INVESTIGATION OF SLOSHING IN A PRISMATIC TANK FILLED WITH DIFFERENT LIQUID LEVEL

Elif ERZAN TOPÇU[*]   Eyüp KILIÇ[**]   Kadir ÇAVDAR[*]   İlker KUZUCU[***]

[*]Uludağ University, Faculty of Engineering, Department of Mechanical Engineering, 16059, Bursa, Turkey
erzan@uludag.edu.tr, cavdar@uludag.edu.tr

[**]Uludağ University, Graduate School of Natural and Advanced Sciences, 16059, Bursa, Turkey
[***] AKA Automotive, Örnek köy Yolu No: 1/1 Orhangazi, 16800, Bursa, Turkey

Abstract: In this study, sloshing behavior in a prismatic tank that is approximately the same volume with a vehicle' s fuel tank is investigated by Computational Fluid Dynamics (CFD) method. Tank is modeled with vertical baffle and without baffle. The tank is filled with water where the rate of 50%-70% and the dynamic behavior of the system examined for both cases. The tank is subjected harmonic motion at the lateral direction, the velocity change of fluid and the pressure at the tank wall are examined.

Keywords: Sloshing, tank baffle, fuel tank

Introduction

The fuel tank is called tank which stores the fuel used to provide the energy required for operation of the vehicle. These tanks can be produced in different sizes and different materials. At last years, it can be said that the investigation of the sloshing event in the fuel tank has gained importance in the automotive industry because of more detailed analysis of vibration and noise in the vehicle (Jadon et al. 2014, Kingsley 2005, Wiesche 2003, Chitkara et al. 2013, Kılıç 2015).

Free liquid surface is formed on the liquid surface of the tank partially filled with liquid fluid. The movement of the surface is defined as sloshing. Free liquid surface shows various types of motion according to the shape of the tank movement and geometry of the tank. These can be classified such as simple planar, non-planar, random shock, symmetric, asymmetric, quasi periodic and chaotic. The amplitude of the sloshing movement depends on the shape of the actuation, the depth of the liquid in the tank, the geometry of the tank and the fluid properties (İbrahim et al. 2001, İbrahim 2005, Akyıldız et al. 2006).

The movement of the fluid in the tank is interested in many engineering systems such as fuel tank, space vehicles and high water towers. Pressure forces at the tank generated as a result of sloshing motion can lead to strain and security problems in mechanical systems. Therefore, determination of distribution of the hydrodynamic pressure and forces and natural frequency of the free liquid surface during sloshing is important (İbrahim 2005, Akyıldız and Ünal 2006). When evaluated according to the tank acceleration, external signals, tank settlement and liquid level of the tank, these loads should not exceed a certain maximum value and should remain within safety limits.

The studies done in the automotive field are investigated widely and summarized below. Wiesche (2003) made investigations from theoretical studies and industrial applications to calculate numerically the sloshing behavior of the viscous liquid in the fuel tanks with different geometries. The Volume of Fluid method (VOF) was used to calculate the free surface flow and prismatic, spherical and non-symmetric fuel tanks were analyzed. Jadon et al. (2014) used a multi physics based numerical method to estimate the sound change from sloshing behavior. During the study, the sloshing model was created by using Computational Fluid Dynamics (CFD), Finite Element Method (FEM) and the Boundary Element Method (BEM). The vibration calculations were carried out under LS-DYNA program. Many parameters such as tank surface pressure, surface integral force, momentum, the average kinetic energy were investigated together with these systems. Chitkara et al. (2013) investigated the sloshing for partially filled tanks using VOF method and analyzed two different geometries using computational simulations considering 40% of fuel and 60% of air inside a 40 liters fuel tank under longitudinal acceleration. Iu et al. (2004) studied on the noise caused by sloshing. Several baffle designs were investigated to suppress the fuel slosh by using FLOW-3D CFD software theoretically and experimentally. Estimated mean kinetic energy and average turbulent kinetic energy of the fluid obtained from the computer simulations were used to compare with sound measurements obtained from experiments. İbrahim et al. (2001) made a very large review study on dynamics of liquid sloshing. Information is given about 1319 publications on sloshing event made up to publication date. Akyıldız and Ünal (2006) were investigated the sloshing pressure variations and the three dimensional behavior of the liquid in the

partially filled prismatic tank by experimental and theoretical studies. Çelebi and Akyıldız (2001) investigated the sloshing event in the partially filled tank with and without baffle structure. Jung et al. (2012) analyzed the lateral oscillating movement of the partially filled fluid tank and investigated the effect of the length of baffle vertically placed into the tank. VOF method was used for monitoring the fluid motion and pressure changes were investigated according to the different baffle height. Kingsley (2005) made various sloshing optimization studies to develop the liquid tank design and analysis. In the study computational fluid dynamics and finite element methods were used.

In this study, sloshing behavior in a prismatic tank with 50 lt volume and 0.3-0.7-0.24 m the width, the length and height is investigated by CFD method. The tank is filled with water where the rate of 50%-70% and the dynamic behavior of the system examined for both cases. Tank is modeled with vertical baffle and without baffle, and subjected to the lateral harmonic movement. The velocity changes of fluid and the pressure values at the tank wall are examined.

Materials and Methods
1. Mathematical model of sloshing
In this section, basic equations of fluid motion and mathematical models of sloshing event are presented briefly. Basic equations for mathematical modeling of sloshing are continuity, momentum and fluid volume VOF equations.

The continuity equation for a control volume with dimensions dx, dy and dz in cartesian coordinate system can be defined generally as below (Çengel and Cımbala 2005, Umur 2009);

$$\frac{1}{\rho}\frac{D\rho}{Dt} + \nabla \vec{V} = 0 \tag{1}$$

Momentum equation with the assumption that the fluid is Newtonian, the flow is incompressible and working condition is isothermal can be written as;

$$\rho \frac{D\vec{V}}{Dt} = -\nabla \vec{P} + \rho \vec{g} + \mu \nabla^2 \vec{V} + f \tag{2}$$

The terms defining irregular changes are added to the laminar momentum and continuity equations for turbulent flow and conservation equations for turbulent flow are obtained (Çengel and Cımbala 2005, Umur 2009).

The VOF method is an efficient multi-phase method used to simulate the flow of immiscible liquids (Vaishnav et al., 2014). This method is used for examining the movement of the free surface during sloshing of the liquid in the tank (Jadon et al., 2014). This method developed by Hirt and Nichols (1981) follow the upper surface of the liquid in the container or follow the interphase surface of the system in other words. The liquid defined by the mesh is divided to the fixed or moving small particles to make this follow.

According to linear wave theory, natural frequency of fluid for a rectangular prismatic shaped tank can be defined;

$$\omega_n^2 = g \frac{n\pi}{L} tanh\left(\frac{n\pi}{L}d\right) \tag{3}$$

Here, g: acceleration of gravity (m/s²), L: tank length in the direction of the movement (m), d: fluid level in the tank (m) and n: mod number. Accordingly, it can be seen that the natural frequency of the fluid in the tank prismatic tank changes depending on the fluid level in the tank, the length of the tank in the direction of the warning (Abraham 2001, Kingsley 2005).

2. System Structure and Simulation
The tank that capacity is 50 lt and 0.3- 0.7- 0.24 m width, length and height, the placement of the baffle into the tank and the pressure measurement points are shown in Figure 1.

In this study, the baffle was placed in the middle of the tank and the height of the baffle is taken 42% of the tank height. Because the tank is symmetrical and homogenous, pressure measurement points are positioned only one side wall of the tank. Tank movement is provided so that it can oscillate in the lateral direction indicated by x. The equation of the acceleration representing the described input can be seen below;

$$\ddot{x} = -A\omega^2 sin(\omega t) \tag{4}$$

Here, A: amplitude of the movement (m), ω: angular frequency (rad/s). The input function is given as acceleration input and an appropriate program is written in C language for the analysis. The tank movement and angular frequency are taken as 2 cm, $\omega = \omega_n$ respectively for baffled and unbaffled cases. There are two different phase as air and water in the tank so multiphase flow model is used in the study. The node and element numbers used in modeling are given in Table 1. Analyses are performed using ANSYS Fluent program.
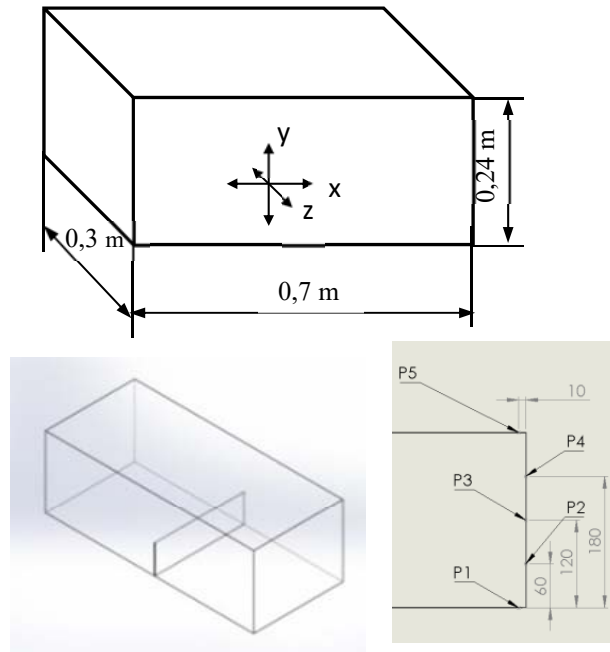
Figure 1. The size of the tank, placement of the baffle and pressure measurement points

Table 1: The number of the node and element

| Tank model	Node number	Element number
Tank with baffle	55025	50400
Tank unbaffled	55800	50730

3. Results and Discussion

In this study, the pressure changes at the wall of the tank and the instant pressure and velocity distribution of the liquid in the baffled and unbaffled tank for 50% and 70% filling rates are obtained as simulation results.

In Figure 2 and Figure 3, pressure changes at the P_1, P_2, P_3 and P_4 points and the pressure and velocity distribution at t=2.35 second for unbaffled tank filled 50% and 70% water are shown respectively.

(a)

(b)   (c)
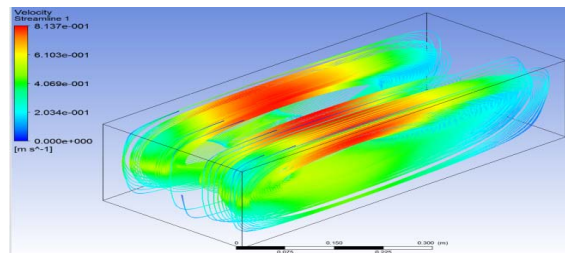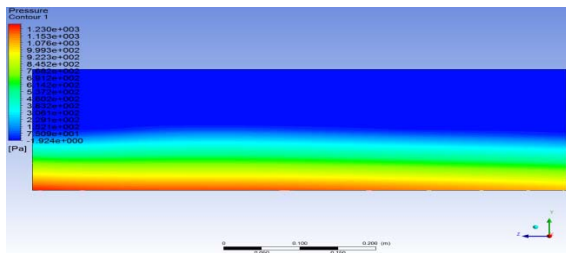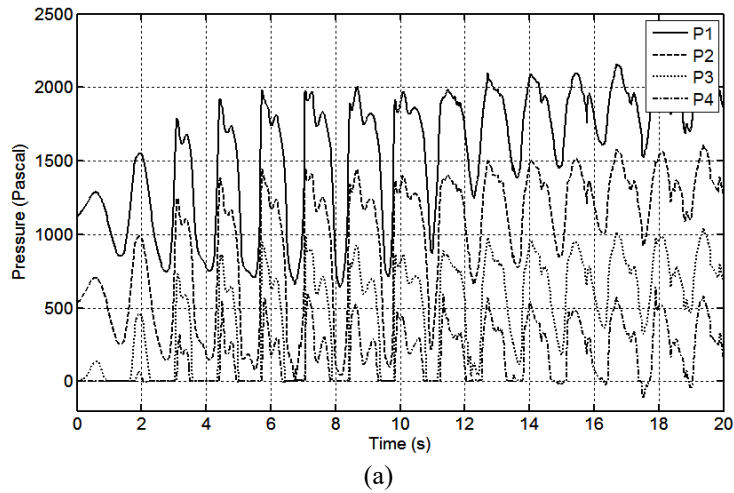
Figure 2. Unbaffled tank (50% filled)
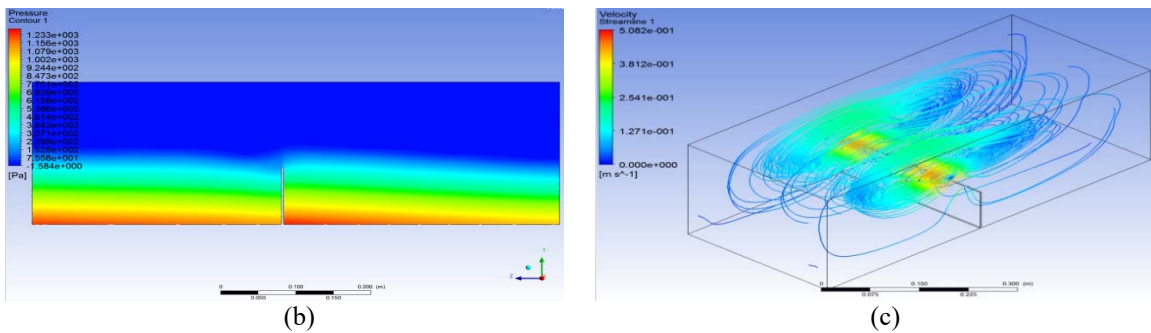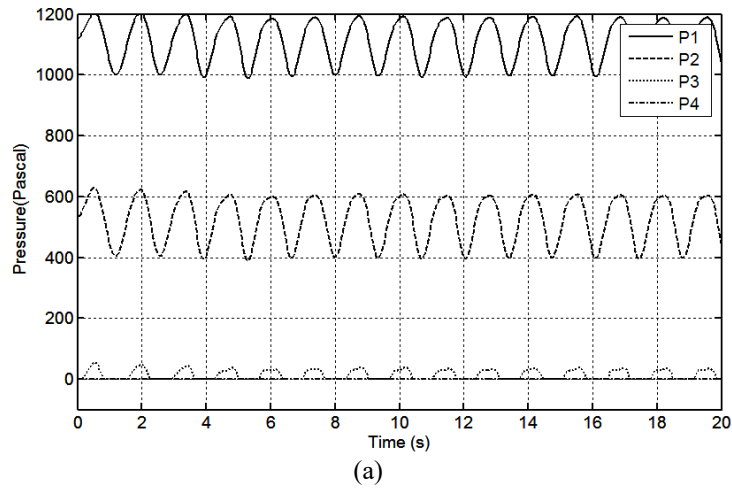a) Pressure-Time changes, b) Instant pressure distribution, c) Instant velocity distribution

(a)

(b)   (c)
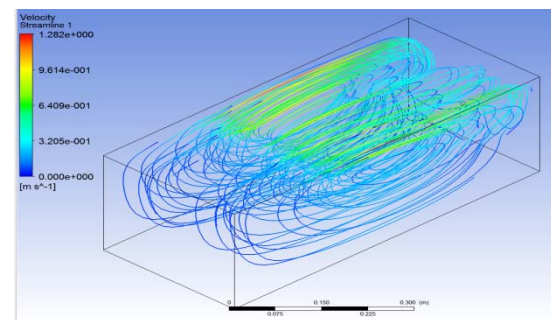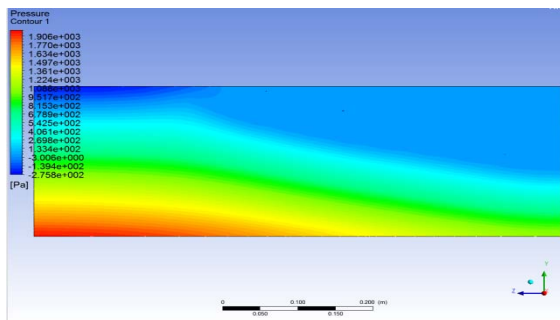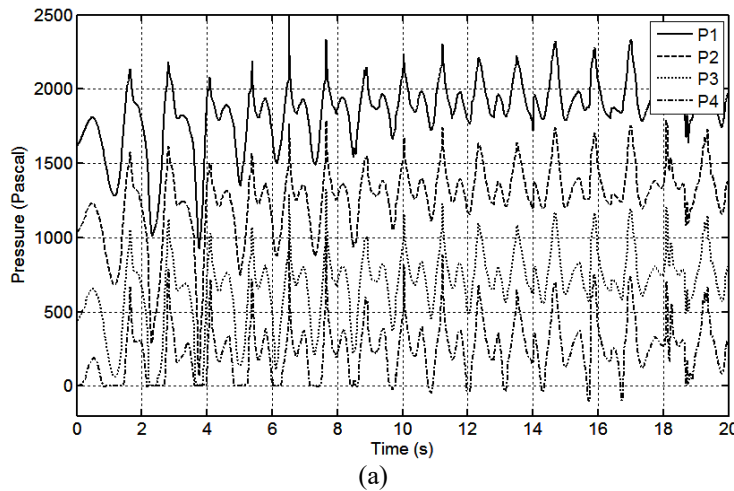
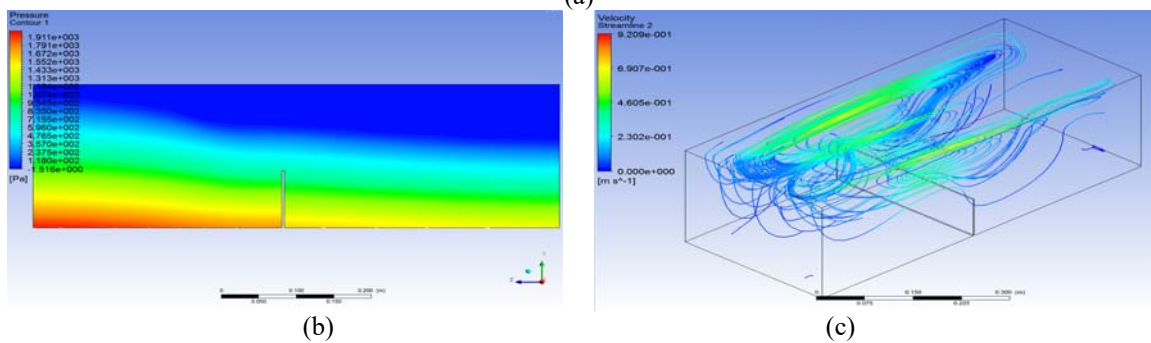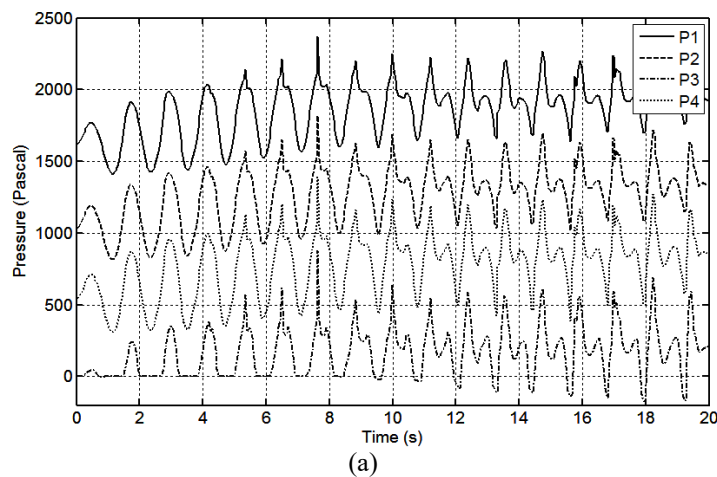**Figure 3.** Unbaffled tank (70% filled)
a) Pressure-Time changes, b) Instant pressure distribution, c) Instant velocity distribution

In Figure 4 and Figure 5, pressure changes at the P_1, P_2, P_3 ve P_4 points and the pressure and velocity distribution at t=2.35 second for baffled tank filled 50% and 70% water are shown respectively.

(a)

(b)

(c)

Figure 4. Baffled tank (50% filled)
a) Pressure-Time changes, b) Instant pressure distribution, c) Instant velocity distribution

(a)

(b)

(c)

Figure 5. Baffled tank (70% filled)
a) Pressure-Time changes, b) Instant pressure distribution, c) Instant velocity distribution

When Figure 2 and Figure 4 are examined, it can be shown that the sloshing behavior vary considerably between 50% filled baffled and unbaffled tanks. When the baffled tank case is investigated, it can be observed that the fluid cannot be reached to the pressure point 4 (P4) and the pressure distribution become more regular form. When the instant pressure and speed distribution are investigated for two cases, it can be shown that the maximum speed value of the baffled case is reduced at the rate of 62.5% approximately.

As it can be seen from Figure 3 and Figure 5, there are no big difference on the pressure values between baffled and unbaffled tanks. However, it can be said that the form of the sloshing behavior was changed and the maximum speed value is reduced at the baffled tank when the instant pressure and speed distribution are observed.

Conclusion

In this study, fluid sloshing behavior in a prismatic tank that has approximately the same volume with a vehicle fuel tank is investigated by CFD method, pressure and instant speed variations are obtained.

Two different tank configurations are modeled as tank with vertical baffle and unbaffled tank. The tank is filled with water where the rate of %50-70 and subjected harmonic motion at the lateral direction, the dynamic behavior of the system examined for both cases. It was seen from the results that the liquid level and the baffle in the tank affects the sloshing behavior of the fluid significantly.   When making design studies, it is important to take into account these parameters such as fluid level and baffle structure placed in the tank.

Acknowledgments

References

Kılıç, E. (2015). Analysis of sloshing in vehicle fuel tank, *Msc Thesis*. Uludağ University. 72 p. (in Turkish)

Ibrahim, R.A., Pilipchuk, V.N., Ikeda, T. (2001). Recent advances in liquid sloshing dynamics, *Appl. Mech. Rev*. 54 (2): 133–199.

Ibrahim, R.A. (2005). *Liquid Sloshing Dynamics: Theory and Applications*, M. Cambridge University Press, New York.

Akyıldız, H., Ünal, N.E. (2006). Sloshing in a three-dimensional rectangular tank: Numerical simulation and experimental validation. *Ocean Engineering*, 33: 2135-2149.

Akyıldız H., M.S. Çelebi. (2001). Numerical Computation of Pressure in a Rigid Rectangular Tank due to Large Amplitude Liquid Sloshing. *Turk J. Engin. Environ. Sci.* 25: 659– 674.

Jung, J.H., Yoon, H. S., Lee, C.Y., and Shin, S.C., (2012). Effect of the vertical baffle height on the liquid sloshing in a threedimensional rectangular tank, *Ocean Engineering*. 44: 79-89.

Hirt, C.V., Nichols, B.D. (1981). Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries. *Journal of Computational p*hysics, 39: 201-225.

Iu, H., Cleghorn, W., and Mills, J., "Design and Analysis of Fuel Tank Baffles to Reduce the Noise Generated From Fuel Sloshing," *SAE Technical Paper* 2004-01-0403, 2004, doi:10.4271/2004-01-0403.

Jadon V., Agawane G., Baghel A., Balide V., Banerjee R., Getta A., Viswanathan H., Awasthi A. (2014) An Experimental and Multiphysics Based Numerical Study to Predict Automotive Fuel Tank Sloshing Noise. *SAE Technical Paper 2014-01-0888,* 2014, doi:10.4271/2014-01-0888.

Kingsley, T.C. (2005). "Multidisciplinary Design and Optimization of Liquid Containers for Sloshing and Impact". University of Pretoria. p :133.

Vaishnav, D., Dong, M., Shah, M., Gomez, F. (2014). Investigation and Development of Fuel Slosh CAE Methodologies.   *SAE Int. J. Passeng. Cars - Mech. Syst. 7(1):2014*, doi:10.4271/2014-01-1632.

Chitkara T.K., Kittur, Z., Soman R. (2013). "Computational Simulation of Fuel Tank Sloshing using CFD Techniques. *SAE International* doi:10.4271/2013-01-2868.

Wiesche S. (2003). Computational slosh Dynamics: theory and industrial application, *Computational mechanic*s. 30: 374-387.

Çengel Y. Cımbala J.M. (2005). *Akışkanlar Mekaniği, Temelleri ve Uygulamaları*. Güven yayıncılık. 938 s.

Umur H. (2009). *Akışkanlar mekaniği*. Dora yayıncılık. 553 s.