some major points. Fluid-flow analysis was confined to the inlet zone and bulk liquid flow. Therefore, the communication between multiple zones was ignored.

In both cases (existing baffle plate and modified baffle plate), the flow was considered to be symmetrical.

As water is half filled, so during analysis we taken all 3 phases (water as fluid, and other half portion is air and solid act a domain for fluid).

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Dimensions and other parameters are also mentioned in WORK DONE part and in Solid works CFD analysis.

All the parameters like speed of the vehicle, dimensions, analysis time after brake applied, pressure, density of fluid, material of baffle plate, and the material of cylindrical vessel will be same for both the cases.

We will only going to change the baffle plate during different analysis.

For case 1

In this analysis, we used the baffle plate which is shown in fig 1, and the result obtained on software at t= 5 sec after brakes were applied on vehicles. After the brake applied it shows a sloshing effect inside the cylindrical vessel this time we get changes in the behavior of the sloshing of water with the help of the Volume Fraction Counter and different results are also can be differentiated.

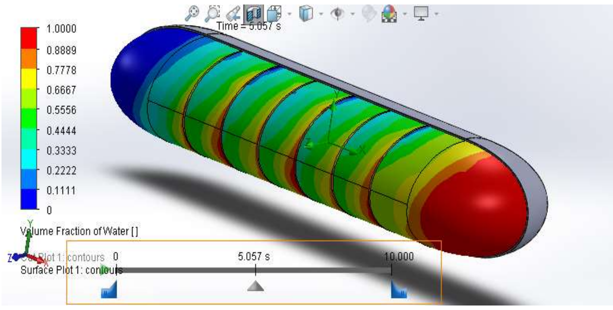

Fig. Different Global goals values for Case 1

For case 2

In this, we used the baffle plate shown below, and the result obtained on software from t=0 till t=10s after brakes applied on the vehicle can be shown in below figure and after brake applied it shows sloshing effect inside the cylindrical vessel and we can see the behavior of the water sloshing.

The results of the 2nd Case is discussed in the Table shown below.

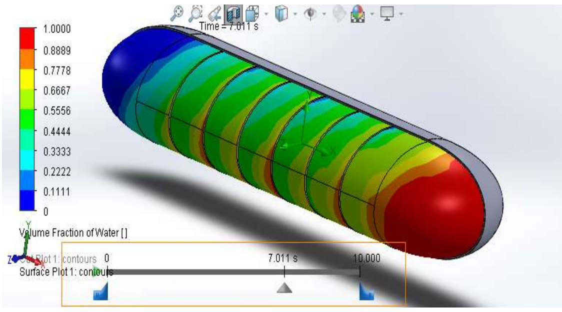

Fig. Volume Fraction Counter for 2nd case at t = 7 sec

Goal Name	Unit	Value	Averaged Value	Progress [%]
GG Av Dynamic Pressure 1	[Pa]	26.10893535	28.35490468	100
GG Av Velocity (Y) 1	[m/s]	-0.02828267	-0.027150469	100
GG Av Turbulent Energy 1	[J/kg]	0.043534076	0.04390755	100
GG Force (Y) 1	[N]	-38906.0949	-38867.19908	100
GG Torque (Y) 1	[N*m]	136.5433958	12.83531958	100

Goal Name	Unit	Value	Averaged Value	Progress [%]
GG Av Dynamic Pressure 1	[Pa]	40.00431752	43.45862377	100
GG Av Turbulent Energy 1	[J/kg]	0.051843471	0.052185061	100
GG Force (Y) 1	[N]	-38385.5746	-38251.48249	100
GG Torque (Y) 1	[N*m]	-157.089399	51.43549562	100

4. Conclusions

For partially filled cylindrical vessel with water as a fluid, sloshing forces and moments are developed as it is subjected to linear acceleration/ deceleration. After simulating in SOLIDWORKS CFD and analyzing the results we can conclude that:

The FLUCTUATION in sloshing forces and moments are more at the lower fill level (bottom of the tank and near the bottom of Baffle plate.

Magnitude of the forces and moment are high in case of existing baffle plate Braking Efficiency also increased.

Scope for Future Work

The problem like sloshing in a cylinder with baffles. Some of them are for future work:

The study can be performed with different shape of Vessel, Different Fluid can be studied. Use of different types of baffles plates and can modified them notice the analysis. The study of baffle plate with different orientation in tank.

The analysis part of any solution tool is very important step. In the present study an evaluation method used for the analysis of facility layout has been discussed. A practical case study of a automobile industry has been taken. There were two alternatives at the evaluation stage of design process, and the factor analysis method has been implemented for selecting the best among them. The score for alternative 1 and 2 are as: 865 and 829 respectively, therefore alternative 1 is selected as best among these. This study is very helpful for the layout designer for selecting the best layout. In future this method can be implement on other industries with more number of alternatives.

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