ICSV14
Cairns • Australia
9-12 July, 2007
14th International Congress on Sound & Vibration

TRANSIENT DYNAMIC RESPONSES OF AN INTERNAL LIQUID-LNG TANK-SEA WATER INTERACTION SYSTEM EXCITED BY WAVES AND EARTHQUAKE LOADS

Y. P. Xiong, J. T. Xing and M. Tan

School of Engineering Sciences, Ship Science, University of Southampton
Southampton, SO17 1BJ, UK
y.p.xiong@ship.soton.ac.uk

Abstract

Sloshing problems in partially filled large LNG carriers are of increasing concern because sloshing loads may endanger LNG carriers in operations. Currently, most investigations on sloshing problems mainly focus on the analysis of liquids in rigid tanks which omitted fluid-structure interactions. Based on a mixed displacement–pressure finite element method developed, the authors recently investigated the natural vibration of an internal liquid–elastic structure–external water interaction system. The simulation demonstrated the significance of the interactions between internal liquid sloshing modes and floating modes of LNG tanks on the external sea water. This paper further studies the dynamic responses of this integrated system subject to sea waves and earthquake excitations. The sea wave loads are modelled by pressure waves with different frequencies applied to a boundary of the external water domain and the ground motion data recorded from El-Centro earthquake is used as an earthquake load to the system. The numerical analysis on the dynamic responses of this coupled system further confirms the necessity to consider fluid-structure interactions for safe LNG ship designs.

1. INTRODUCTION

Sea-wave and earthquake induced sloshing problems in partially filled large LNG carriers are of increasing concern because of the following reasons: 1) the rapid growing LNG market demands new LNG carriers with larger cargo capacity and flexible filling levels in partially loaded conditions; 2) the increasing size of a LNG carrier consisting of thin metal membrane and flexible materials decreases the system natural frequencies approaching to wave exciting frequencies which may cause resonances producing extremely large dynamic loads and affecting ship's motion and stability; 3) the demand for floating production storage and offloading (FPSO) units designed to withstand severe sea states during operation. To address these developing requirements, naval architect has to consider a dynamic design of LNG ships to understand the natural dynamic behaviours of LNG ships operating in sea-ways.

The dynamic analysis of liquid filled LNG tank ships on the sea is a typical fluid-structure interaction problem which necessitates interdisciplinary studies relating to the fluid and flexible structure as well as their physical coupling mechanisms. Due to the complexities of the problems, the earlier studies mainly involved the sloshing problems of the liquid in a rigid container where the fluid-structure interactions were neglected [1-3]. The detailed descriptions on theory of sloshing dynamics in various rigid containers as well as historic publications can be found in a review paper by Faltinsen [4] and a book by Ibrahim [5].

For the safety of the designed tank operating in complex marine environments, designers are required to accurately predict the dynamic behaviours of an integrated liquid – tank interaction system including the effect of fluid-structure interactions. For almost all problems involving fluid-structure interaction dynamics, analytical solutions are not available and recourse to numerical solutions or experimental studies is the only way forward. With the development of computational techniques, more effective numerical methods on sloshing simulations have been reported [6-12]. For example, the book [7] presented some detailed methods leading to the numerical modelling of linear natural vibration analysis of elastic structures coupled to internal fluids. Based on linear approximations, a wide selection of fluid-solid interaction problems have been well formulated and solved using a mixed finite element approach [10-11], in which the displacement in the elastic solid and pressure in the fluid are adopted as variables. Based on this mathematical model and the software FSIAP [13], our previous investigations on the sloshing mechanisms of liquid-container interaction systems [14-17] have shown that the sloshing frequencies of the liquid are almost not affected by structures having a first natural frequency much higher than that of liquid sloshing frequency. However, for larger and flexible tanks as occur in LNG ships, the floating frequencies of the ship are normally of a similar low value to the sloshing frequencies of the liquid in tanks. Therefore, the coupling between the sloshing liquid, the floating structure and seaway is of importance in characterising the dynamic behaviour of the total system. To examine this, a numerical study on natural dynamic characteristics of an integrated liquid- elastic LNG tank-water interaction system was carried out [18]. The present paper intends to further investigate into the dynamic responses of this integrated system subject to sea waves of different frequencies and earthquake loads to reveal the effects of the complex interactions on the dynamic loads.

2. NUMERICAL MODELLING

A generalized LNG liquid-elastic tank-water interaction system investigated in [18] is shown in Fig.1. It consists of a flexible tank of mass density ρ_s within a domain Ω_s and boundary $S_T \cup S_w \cup \Sigma$ with unit normal vector ν_i as shown. The internal liquid and external water are considered as two fluid subdomains identified by super index $(I = 1{,}2)$. The fluid (I) is in a fluid domain $\Omega_f^{(I)}$ enclosed by its boundary $\Gamma_f^{(I)} \cup \Gamma_p^{(I)} \cup \Gamma_w^{(I)} \cup \Sigma^{(I)}$ with a unit normal vector $\eta_f^{(I)}$. In general, the system may be excited by external dynamical forces $\hat{T}_i$, $\hat{f}_i$, $\hat{p}$ and ground acceleration $\hat{w}_i$, (i = 1, 2, 3). Using the displacement of solid structures and the dynamic pressure of fluids, the papers [10,11] presented a variational principle describing the dynamics of complete coupled fluid-structure interaction systems. The derivation of mathematical equations and finite element formulation are neglected herein. The interested readers may refer to the original publications or to a short summary of the model given in the papers [19]. Based on this variational principle and finite element methods, a mixed finite element – substructure / subdomain method as well as the computer code FSIAP [13] were developed and validated [11]. Further validations can be found in previous papers [14-19] in which sloshing frequencies of a 2-D section of a LNG tank, a spherical shell tank and a 3-D rectangular tank were calculated and compared with the available theoretical, experimental and other numerical results. The comparison demonstrates that the sloshing frequencies obtained using FSIAP are more accurate than other numerical approaches [18].

3. NUMERICAL ANALYSIS

Figure 2 shows the geometrical size of a liquid filled tank which is incorporated into an integrated internal liquid-elastic tank-external water interaction system idealized by a finite element mesh shown in Fig.3. The data used in the simulations are as follows: *external water domain*: H_S = 64m, L = 120m; *tank- internal water domain*: H = 30m, h_l = 4m, h_u = 9m, B_l = 32m, B_u = 22m, b = 40m. The tank is treated as a uniform elastic structure of equivalent thickness 0.30m, Young's modulus $E = 9.81\times10^{5}\,\mathrm{N/cm^2}$, Poisson ratio $\mu = 0.31$ and mass density $\rho_s = 2.4\times10^{-3}\,\mathrm{Kg/cm^3}$. The internal fluid is a Liquefied Natural Gas of mass density $\rho_g = 4.74\times10^{-4}\,\mathrm{Kg/cm^3}$ and speed of sound $C_g = 1700\,\mathrm{m/s}$. The external fluid is considered as the sea-water of mass density $\rho_w = 1.025\times10^{-3}\,\mathrm{Kg/cm^3}$ and speed of sound $C_w = 1430\,\mathrm{m/s}$. The draught is 4m for the empty tank and 11m for a 50% filling level h_f = 15m, respectively. Fig.2 also indicates the locations of the selected displacement response points 13, 45,105 and 172 on the tank and the pressure response points P335, P367, P374 and P541, P547 and P551in the internal and external fluid domains, respectively.

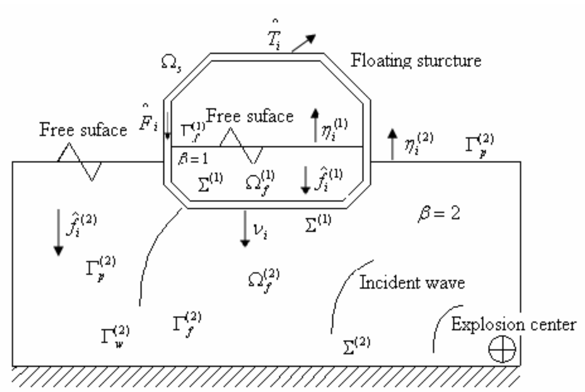


Figure 1. A general LNG ship-water interaction system.

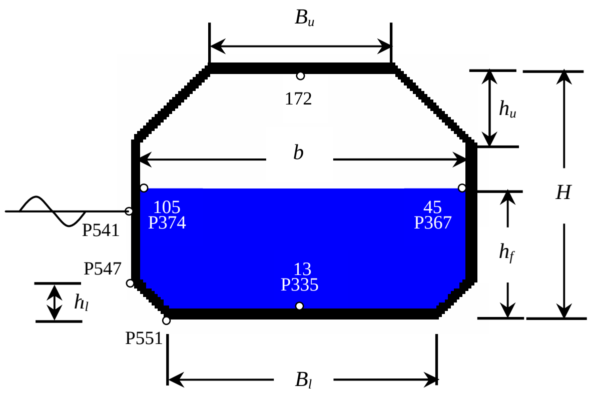


Figure 2. Geometrical size of a filled tank.

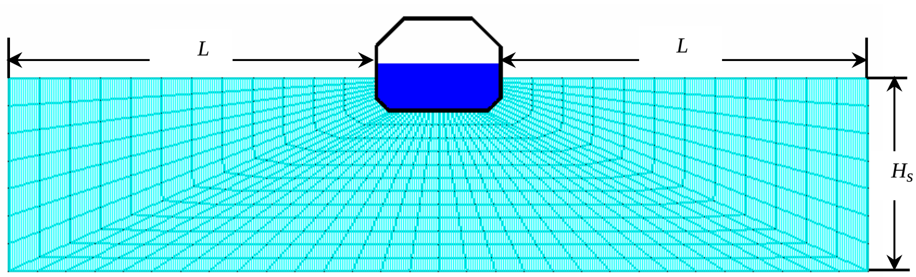


Figure 3. The finite element idealization of an internal liquid – LND tank – external water system.

The tank is modelled using 104 four-node plane strain elements involving a total of 208 solid nodes. The internal liquid domain is divided into 336 four-node plane pressure elements with a total of 375 nodes and the external water domain is idealised by 384 four-node plane pressure elements with a total of 429 nodes. On both internal and external fluid-solid interaction interfaces, the corresponding interface coupling elements are used to realise fluid-solid interaction conditions.

3.1 Natural Vibration Characteristics

As shown in Fig.3 the integrated internal liquid - elastic LNG Tank - external water interaction system includes two separate free surfaces in the internal liquid and external water domains, respectively. As a result of this, a large number of sloshing modes exist. As presented in the paper [18], the frequency of the 25-th mode of this integrated system is only 0.281Hz. For the obtained modes, Mode 2 shows the tank and external water in an out-of-phase rolling motion. Mode 3 represents a symmetric system motion of the internal liquid, external water surface having two nodes together with the tank in vertical heave motion experiencing little elastic deformation. Similar symmetric patterns are observed in the 6th, 10th 14th and 17th modes. Fig. 4 shows four selected modes in which Mode 7 has an anti-symmetric pattern with both sloshing motions of internal liquid and external water whereas Mode 9 describes a tank rolling motion coupling with sloshing effect of internal liquid. Mode 16 shows a deformation of elastic tank in the type of horizontal expansion and vertical contraction. A high order sloshing mode, coupling with the tank rolling motion, in both the internal and external liquid domains are observed in Mode 21.

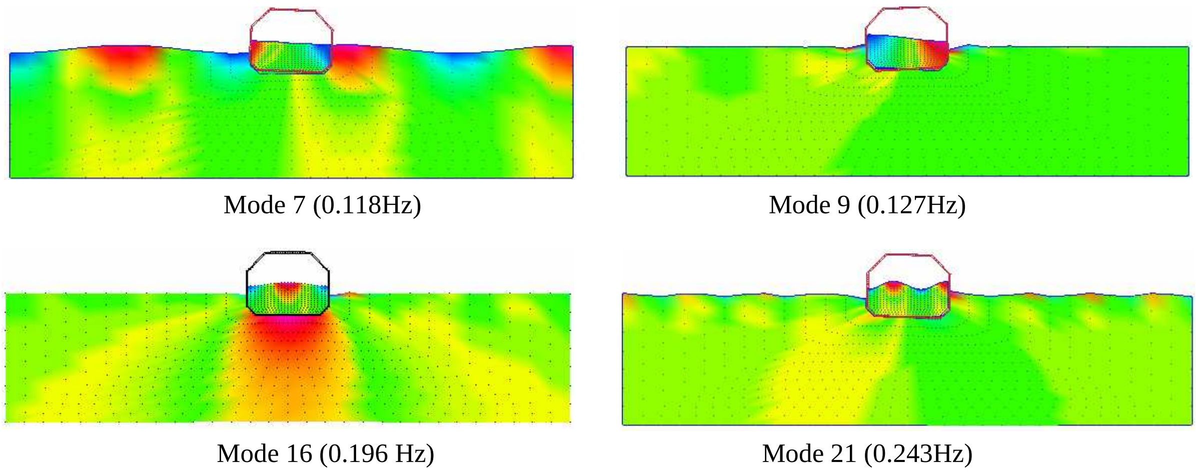


Figure 4. Selected modes of internal liquid-tank-external water interaction system.

3.2 Dynamic Response to Regular Sea Waves

To study dynamic responses of the integrated system, a unit amplitude sinusoidal pressure wave $p = \cos 2\pi ft$ is uniformly distributed along the left vertical boundary of the external water domain to excite the motion of the system. To examine the sloshing dynamic response, we choose two lower frequencies 0.5 Hz and 0.1 Hz to conduct the numerical simulations. The chosen excitation pressure wave is applied to the system at the initial time t = 0 at which the amplitude and the first time derivative of the excitation function $p = \cos 2\pi ft$ take the value $p = 1$ and $\dot{p} = 0$ as an impulse load to simulate possible sudden loads existing in complex sea environments. The calculated dynamic response is a summation of the responses of all modes of the system produced by the initial conditions and the forced dynamic responses having a same frequency of the excitation pressure. The initial responses tend to zero if damping is considered. For the case of excitation frequency 0.5 Hz damping is neglected whereas for the excitation frequency 0.1 Hz, which is near to the first sloshing frequency 0.127 Hz of the system and hence results a very big dynamic responses due to the resonance, the mode damping coefficients of value 0.2 [21] is added to all 60 retained modes to suppress this resonance.

The selected points to obtain the time histories of dynamic displacement or pressure responses are indicated in Fig.3. Figure 5 shows the vertical and horizontal displacement responses at the selected points on the tank system with an added mode damping factor 0.2 and excited by the pressure wave of frequency 0.1 Hz. Due to the damping effect, the response components caused by the initial conditions are damped out and stable forced responses are reached. As shown in Fig. 5, the tank vertical displacement amplitude of the stable forced response at Point 45 is about 4 m which could affect the safe operation of the LNG tank. As indicated in paper [18] that the first sloshing frequency 0.127 Hz of the system is produced due to the external water coupling with the internal liquid of the filled tank. Therefore, it is necessary to consider the integrated system interactions in the design of a LNG ship. To examine the transient dynamic pressure response caused by the initial impulse load and damping effect, Fig.6 shows the dynamic pressures at the selected points on the tank wall during the first 20 seconds with different mode damping factors. As mentioned previously, due to the initial conditions, a higher frequency transient component of about 0.8 Hz is observed in Fig.6a), which corresponds to the first elastic tank mode in which the tank bottom experiences an obvious deformation [18]. The damping effects on the pressure responses can be easily seen in Fig.6, i.e., sloshing pressures on the side tank wall are greatly reduced as damping increased.

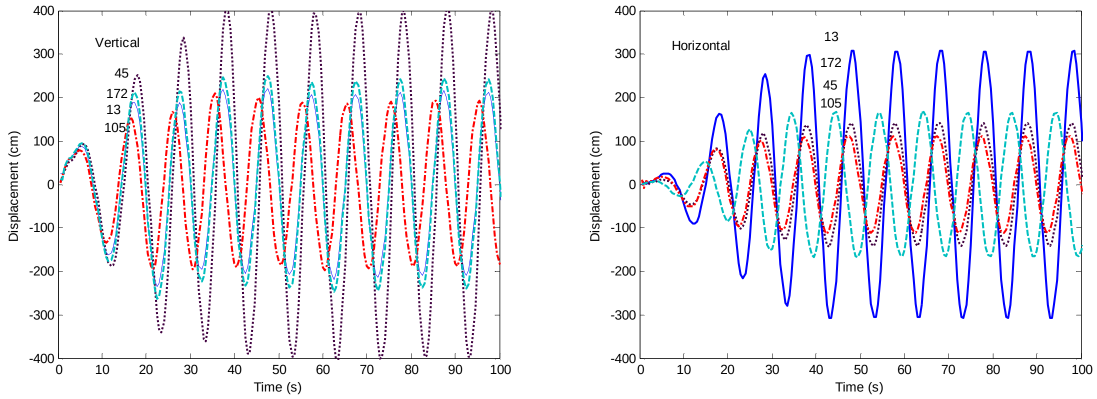
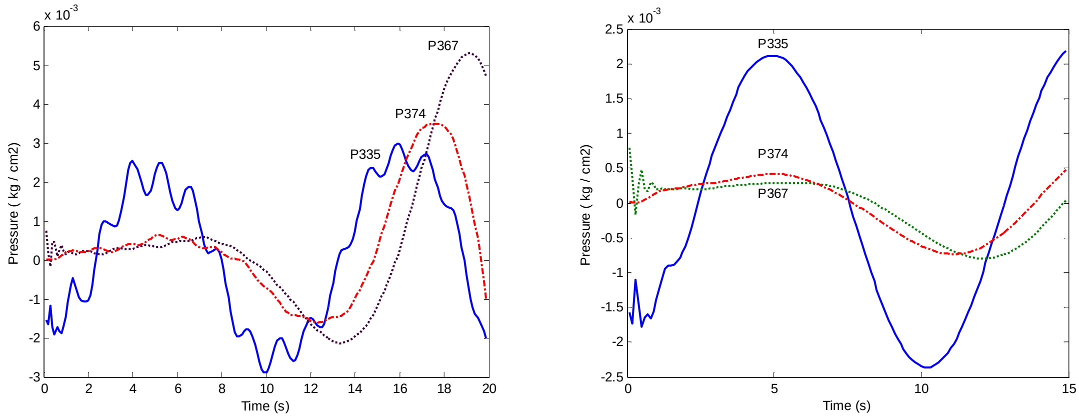


Figure 5. Vertical and horizontal displacement responses at chosen points of the tank (f = 0.1Hz).



a) b)

Figure 6. Dynamic pressure response curves at the selected points on the internal tank wall at frequency f = 0.1Hz: mode damping factor a) 0.05 ; b) 0.2 .

Figures 7 and 8 present the dynamic displacement and pressure responses at the selected points of the system, with no damping considered, excited by the pressure wave of frequency 0.5 Hz. Comparing with Figs.5 and 6, we find that both the amplitudes of the displacement and pressure responses are small due to no resonance. It should be noted that only unit amplitude of wave excitation is used in this example. For practical cases, the dynamic responses will be amplified proportionally to the amplitude of excitation forces and therefore large dynamic forces to LNG tanks might be experienced although there is no resonance. It is also observed from Fig.7 that the horizontal displacement responses at two opposite points 45 and 105 of the tank walls, as well as the vertical displacement responses at the top point 172 and bottom point 13 are all out of phase, respectively. This is caused by the response components of the Mode 16 of the coupling system. This mode shows a tank elastic deformation in the type of horizontal expansion / contraction and vertical contraction / expansion.

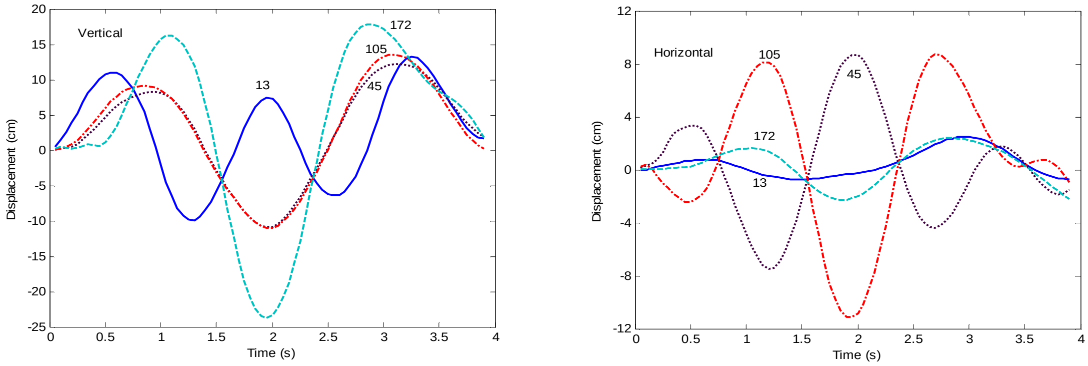


Figure 7. Vertical and horizontal displacement responses at chosen points of the tank ($f = 0.5$ Hz).

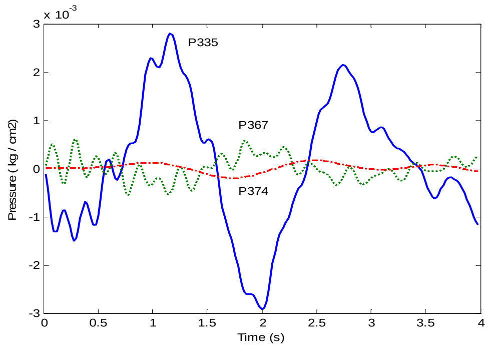


Figure 8. Pressure responses at selected points on internal tank wall ($f = 0.5$Hz).

3.3 Dynamic Response to Earthquake Excitation

As an example, the time history data of the El Centro East-West horizontal earthquake [21], shown in Fig. 9a), is used as a boundary acceleration applied to both left and right vertical boundaries to simulate earthquake excitation to the system, which may be considered as a practical case of a LNG ships in a port. The maximum peak acceleration is about 0.22g and the dominant frequencies are 3.9 Hz, 9.8 Hz, 37 Hz and 48 Hz as shown in the power spectrum in Fig. 9b).

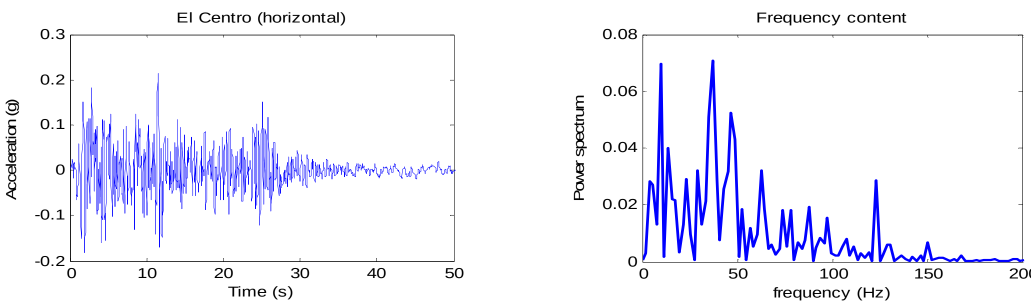


Figure 9. El Centro East-West earthquake data [21]: a) time history; b) power spectrum.

The dynamic displacement and pressure responses at the selected points of the system are shown in Figs.10 and 11, respectively. It can be seen from these two figures that the amplitudes of the displacement and the pressure are relatively small compared with the case of harmonic pressure wave excitations in section 3.2, because the natural sloshing frequencies of the system are much lower than the dominant frequencies around which the main earthquake energy is distributed.

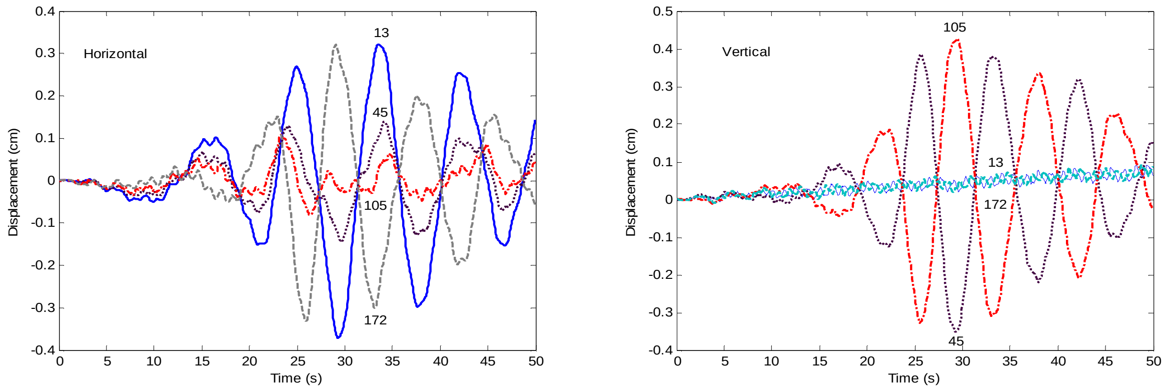
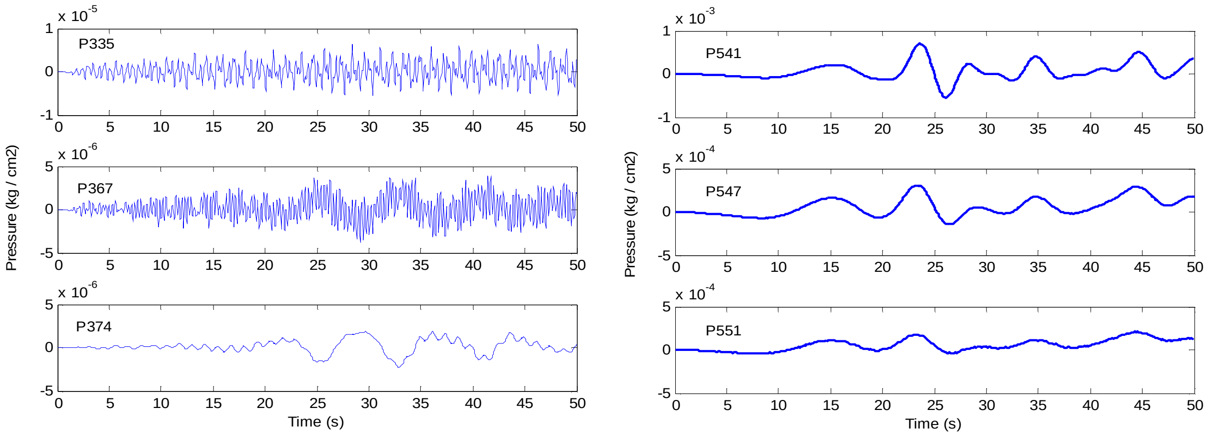


Figure 10. Horizontal and vertical displacement responses at the chosen points of the system excited by the earthquake ground motion.



a) b)

Figure 11. The dynamic pressure responses at selected points on internal a) and external b) tank walls due to the earthquake ground motion excitation.

4. CONCLUSIONS AND DISCUSSIONS

This paper deals with sloshing dynamics of an integrated internal liquid–elastic tank–external water interaction system subject to regular pressure waves and earthquake excitations. It has demonstrated that due to the complex interactions between the external water, internal liquids and elastic tank, the mode density of natural frequencies of the system is greatly increased. There exist a large number of sloshing modes in the frequency range of sea waves, therefore possibilities of sloshing resonances are increased. The calculation on the dynamic response of the system excited by the pressure wave of frequency 0.1 Hz near to the first sloshing frequency of the integrated system shows this possible resonance, which produces larger hydrodynamic forces and tank displacements. For safe design and operations of LNG ships, to avoid any natural frequencies with hidden sloshing resonance is an essential problem to be addressed early in the design stage.

The numerical simulations have demonstrated that the developed mixed displacement and pressure finite element method and the corresponding software provide an essential mean to investigate the detailed natural characteristics and dynamic responses of the integrated liquid-tank-sea water interaction system. This enables LNG ship designers to foresee possible sloshing resonances and to investigate methods to avoid these resonances in the stage of LNG ship designs.

Nonlinear free-surface effect is not considered in the present study. To predict the impact loads on LNG carriers operating at sever sea states, non-linear analysis may be needed.

REFERENCES

[1] N.N.Moiseev, "Introduction to the theory of oscillations of liquid-containing bodies", *Advances in Applied Mechanics*, **8**: 233-289 (1964).

[2] H.N.Abramson, "The dynamic behaviour of liquids in moving containers, with applications to space vehicle technology", *Technical report NASA-SP106*. (1996).

[3] B.F.Chen and H.W.Chiang, "Complete two-dimensional analysis of sea-wave-induced fully non-linear sloshing fluid in a rigid floating tank", *Ocean Engineering* **27**: 953-977 (2000).

[4] M.O. Faltinsen, and O.F. Rognebakke, Sloshing, keynote lecture, *NAV '2000*, 2000, Venice, Italy.

[5] R.A. Ibrahim, *Liquid sloshing dynamics,* Oxford: Cambridge University Press, 2005.

[6] G.X.Wu, W.Q. Ma and R. Eatock Taylor, "Numerical simulation of sloshing waves in a 3D tank based on a finite element method", *Applied Ocean Research*, **20**: 337-355(1998).

[7] H.J.P. Morand and R. Ohayon, *Fluid Structure Interaction* London: John Wiley & Sons, 1995.

[8] M.Arai, , L.Y. Cheng, A. Kumano and T. Miyamoto, "A technique for stable numerical computation of Hydrodynamic impact pressure in sloshing simulation. *J. Soc. Naval Arch. Japan*, **191**: 299-307(2002).

[9] S. Aus der Wiesche, "Computational slosh dynamics: theory and industrial application", *Computational Mechanics* **30**: 374-387(2003).

[10] J.T.Xing and W.G.Price, "A mixed finite element method for the dynamic analysis of coupled fluid-solid interaction problems", *Proc. R. Soc. Lond.*, A**433**: 235-255 (1991).

[11] J.T.Xing, W.G.Price and Q.H.Du, "Mixed finite element substructure-subdomain methods for the dynamical analysis of coupled fluid-solid interaction problems", *Phil. Trans. R. S. Lond.* A **354**, 259-295 (1996).

[12] J.T.Xing, W.G.Price and A. Wang, "Transient analysis of the ship-water interaction system excited by a pressure water wave", *Marine Structures*, **10**:305-321 (1997).

[13] J T Xing, "*User manual: fluid-structure interaction analysis program-FSIAP*", School of Engineering Sciences, University of Southampton, UK (2005).

[14] J.T.Xing, Y.P.Xiong, M.Tan and M.Toyota, "Vibration problem of a spherical tank containing jet propellant: numerical simulations", Ship Science Report No. 141, ISSN0140-3818, December 6, 2006. School of Engineering Sciences, University of Southampton.

[15] Y.P.Xiong, J.T. Xing, and W.G. Price, "The interactive dynamic behaviour of an air-liquid-elastic spherical tank system", *Proc. of 2006 ASME Pressure Vessels and Piping Division Conf.*, Vancouver, BC, Canada, 23-27 July 2006, pp.1-8 (2006).

[16] M. Tan, M., Y.P. Xiong, J.T. Xing and M.Toyoda, "A numerical investigation of natural characteristics of a partially filled tank using a substructure method". In *Proceedings of Hydroelasticity '2006: Hydroelasticity in Marine Technology*. Beijing, China, National Defence Industry Press, 181-190 (2006).

[17] M. Toyota, M., J.T. Xing, Y.P. Xiong and M.Tan, "An experimental study on vibration characteristics of a thin spherical tank–water interaction system". In, *Proceedings of Hydroelasticity '2006: Hydroelasticity in Marine Technology*. Beijing, China, National Defence Industry Press, 191-198 (2006）.

[18] Y.P.Xiong and J.T. Xing, "Natural dynamic characteristics of an integrated liquid – LNG tank – water interaction system", *Proc. of International Conference on Advancements in Marine Structures*, Glasgow, UK, 12-14 March 2007, pp.313-321 (2007).

[19] J.T.Xing, Y.P.Xiong and M. Tan, "The natural vibration characteristics of a water-shell tank interaction system", *Proc. of International Conference on Advancements in Marine Structures*, Glasgow, UK, 12-14 March 2007, pp.305-312 (2007).

[20] Y. Tang, R.A. Uras and Y.W.Chang, "Effect of viscosity on dynamic response of a liquid storage tank", Argonne National Laboratory Report, No.930702-33, Argonne, Illinois (1993).

[21] T. Irvine, Vibration data. EL Centro Earthquake Page: www.vibrationdata.com/elcentro.htm.