Sloshing effect, design and optimisation of water ballast tank

C L Dumitrache\textsuperscript{1}, D Deleanu\textsuperscript{2}, C Scurtu\textsuperscript{3}

\textsuperscript{1,2}Maritime University of Constanta, Department of General Engineering Sciences, Mircea cel Batran street, No. 104, Constanta, 900663, Romania
\textsuperscript{3}“Mircea cel Bătrân” Naval Academy of Constanta, 1\textsuperscript{st} Fulgerului street, Constanta, 900218, Romania

E-mail: ldumitr@yahoo.com

Abstract. In this article the authors realise the study regarding to the behaviour of water ballast tank during sloshing effect. The designing operation of water ballast tank (WBT) was performed using NX Siemens. The purposes of this article are to evaluate different stages of sloshing effect when the total pressure exerted by the fluid is changing quickly with time. We simulate using CFX Ansys different complex stages of sloshing inside of WBT without baffle design and stages when WBT has baffle design used to suppressed sloshing effect in an accelerated tank.

1. Introduction

The sloshing effect refers to the movement of free surface of a liquid inside of container due to the movement of its container. The liquid sloshing is considered to be an important factor in various area such as cargo ships (tankers) which transporting petroleum liquids or other liquids (water inside of ballast tanks), aircrafts fuel tanks, large storage volumes systems which may be influenced by seismic loadings. Sloshing can produce big problems so is essential to apply the prevention measures. For example in earthquake, the sloshing motion of shore-oil tanks will bring large fluid pressures and impact loads, which might destroy the structure of tanks. In this way, fire disaster or wide-area environmental pollution will occur, which are extremely dangerous.

The ship motion of tankers in sea waves might cause sloshing in partly filled tank, which will lead to instability of tankers. Severe sloshing motion may produce heavy impact force to tank walls and structure and damage them. After, the leakage of oil is a big problem of personal safety and environment. The sloshing motion will become advantageous such as the roll-reduction tank that use the force and moment provided by sloshing motion in the tank to reduce the ship motion in wave. Sloshing has a strong interaction between liquid and wall structure that restrict the liquid motion. Sloshing motion is a highly nonlinear fluid movement which means large motion of free surface, fast change of wet boundary and fluid-structure coupling. Sloshing is one of complexity problem and nowadays is still important topic in aerospace and marine fields.

A long history of sloshing research demonstrates the continuing attraction because of its importance in applications. The effects of the sloshing phenomenon on cargo ships structure have been investigated by many researchers. For example, Mikelis and Journee (1984)\textsuperscript{[1]} presented an approach.
with finite differences in the two-dimensional space of formation and development of sloshing phenomenon on ships with partially filled cargo tankers or water ballast tankers comparing analytical results with measured pressures and moments of bending, resulting an acceptable correlation between them.

The problem of complete coupling between the sloshing phenomenon and the movement of metal wall structure has been approached relatively recently for the first time since it is complex inherent to such models. For example, Kim, 2002 [2], Rognebakke and Faltinsen, 2003 [3], Kim et al., 2006 [4], Lee et al., 2007a & b [5] [6], demonstrated the importance of the interaction between the sloshing phenomenon, the metal structure and the movement of the ship especially when the volume of fluid cargo holds relative to the entire volume of the ship exceeds a certain critical value.

Recently, Lee et al., 2007a [5] conducted a sensitivity study of a parameters for an LNG (liquefied natural gas) tanker using CFD (Computer Fluids Dynamics analysis) with the conclusion that the viscosity and density of the simulated fluids don’t have one sensible effect on sloshing phenomenon.

2. The mathematical model

A mathematical model is a mathematical interpretation using abstract instruments of the essential aspects of a phenomenon or system. On these models it is builds CFD finite volume formulation with which it will continue to work modeling the sloshing phenomenon on this article. The continuity equation describes the conservative transport of a finite amount of fluid. The Law of Mass Conservation shows that in mechanics, the matter is not created or destroyed. For a three-dimensional, incompressible and in motion, the continuity equation is:

\[
\frac{1}{r} \frac{\partial}{\partial r} (ru_r) + \frac{1}{r} \frac{\partial}{\partial \phi} (u_\phi) + \frac{\partial}{\partial z} (u_z) = 0
\]  

(1)

where \( u_r, u_\phi, \) and \( u_z \) are the components of fluid velocity in a volume of finite reference, and \( r, \phi, \) and \( z \) are the coordinates of a cylindrical reference system.

Navier-Stokes equations are those equations that can describe in newtonian terms the movement of viscous fluid element with finite volume. These equations are also known as the moment conservation equations in fluid mechanics. For \( r \) coordinate, we have:

\[
\rho \left( \frac{\partial}{\partial t} (u_r) + u_r \frac{\partial}{\partial r} (u_r) + \frac{u_\phi}{r} \frac{\partial}{\partial \phi} (u_r) + u_z \frac{\partial}{\partial z} (u_r) - \frac{(u_\phi u_r)}{r} \right) =
\]

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

(2)

For \( \phi \) coordinate, we have:

\[
\rho \left( \frac{\partial}{\partial t} (u_\phi) + u_r \frac{\partial}{\partial r} (u_\phi) + \frac{u_\phi}{r} \frac{\partial}{\partial \phi} (u_\phi) + u_z \frac{\partial}{\partial z} (u_\phi) - \frac{(u_\phi u_\phi)}{r} \right) =
\]

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

(3)

For \( z \) coordinate, we have:

\[
\rho \left( \frac{\partial}{\partial t} (u_z) + u_r \frac{\partial}{\partial r} (u_z) + \frac{u_\phi}{r} \frac{\partial}{\partial \phi} (u_z) + u_z \frac{\partial}{\partial z} (u_z) \right) =
\]
w_here \( p \) is the static pressure, \( u_r, \phi, z \) are the components of the velocity vector on the coordinates reference system, \( \mu \) is the dynamic viscosity, and \( \rho g_r, \phi, z \) are the gravitational force components on coordinate axes.

In the sloshing phenomenon the tank is divided between the cargo fluid domain and another one above which is the atmospheric air. So any modeling must in principle be multiphase and on the tank volume the speeds fields will be divided between two phases, liquid and gaseous.

The moment equation for a such multiphase system is:

\[
\frac{\partial}{\partial t} \left( \rho \vec{V} \right) + \nabla \left( \rho \vec{V} \vec{V} \right) = -\nabla p + \nabla \left( \vec{\tau} \right) + \rho \vec{g} + \vec{F}
\]

(5)

where \( p \) is the static pressure, \( \vec{\tau} \) is the stress tensor of the finite volume, \( \rho g \) are the vectors of gravitational force and \( F \) is the external forces (eg. force which is born through phase dispersion).

3. Simulation of sloshing effect with finite elements and volumes on water ballast tank

It is obvious that simulation of complex phenomenon such as the sloshing phenomenon is suspect to involve massive resources calculation.

First of all, the presence of two fluids are clear that ANSYS CFX used to simulate the behavior of two fluids, (seawater and air from the ballast tank), requires itself the multiphase flow model. Due to the movement of the ballast/cargo tanks is complex involving pitching and rolling of ship, it is clear that the simulation is done with the ANSYS CFX transient module.

The simplified CAD models for this paper are part of the ballast tank structure from an oil chemical tanker with the following dimensions:

- length over all (LOA) = 105.50 m;
- length between perpendicular (LBP) = 99.30 m;
- beam width = 16.80 m;
- gross tonnage = 3997 mt.

It has not been taken into account that the joints of the naval steel plates have been welded, but the most dangerous situation to create strong stress concentrators has been taken into account.

As a comparative study, two models were created:

- a simple ballast tank model with the dimensions shown in Figure 1;
- an optimized model with internal baffles to reduce the sloshing effect shown in Figure 2.

![Figure 1. Section viewing of simple ballast tank](image-url)
The CAD model is obviously simplified lacking the exact modeling of the ribs or all the gussets given that such a model would require a massive computational effort. For the same reasons, the dimensions in millimeters that are identical for the two models do not correspond to the actual dimensions of a ballast tank. It can be seen that this tank consists of two symmetrical vertical side faces, marked "symm1" and "symm2", located at a distance of 3 meters defined as boundaries limits "symmetry" type, and the winding surfaces of the tank, comprising the vertical wall coinciding with the position of the ship's keel and other unsymmetrical surfaces defined as boundaries limits "wall" type, all of them are marked with "wall".

The volume that is washed by the water in the tank for each model can be discretized using the finite element method and the mesh structures are presented below:
The mesh model in figure 3 consists of 400,858 nodes distributed in 378,724 elements and has a volume of 24,747 cubic meters. The mesh model in figure 4 consists of 550,247 nodes distributed in 3,094,289 elements and has a volume of 24,540 cubic meters. Within each model of the ballast tank there will be a quantity of seawater that will have the same height of 0.6 meters and with this amount of water we will simulate the effect of the free surface of the liquid which will ultimately determine the sloshing effect.

The analysis of the transient phenomena of the sloshing effect was carried out for 16 seconds by moving the tank at a velocity $v = 3\, \text{m/second}$ in the direction of $Ox$, corresponding to the pitching motion of the ship, also taking into account the expressions presented below:

$$
\text{fluid } Ht = 0.6[m] \\
\text{fluid Den} = 998[\text{kg m}^{-3}] \\
\text{fluidVF if y < fluid Ht, 1.0} * \text{if y > 0.1}[m, 0] \\
\text{HydroP fluid Den} * g * (\text{fluid Ht - y}) * \text{fluidVF}
$$

(6)

where "fluidHt" represents the height of the seawater column in the ballast tank (equal to 0.6 meters), "fluidDen" is the water density (998 km$^{-3}$), "fluidVF" is the volume of fluid moved by the sloshing effect and "HydroP" is the relative pressure exerted by the fluid on the walls of the ballast tank.

In this air/liquid flow analysis the air density in the tank enclosure is 1,185 kg/m$^3$ and the superficial air/liquid interface coefficient is 0.072 Nm$^{-1}$.

The following are the results for the seconds 0, 0.2, 0.4, 0.6, 0.8, 1 sec, up to 2 sec steps, with animated files showing the evolution of the total fluid pressure throughout the 16 seconds interval.

Figure 5. Total pressure at 0 sec at simple ballast tank and optimized ballast tank

Figure 6. Total pressure at 0.2 sec at simple ballast tank and optimized ballast tank
Figure 7. Total pressure at 0.4 sec at simple ballast tank and optimized ballast tank

Figure 8. Total pressure at 0.6 sec at simple ballast tank and optimized ballast tank

Figure 9. Total pressure at 0.8 sec at simple ballast tank and optimized ballast tank

Figure 10. Total pressure at 1 sec at simple ballast tank and optimized ballast tank
Figure 11. Total pressure at 1.2 sec at simple ballast tank and optimized ballast tank

Figure 12. Total pressure at 1.4 sec at simple ballast tank and optimized ballast tank

Figure 13. Total pressure at 1.6 sec at simple ballast tank and optimized ballast tank

Figure 14. Total pressure at 1.8 sec at simple ballast tank and optimized ballast tank
4. Conclusions

Due to the fact that a pitching motion of $v = 3\text{m/s}$ corresponding to a speed of 5,825 knots was imposed on the ship, it will make the water contained in the ballast tanks remain inertial resulting in an imbalance in the fluid mass and will form an internal wave which itself is the effect of sloshing.

The ship does not travel at high speed and the ballast tank models presented in this article and the amount of water contained therein, make the total pressures exerted by the fluid to be small. It can be noticed, however, that there is a difference between the pressure values in the simple tank and those in the tank that is optimized with internal baffles. These fluid pressure values can be further imported into a structural Transient structural calculation module to determine the stresses and deformations in the structure of the material from which the ballast tanks are made. All these stresses and deformations will be determined and will be the subjects of a future article.

5. References

[1] Mikelis, N.E. and Journee, J.M.J., Experimental and numerical simulations of sloshing behaviour in liquid cargo tanks and its effect on ship motions. National Conference on Numerical Methods for Transient and Coupled Problems, Venice, Italy, 9-13, 1984;
[2] Kim, Y., A numerical study on sloshing flows coupled with ship motion – the anti-rolling tank problem. *Journal of Ship Research*, 46(1), 52-62, 2002;
[3] Rognebakke, O.F. and Faltinsen, O.M., Coupling of sloshing and ship motions. *Journal of Ship Research*, 47(3), 208-221, 2003;
[4] Kim, Y., Nam, B.W., Kim, D.W., Lee, Y.B. and Lee, J.H., Study on couple effects of sloshing and ship motion. Proceedings of the Sixteenth International Offshore and Polar Engineering Conference, San Francisco, California, USA, 3, 225-229, 2006;
[5] Lee, D.H., Kim, M.H., Kwon, S.H., Kim, J.W. and Lee, Y.B., A parametric sensitivity study on LNG tank sloshing loads by numerical simulations. Ocean Engineering, 34, 3-9, 2007a;
[6] Lee, S.J., Kim, M.H., Lee, D.H., Kim, J.W. and Kim, Y.H., The effects of LNG-tank sloshing on the global motions of LNG carriers. Ocean Engineering, 34, 10-20, 2007b.