SLOSHING EFFECT AND MITIGATION SOLUTION OF FLOATING OIL STORAGE TANK

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ABSTRACT

In the present study, a hybrid frequency-time domain simulation scheme is used to analyze the dynamic response of sea-wave-induced fully non-linear sloshing fluid in a floating oil storage tank. The hydrodynamic coefficients and wave forces are firstly obtained by a potential-theory-based three-dimensional (3D) radiation/diffraction panel program (DIFFRACT) in frequency domain. Then, a time domain model based on frequency domain data is built upon the Cummins equations to study the corresponding simulations of tank motions. State-space models are proposed as approximate representations of the convolutions in this equation. Navier-Stokes equations are applied to simulate the nonlinear fluid sloshing in time-domain and solved using the finite difference method (FDM). The volume of fluid method (VOF) is used to track the non-linear free surface. The multi-cable mooring system is used as a sea-keeping approach. During simulation time, the sloshing model, the mooring model and the floating tank model are coupled so that the interaction between them can be considered. The simulation scheme is applied for parametric studies of the dynamic response of sea-wave-induced fully non-linear sloshing fluid in a floating rectangular tank. The coupling effects between floating tank motions and sloshing fluid inside the tank are found to be significant. Then, baffles are applied as a sloshing mitigation solution. Rigid baffles are modeled by using internal-obstacle boundary conditions. In order to show the effect of baffles, some results of the coupled dynamic system such as the dynamic response of the floating tank and sloshing elevation of liquid inside the storage tank will be presented and compared with corresponding results of the cases without baffles. These studies are important for the floating storage system under sea conditions.

Keywords: Sloshing, Navier–Stokes equations, floating tank, state-space model, baffles.

1. INTRODUCTION

In land-scarce island countries and countries with long coastlines namely Japan, USA, Indonesia and Singapore, the use of floating storage systems (FSS) to contain oil and liquefied natural gas (LNG) has become more and more popular. For example, two major floating oil storage systems

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were constructed at Shirashima and Kamigoto Islands in 1996 and 1988, respectively. The application of these systems provides many advantages. These systems not only keep explosive, inflammable material safely away from populated areas on land but also allow fast construction duration. Moreover, they are protected from earthquakes and differential settlement. However, during liquid loading and offloading operations, the liquid inside the floating storage tank is also prone to violent sloshing under sea wave condition. The large liquid movement creates highly localized impact pressure on tank walls which may in turn cause structural damages and may even create sufficient moments to affect the stability of the floating tank, especially under extreme sea condition. Also, if the forcing frequency is near the natural sloshing frequency, the high dynamic pressures due to resonance may damage the tank walls, and the consequent oil spill will have a tremendous environmental impact on the surrounding area.

Sloshing phenomenon in a rectangular tank has been widely studied for many years using various theories and methods (Faltinsen 1978; Nakayama and Washizu 1981; Wang and Khoo 2005). However, most of investigations mentioned above studied sloshing fluid in fixed tanks due to earthquakes or moving vehicles, and few studies have been given to sloshing fluid in floating tanks. Furthermore, the forcing function was limited to a single degree of freedom (DOF) of motion (surge, heave or pitch) and the interaction between the sloshing fluid and the floating tank motion was neglected. For real maritime analyses, the simultaneous actions of two-dimensional accelerations with three degrees of freedom should be investigated and the coupled effects among them may be important (Kim et al. 2007; Tuyen et al. 2012). Sloshing flow in floating tanks is mostly generated by tank motions under sea conditions but the slosh-induced forces and moments themselves affect the tank motion in return. Therefore, the sloshing fluid induced hydrodynamic forces should also be a part of the forcing function of the tank motion. In addition, the tank motion and sloshing problem should be studied at the same time. Kim et al. (2007) included these coupling effects in their studies using Cummins equations and the convolution terms are integrated directly. This approach will need more computational effort compared to identification methods by using the state-space model to replace the convolution terms (Taghipour 2008). Moreover, the height function was used in their model to track the free surface of sloshing-fluid that restricts the free surface to be single-valued and thus the model is not applicable to simulate the broken free surface.

In this paper, sloshing in floating tanks is investigated and the coupling effects between the tank motion and liquid sloshing are also studied. The sloshing pressures acting on the tank walls are considered as a part of the forcing function of the tank motion. The FDM scheme is applied to solve Navier-Stokes equations and VOF is used to capture the free surface of the sloshing fluid. The Cummins equation is used in time-domain to obtain the tank motion so that the fluid memory effects can be included. The convolution integral is replaced by the state-space models to save computational time. Moreover, baffles are proposed and studied as a sloshing mitigation solution. The characteristics of sloshing, tank motions and baffle parametric studies are presented.

2. MODELING OF FLOATING TANK

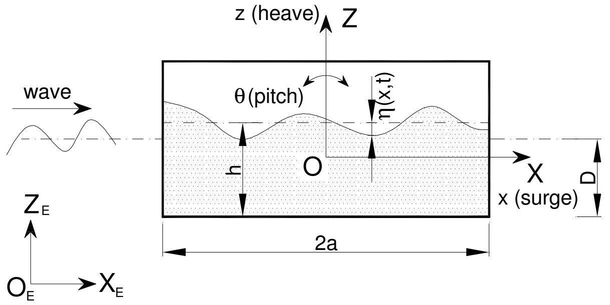


Figure 1: Definition of reference frames and motion variables.

To model the motion of a floating tank and sloshing fluid in the tank, two reference frames or coordinate systems, namely the Earth-fixed coordinate system and the body-fixed coordinate system, are defined in Figure 1. The floating object motion is a classic problem usually solved in frequency domain. However, to include nonlinear sloshing effect, a hybrid frequency-time domain model based on Cummins (1962) equations is developed. To date, it has been utilized successfully in different motion analysis applications (Taghipour 2008; Tuyen et al. 2012).

$$[\mathbf{M}+\mathbf{A}(\infty)]\frac{\partial^2 \vec{\xi}(t)}{\partial t^2}+\int_0^t \mathbf{K}(t-\tau)\frac{\partial \vec{\xi}(\tau)}{\partial \tau}d\tau+\mathbf{C}\vec{\xi}(t)=\vec{F}(t) \tag{1}$$

where $\vec{\xi}(t)=(x,z,\theta)$ is the displacement vector of tank motion, $\vec{F}(t)$ the excitation force vector including all the external and internal forces on the tank; **M** the matrix of mass including mass of the tank and mass of fluid in the tank; **A** the added mass matrix; **B** the matrix of damping and **C** the matrix of restoring coefficients. All these hydrodynamic variables are evaluated by using DIFFACT, a radiation/diffraction panel program (Sun et al. 2009). The **K**(t) is known as the retardation function or memory function which has relations with added mass and potential damping (Ogilvie 1964)

$$\mathbf{K}(t)=\frac{2}{\pi}\int_0^\infty [\mathbf{B}(\omega)-\mathbf{B}(\infty)]\cos(\omega t)\,d\omega=-\frac{2}{\pi}\int_0^\infty \omega[\mathbf{A}(\omega)-\mathbf{A}(\infty)]\sin(\omega t)\,d\omega \tag{2}$$

3. MODELING OF SLOSHING FLUID

Assuming an incompressible fluid, the flow inside the tank is governed by the continuity and Navier-Stokes equations which represent the conservation of mass and momentum per unit mass in fluid domain, respectively

$$\frac{\partial u_i}{\partial x_i}=0;\quad \frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\nu\frac{\partial^2 u_i}{\partial x_j^2}+f_i \tag{3}$$

where *i, j*=1, 2 for two-dimensional flows, u_i denotes the *i*-th component of the fluid velocity vector, ρ the density ($\rho = \rho_g$ in gas and $\rho = \rho_l$ in liquid), p the pressure, ν the kinematic viscosity and f_i the *i*-th component of the body force vector consisting of the gravitational acceleration and the translational and rotational inertia forces. Internal-obstacle boundary condition is applied to model baffles (Nichols et al. 1980).

4. COUPLING TANK MOTION AND SLOSHING FLUID

The coupling between sloshing fluid and tank motion can be modelled by including the sloshing force vector $\vec{F}_{slosh}(t)$ in the excitation force vector $\vec{F}(t)$ in the right hand side of equation (1)

$$\vec{F}(t) = \vec{F}_{ext}(t) + \vec{F}_{slosh}(t) + \vec{F}_{mor}(t) \tag{4}$$

where $\vec{F}_{ext}(t)$ is the external excitation force vector acting on the outside wall of the tank due to wave reactions, $\vec{F}_{mor}(t)$ the external excitation force vector acting on the outside wall of the tank due to the mooring lines used as a sea-keeping system in this study, $\vec{F}_{slosh}(t)$ the sloshing-induced force vector acting internally on the tank walls. These sloshing forces and moments can be obtained by integrating over the effect of pressures acting over the corresponding walls of the tank and including them as part of the forcing function of the tank motion

$$\vec{F}_{slosh}(t) = \int_{S_{\text{tank}}} p \begin{pmatrix} \vec{n} \\ \vec{r} \times \vec{n} \end{pmatrix} dS \tag{5}$$

As mentioned in an earlier section, the tank motion will result in sloshing of fluid in the tank and tensile forces of the mooring system. Then the hydrodynamic forces generated by the sloshing fluid and the mooring forces will affect the tank motions in return. When the equations of motion of the floating tank are solved, the corresponding dynamic acceleration of surge, heave and pitch motions will be used as the forcing functions of the liquid motion in the tank and the corresponding motions will be drifts of the upper ends of the mooring lines.

5. SLOSHING EFFECT IN FLOATING STORAGE TANK – NUMERICAL EXAMPLES

The following numerical examples are presented to demonstrate the coupling effects of between sloshing liquid and floating tank motions by using the FDM to solve Navier-Stokes equations. MATLAB/Simulink is used to identify state-space models and perform the simulation in the time domain. Wave forces and sloshing forces are taken as input and output is the response for each mode of motion. A Runge-Kutta method is chosen to solve the differential equations. The detailed numerical implementation and algorithm can be found in Tuyen et al. (2012).

5.1. Parametric studies for different wave frequencies

In the following section, the coupled model is used to study effect of different wave frequencies on the coupled sloshing-floating tank motion problem so that resonant frequency areas can be determined for both dynamic responses of a floating tank and sloshing response of liquid inside the tank. The main parameters of the floating rectangular tank are given as: overall length $2a$=40m, breadth B=10m, height H=10m, design draught D=7m. In real scenarios, floating tanks are divided into many compartments so that the structures of tank become stiffer and the sloshing flow inside the tank tends to be less violent. The floating tank is divided into three compartments in length: 15m, 10m, and 15m. In this case, the sloshing flows in the multi-compartment tank and different fluid arrangement should be investigated. However, the main purpose of this paper focuses on the effects of baffles on coupled sloshing-floating tank motion system; thus, only the sloshing flow in the central compartment is considered to simplify the problem and to have a clearer view. The liquid height inside the tank is h=6m. In this investigation, the same values of these parameters are used for all cases except wave frequencies varying from ω=0.01 to 2.0 rad/s. The simulation time is t=200s.

Figure 2 shows the effect of wave frequencies on the maximum sloshing elevation of liquid. It can be seen that there are four values of sloshing resonant frequencies $\omega = 0.28,\ 0.7,\ 0.9$ and 1.8 rad/s which are near to resonant frequencies of tank motions (0.28, 0.7 and 0.9 rad/s) and the natural frequency of sloshing fluid (1.8 rad/s for h=6m). It means that the fluid also becomes violent when wave frequency is near to motion resonant frequencies because of large motion amplitudes.

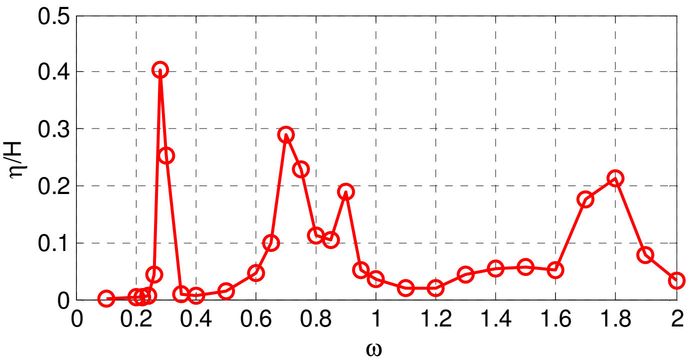
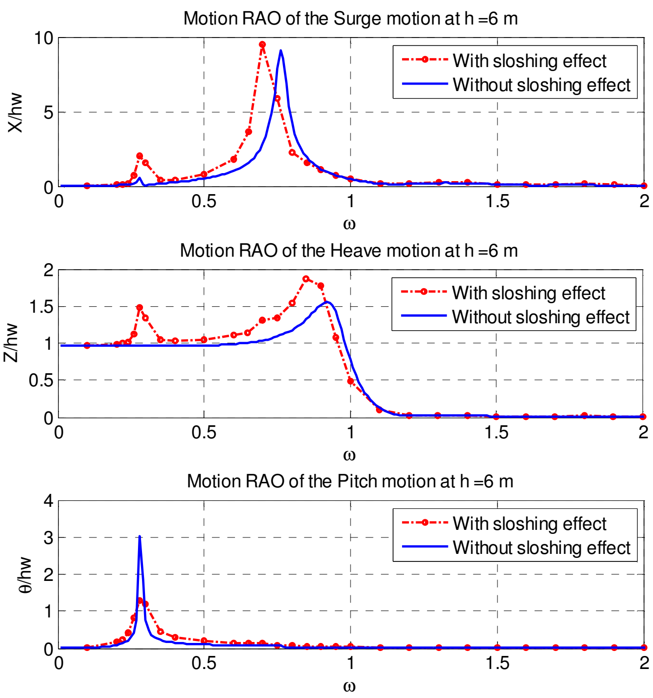


Figure 2: Effect of wave frequencies on maximum sloshing elevation of fluid.

The motion RAO in three DOF of the tank is showed in Figure 3 and compared to motion RAO without sloshing effect. When sloshing effect is considered, the resonant response amplitudes become larger and the resonant frequencies are shifted to the left hand side for surge and heave motions. Moreover, one more resonant frequency with smaller response amplitude is found near to the resonant frequency of the pitch motion. It means that with sloshing effect, there are two resonant areas for surge and heave motions, one near to natural frequency with out sloshing effect and the other near to natural frequency of the pitch motion. For the pitch motion, motion RAO chart becomes boarder at frequencies near to resonant frequency and the resonant response amplitude is also smaller. Based on this good effect, ART can be designed to minimize sloshing effect on rotational motions when excitation frequencies are near to natural frequency of motion. It is also noted that the sloshing increases the pitching amplitude for other out of resonant wave frequencies.



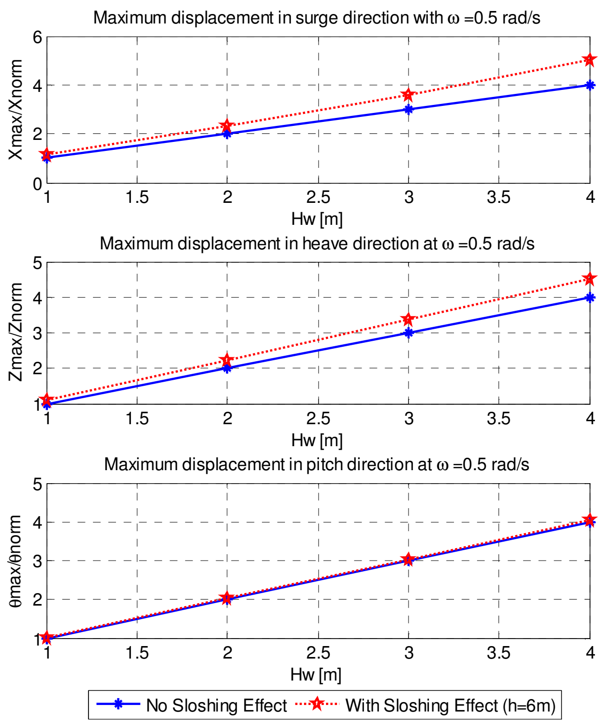


Figure 3: Motion RAO in three DOF of floating tank

Figure 4: Effect of wave height on the tank's dynamic response with ω = 0.5 rad/s

5.2. Parametric studies for different wave heights

In this section, the same parameters of the tank and the mooring system with the previous example are used. The sloshing liquid height h=6m and wave frequency $\omega = 0.5$ rad/s are applied for all considered cases. Various wave heights from H_w=1-4m are simulated in Simulink with simulation time of t=200s.

The simulation results for the dynamic response of the tank are shown in Figure 4 where X_{norm}, Z_{norm} and θ_{norm} are maximum displacements of the tank without sloshing effect in surge, heave and pitch directions respectively under regular wave H_w=1m. These results are also compared with the results obtained for the tank without sloshing effect. From the figure, it can be seen that under wave frequency $\omega = 0.5$ rad/s, sloshing enlarges the dynamic response of the floating tank. Moreover, it can be observed that the higher the wave height is the larger the tank displacement is and the maximum displacements of the tank are not proportional to wave amplitudes like in cases without sloshing effects anymore. It is due to nonlinear effects of sloshing fluid inside the floating tank which make the coupled sloshing-floating tank motion problem nonlinear.

6. EFFECT OF BAFFLES IN COUPLED SLOSHING-FLOATING TANK MOTION

In the following examples, baffles are proposed as a sloshing mitigation solution and the effects of baffles in the coupling problem between sloshing liquid and floating tank motions will be studied.

6.1. Effect of baffle height

The regular wave with frequency $\omega = 2.0$ rad/s and wave height $H_W / H = 0.1$ as well as the liquid filling ratio $\beta = h / H = 0.6$ is used for the simulation. The vertical baffle is employed in this section. The baffle height ratios $H_b / H = 0.1 - 0.5$ are simulated and the numerical results are compared with the case without presence of baffles. The effect of baffle heights on maximum displacements of the floating tank with three degree of freedom is presented in Figure 5, where $\xi_{\max 0}$ is the maximum displacement of the tank without baffle effect. From the figure, it is obvious that when the height of the baffle increases, the effect of baffle on the dynamic responses of the tank becomes more significant. In this example, it can be found that the effect of the baffle on surge motion is larger on heave and pitch motions. Moreover, the numerical results from the figure also show that the effect of the baffle can reduce the displacement of the floating tank.

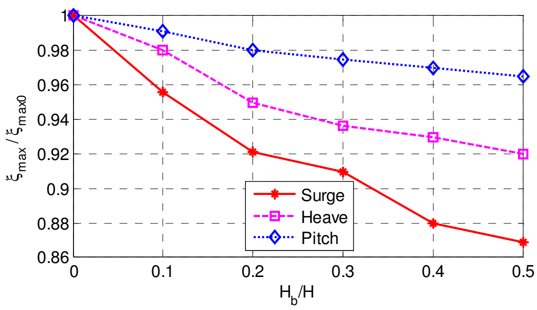


Figure 5: Effect of baffle height on dynamic responses of floating tank

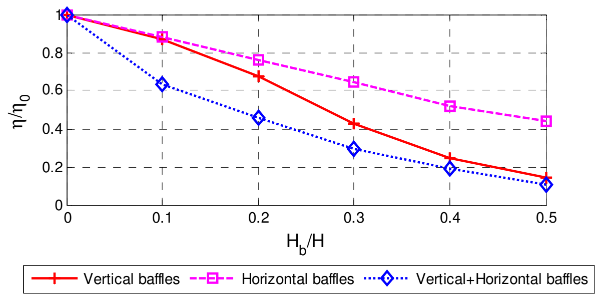


Figure 6: Effect of baffle type on the sloshing elevation of fluid with $\omega = 2.0$ rad/s

6.2. Effect of baffle type

Effect of different types of baffle on sloshing and motion response of sloshing-floating tank motion problem is simulated in this section. Two types of baffles, vertical and horizontal baffles, will be employed in this example. Firstly, two types of baffle are studied separately and then combination of them is considered so that the effective solution can be achieved. The same parameters as used in previous section will be applied for this example and the wave frequency $\omega = 2.0$ rad/s is used for the numerical simulation. The ratios of $H_b / H = 0.5$ are studied and the numerical results are compared with the results without baffle effect. The effect of different types of baffle on the sloshing elevation of the fluid is shown in Figure 6. From this figure, one can see that combination of vertical and horizontal baffles is the most effective solution to mitigate sloshing effect especially at the small values of H_b / H. With the same height H_b, effect of vertical baffles is larger than that of horizontal baffle. It is also noted that the higher baffles are, the more significant the effect of baffles on sloshing elevation is for all cases of baffle application.

7. CONCLUSIONS

The complicated coupled sloshing-floating tank motion problem of baffled and un-baffled floating tanks is solved by using the FDM and hybrid frequency-time scheme. Some findings can be concluded. Sloshing effect may enlarge dynamic responses of the tank at frequencies near to the resonant area for surge and heave motions and at frequencies out of resonant areas for pitch motion. At frequencies near to the pitching resonant area, sloshing effect may damp out dynamic response of the floating tank. With the sloshing effects, the motion of the floating tank and liquid sloshing will have multi-resonant frequencies. The higher the wave amplitudes are, the larger the dynamic responses of the tank and sloshing liquid are. With nonlinear sloshing effects, the tank displacement and sloshing elevation are not proportional to wave amplitudes. The studies also show that the effects of baffles on dynamic responses of the coupled system become more significant when the dimension of baffles is increased. Among different types of baffles, the combination between vertical and horizontal baffles is a good solution to reduce sloshing free surface displacements.

8. ACKNOWLEDGMENTS

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REFERENCES

Cummins W (1962). The impulse response function and ship motions. Schiffstechnik, pp. 101-109.

Faltinsen OM (1978). A numerical nonlinear method of sloshing in tanks with two-dimensional flow. Journal of Ship Research. 22, pp. 193-202.

Kim Y, Nam BW, Kim DW and Kim YS (2007). Study on coupling effects of ship motion and sloshing. Ocean Engineering. 34(16), pp. 2176-2187.

Nakayama T and Washizu K (1981). The boundary element method applied to the analysis of two-dimensional nonlinear sloshing problems. International Journal for Numerical Methods in Engineering. 17, pp. 1631-1646.

Nichols BD, Hirt CW and Hotchkiss RS (1980). SOLA-VOF: A solution algorithm for transient fluid flow with multiple free-boundaries. Technical Report LA-8355. Los Alamos Scientific Laboratory, New Mexico, USA.

Ogilvie T (1964). Recent progress towards the understanding and prediction of ship motions. Proceedings of 5th Symposium on Naval Hydrodynamic, ONR, Washington, D.C., pp. 3-128.

Sun L, Zang J, Taylor RE and Taylor PH (2009). DIFFRACT program manual. University of Oxford, Oxford, UK.

Taghipour R (2008). Efficient prediction of dynamic response for flexible and multi-body marine structures. Ph. D. thesis, Norwegian University of Science and Technology.

Tuyen LV, Ang KK and Hai LV (2012). Hybrid frequency-time domain model for coupled sloshing-floating tank motion problem. Proceedings of the International Conference on Advances in Computational Mechanics (ACOME-2012), Ho Chi Minh, pp. 656-668.

Wang CZ and Khoo BC (2005). Finite element analysis of two-dimensional nonlinear sloshing problems in random excitations. Ocean Engineering. 32, pp. 107-133.