THE EFFECTS OF TANK SLOSHING ON LNG VESSEL AND FLOATING TERMINAL RESPONSES

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INTRODUCTION

In the conventional ship-motion analysis, the effects of inner free surface have been usually ignored. Recent experimental and numerical studies have shown that the coupling effect between liquid cargo sloshing and LNG(Liquefied Natural Gas) ship motion can be significant at certain frequency range of partially filled tanks. This is of great concern to the LNG FPSO/FSRU operation in the production site and offloading operation of LNG carriers close to LNG terminal. The coupling effects are expected to become more important as the size of LNG carriers significantly increases with rapidly growing demand.

The coupling between ship motion and sloshing has been studied by Molin et al(2002), Malenica(2003), and Newman(2005) based on linear potential theory in the frequency domain. In time domain, Kim et al.(2003,2007) studied the sloshing effect on ship motion with 2-D and 3-D viscous FDM sloshing codes. Lee et al.(2007) also investigated the sloshing effect of multiple tanks on ship's roll motion with 3-D FDM calculation, which is further extended in this paper to include two floating-body interactions. In the present study, a potential-viscous hybrid method for multiple-vessel responses with multiple tanks is developed. The ship motion is solved in time domain by using linear potential theory and three-dimensional panel method, while the liquid sloshing in the inner tanks is solved by 3D-FDM Navier-Stokes solver including free-surface nonlinearity through SURF scheme. However, for simplicity, the single-valued surface profile is assumed in the sloshing calculation i.e. very violent free-surface motions such as overturning and splash are not considered. For comparison, an equivalent linear potential program in frequency domain is independently developed to solve the same interaction problem assuming small liquid motions. When the inner-fluid motion is mild, both approaches should produce similar coupling effects unless viscous effects are not negligible.

In the present study, the ship and liquid-cargo motions are coupled in time domain by the kinematic and dynamic relations in that the vessel motions excite the tank sloshing, while the sloshing-induced loads in turn influence vessel motions. The calculated ship motions with or without considering liquid sloshing are compared with the model test results. The model test was conducted by MARIN as a part of SALT JIP (Gaillarde, 2004). The numerical results generally compare well with the measured data.

After verifying the single-body case through comparison with experimental data, the ship and liquid motion interactions are further extended to two floating body problems in side-by-side offloading arrangement. In this case, the LNGC motions can be increased by the two-body interaction effects and the increased motion can further excite the inner tanks and vise versa. In addition, the roll motion of LNGC can be excited by two-body interactions even in the head-sea condition, which is otherwise zero due to the geometric symmetry. Therefore, it is expected that the ship-motion and tank-sloshing interaction effects are even more pronounced during the side-by-side offloading operation.

NUMERICAL RESULTS AND DISCUSSIONS

In the present study, the interactions of floating offshore terminal and LNGC with two liquid tanks are considered. Fig. 1 represents the mesh generated for the two floating bodies in side-by-side arrangement. The length, breadth, and draft of the floating terminal and LNGC are 428m-70m-14.5m and 270m-43.4m-11.9m, respectively. The gap between the two bodies is 6m in water depth of 100m. The LNGC has two (40m-35.7m and 45.5m-35.7m) rectangular tanks inside. The distance from the keel to the tank bottom is 2.6m.

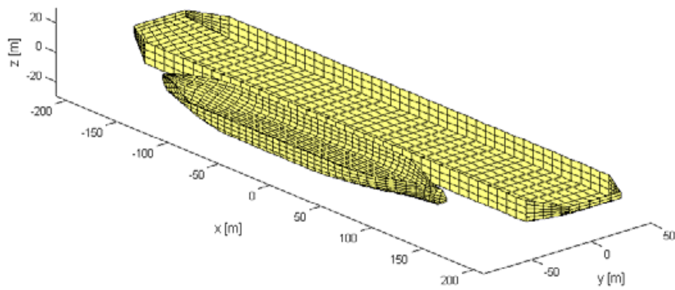

FIG. 1. GRID GENERATION OF HULL FOR 3D PANEL METHOD (NUMBER OF PANELS=1754).

The results of the diffraction/radiation analysis by WAMIT (Lee, 1995) of the two floating bodies include added mass and radiation-damping coefficients, RAOs(response amplitude operator), and wave-force LTFs(linear transfer function), and second-order mean drift forces. After Fourier transform of the frequency-domain equation, the equivalent time-domain equation including a convolution integral can be developed. The slowly varying drift motions are calculated by applying the so-called Newman's approximation method. The predicted RAOs of a barge-type FPSO (285m-63m-13m) of the same shape as the floating terminal compared well against Marin's experimental data (Lee, 2007). Fig.2 shows the effects of inner-tank sloshing on the Marin's FPSO roll motions at 18% fill ratio. The numerically predicted results with the present viscous-potential hybrid method in time domain agree better than the potential-theory-alone case in frequency domain when compared against the measurement.

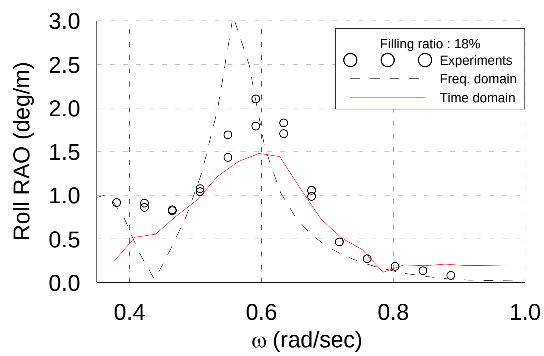

FIG. 2. MOTION-SLOSHING COUPLING EFFECT OF MARIN FPSO IN ROLL. (WAVE HEADING=90DEG)

In the following, the effects of liquid sloshing for Fig.1 arrangement are considered. First, LNGC alone under beam sea condition is presented in Fig. 3. The coupling in frequency domain is done by adding sloshing added mass to ship added mass with inner-free-surface hydrostatic correction, while the sloshing calculation in time domain is done by coupling CHARM3D (time-domain ship motion program, Kim et al., 1999) and ABSLO3D (time-domain sloshing program). When there is no sloshing fluid, both frequency domain and time domain results agree well and show roll natural frequency at 0.47 rad/s. If filling level is 18%, roll peak amplitude is reduced and the natural frequency is moved to 0.72rad/s. The frequency-domain result is over-predicted because of neglecting viscous and nonlinear sloshing effects. When the filling level is increased to 56%, two separated peaks appear and the second peak is observed at 0.9rad/s. The amplitudes of both peaks are reduced compared to that of 18% fill ratio. The RAOs of the time domain is obtained from the ratio of roll spectrum (generated from time histories) to incident wave spectrum. The input environment is JONSWAP spectrum with Hs=2m, Tp=12s, and enhancement parameter=3. The lowest and the second lowest sloshing roll natural frequencies of the tanks are 0.58/1.53 rad/s for 18% fill ratio and 0.86/1.85 rad/s for 56% fill ratio.

Next, the results of the LNGC connected by hawsers to the floating terminal in beam sea condition are shown in Fig. 4. The floating terminal has fenders and is moored at 100-m water depth. The reaction of hawsers and fenders are modeled by equivalent nonlinear springs (Lee, 2007). By comparing Fig.3 and 4, we can observe the two-body interaction effects during the side-by-side offloading operation. When there is no sloshing and viscous effect, it is confirmed that the time-domain and frequency-domain calculations produce the same RAOs.

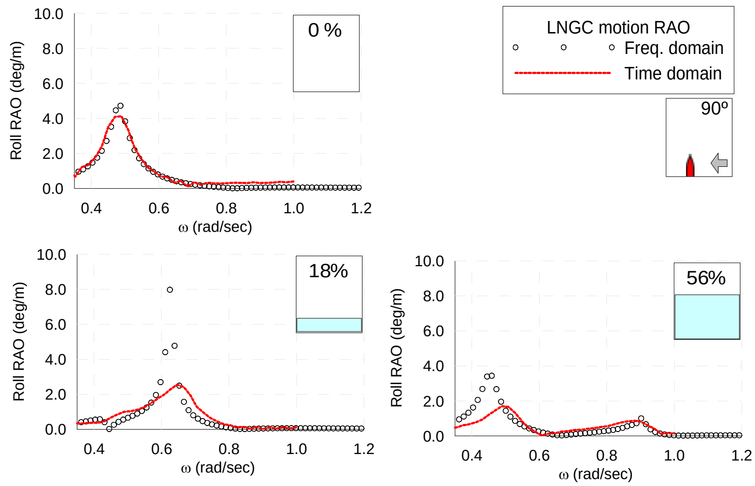

FIG. 3. MOTION-SLOSHING COUPLING EFFECT OF ROLL RAO. (LNGC ONLY, WAVE HEADING=90DEG)

In the multi-body case, due to the additional resonance among multiple bodies, more sharp peaks are present and the convergence of the corresponding convolution integral in time domain becomes slower than the single-body case. When irregular frequencies are not removed, it is very difficult to differentiate between the physical resonance peaks and non-physical irregular frequencies. So, irregular frequencies are all removed in a priori in the present calculations. When there is no sloshing fluid in Fig.4, the roll natural frequency is 0.47rad/s and the two-body interaction effects do not appear to be significant in this case. In case of 18% fill ratio, the roll RAO peak is split into two peaks at 0.43 and 0.61rad/s. In the LNGC only case (Fig.3), this split phenomenon was rather unclear. The second peak is caused by the lowest natural mode of the sloshing fluid at 0.585 rad/s. Due to the second peak, the RAO near 0.6-0.7rad/s is significantly increased compared to the bare-hull case without sloshing, which means that when the incident wave spectrum peaks near 0.6-0.7 rad/s, the LNGC roll motion is to significantly increase due to the sloshing phenomenon. Another small peak at 0.9rad/s appears to be caused by the two-body interaction effect. For the filling level 56% case, the weaker second peak is moved to 0.82rad/s, which is close to the lowest sloshing mode (0.86 rad/s) at that fill ratio. The second peak, however, does not play an important role in this case when compared to the 18% case. The largest peak amplitude near 0.52rad/s is significantly increased compared to that of LNGC-alone case with the same 56% fill ratio.

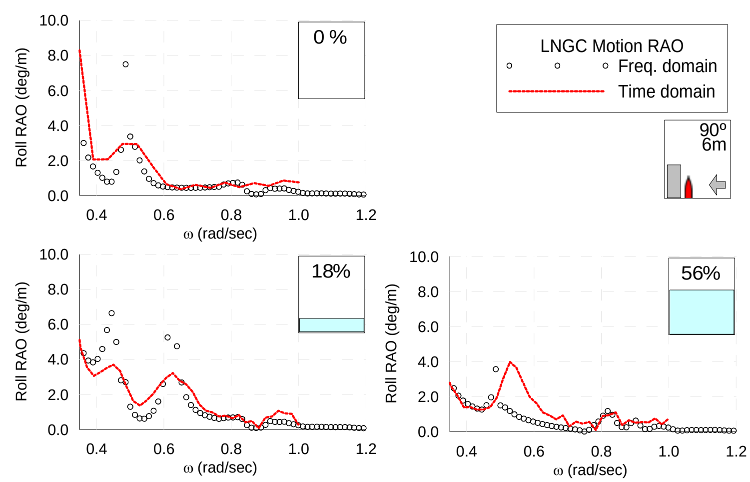

FIG. 4. MOTION-SLOSHING COUPLING EFFECT OF ROLL RAO. (LNGC WITH FT, WAVE HEADING=90DEG)

Since time-domain approach is adopted, the motion of the entire system including inner-fluid sloshing can be shown simultaneously in animation, which will help to better understand the overall physics. Fig.5 is the example of a snap shot for such an animation.

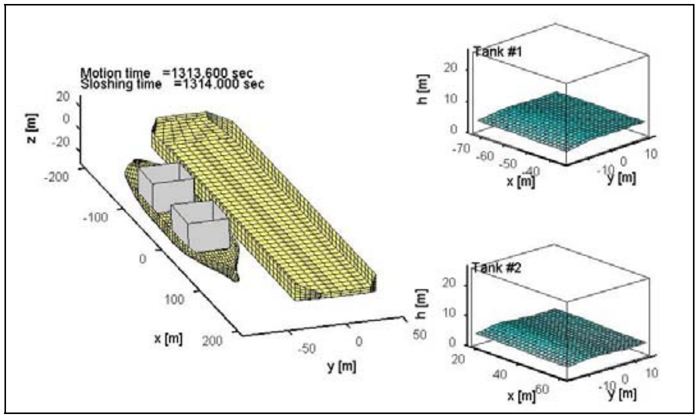

FIG. 5. SNAPSHOT OF MOTION-SLOSHING TIME DOMAIN ANIMATION.

CONCLUSIONS

The interaction effects between ship motion and inner-tank liquid sloshing are investigated by a newly developed potential-viscous hybrid time-domain computer program. The results are also compared with an independently developed linear-potential-theory-based code in the frequency domain. The time-domain sloshing program is based on the Navier-Stokes-equation solver including SURF method to include both viscous and nonlinear free-surface effects. During the time marching, the tank sloshing program is coupled with the vessel-motion program so that the influence of tank sloshing on vessel motions can be assessed. The inner-tank-sloshing effect is characterized by the increase in inertia forces (added mass) and the decrease in restoring forces. Although the frequency-domain analysis is based on linear potential theory, the qualitative interaction effects can be well captured. By using the potential-viscous hybrid method in time domain, we have better quantitative agreement compared with available experimental data since both viscous and nonlinear free-surface effects are included. The peak frequency of roll motions can be shifted due to the tank sloshing effect. The secondary peak appears near the sloshing natural frequency. The relocated peaks can appreciably increase vessel motions in certain frequency range. The liquid-sloshing and vessel-motion interactions can be further intensified in the case of multiple floating bodies.

ACKNOWLEDGEMENTS

This work was supported by the OTRC (Offshore Technology Research Center) and ABS (American Bureau of Shipping).

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