Proceedings of the 37th International Conference on Ocean, Offshore & Arctic Engineering
OMAE 2018
June 17-22, 2018, Madrid, Spain

OMAE 2018-78673

DYNAMIC RESPONSE ANALYSIS OF FLOATING STORAGE TANK SYSTEM CONSIDERING HYDRODYNAMIC AND MECHANICAL INTERACTIONS

Ling Wan
Newcastle Research & Innovation Institute Pte Ltd (NewRIIS), Newcastle University in Singapore

Chi Zhang
Department of Civil and Environmental Engineering, National University of Singapore

Allan Ross Magee
Department of Civil and Environmental Engineering, National University of Singapore

Jingzhe Jin
Sintef Ocean
Trondheim, Norway

Mengmeng Han
Department of Civil and Environmental Engineering, National University of Singapore

Kok Keng Ang
Department of Civil and Environmental Engineering, National University of Singapore

Øyvind Hellan
Sintef Ocean
Trondheim, Norway

ABSTRACT

For better utilization of ocean and coastal space, hydrocarbon products can be stored in the floating tanks, which can be enclosed by barge system. The barge system can be moored through pile foundations. The tanks are moored through marine fenders connected to barges. In the system, hydrodynamic and mechanical interaction problems are involved. Different scenarios including two barge, three barge and four barge systems are investigated. In addition, one tank plus four barge system are also studied. Hydrodynamic interactions between different bodies are firstly studied to investigate the significance of interaction. Different barge configurations are then considered in terms of mechanical interaction significance. Tank dynamic responses with and without hydrodynamic interaction are evaluated.

Key words: hydrodynamic interaction, mechanical interaction, barge configuration, dynamic response analysis

INTRODUCTION

Land is becoming very scarce and expensive in coastal cities such as Singapore, Osaka, etc. Very large floating structures (VLFSs) [1, 2] are more suitable for offshore space exploitation compared with conventional land reclamation approach which is becoming time-consuming, environmentally unfriendly and expensive as the water depth gets larger. There are different types of VLFSs including floating bridges [3, 4], floating entertainment facilities, floating storage facilities, floating city, floating fish farm [5, 6], etc. One VLFS concept was proposed and developed for storing crude oil or hydrocarbon in the coastal region in Singapore with a potential application and deployment also in other coastal regions. This study will focus on the investigation of some basic features and scenarios in this application. Until now, there are only two floating fuel storage facilities in the world and both of them are located in Japan: one is Kamigoto Oil Storage Base and the other is Shirashima Oil Storage Base [7], which are shown in Figs. 1a and 1b, respectively.

Figure 1. (a) Kamigoto (left), (b) Shirashima oil storage bases (right)

Figure 2 shows the floating storage facility that was proposed for Singapore coastal waters. It consists of several modular floating tanks assembled together with barges that provide space for the associated equipment and workers quarters. Each tank in this concept is moored by mooring fenders around its periphery. It is noted that there are several bodies in close proximity in this proposed concept. The hydrodynamic interactions can be important, and can affect the body dynamic performance. The hydrodynamic interaction effects are investigated in this study.

The hydrodynamic interaction has been widely investigated in scenarios with side-by side operations between two floating bodies carried out. Buchner etc. [8] carried out numerical and experimental study on two body side-by-side mooring to an FPSO, and found that two floating bodies in close proximity results in a strong and complex hydrodynamic interaction and numerical exaggeration, the viscous effects of water between bodies should be considered, and a free surface lid method is deployed. The complete retardation functions matrix should be taken into account when using time domain model, since the coupling terms play vital roles. This was also found by Huijsmans etc. [9] and Koo etc. [10], and it is also suggested that finer mesh of panels should be used if it is calculated using standard linear diffraction codes when two bodies are in close proximity. Hong etc. [11] also did numerical and experimental studies on hydrodynamic interaction of side-by-side moored multiple vessels. In his study, he used higher order boundary element method (HOBEM) and achieved satisfactorily good agreements with experiments, since HOBEM can represent abrupt change of body geometry by using higher-order interpolation functions [12]. In the constant panel method, besides the lid method, pressure damping model and Newtonian Cooling damping model were introduced by Markeng, etc. [13] to suppress the gap resonance by introducing the free surface damping model in the simulation. Similar method was also applied through dissipation term in the fluid by a dissipation zone in HydroStar [14] developed by BV. In this study, a Newtonian Cooling damping model with different damping parameters are applied. Besides the hydrodynamic interaction, different barge configurations also influence barge dynamic performance.

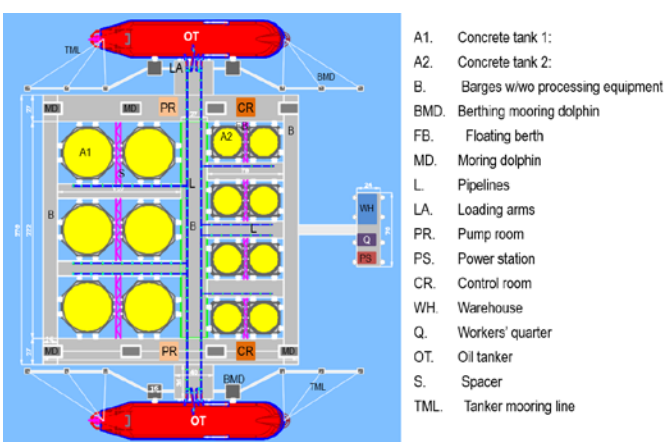

Figure 2. Proposed floating oil storage facility

Fender system [15] is used in the mooring of the tanks inside the concept. The fender can dissipate energy from ship or tank impact, and can also provide stiffness which affects the tank dynamic properties. In addition, fenders can also induce local stress due to relatively small contact area [16], and this should be taken into consideration from structural point of view. The fender system parametric design are investigated by Wan etc. [17]. In this paper, fenders are used in the study for tank dynamic response analysis. To prevent some disadvantages of using fender system, a mooring rope combined with fender system is proposed [18].

NUMERICAL MODEL

Time domain model is more applicable [19] for cases with viscous effect, nonlinear mechanical couplings, transient loading events etc.. Hydrodynamic properties of the bodies are firstly calculated in frequency domain, and then time domain model can be established through retardation functions [20]. When there is liquid in the tank, free surface effects may also influence the tank dynamic motions under partially filled condition, an engineering approach of considering this free surface effect in time domain model is proposed in [21]. In frequency domain, simulation is carried out using Newtonian cooling damping model that a dissipation term is introduced into the kinematic free surface condition. This parameter is denoted as ε in this study. Hydrodynamic properties of all the bodies involved are then transferred to time domain and the complete retardation function matrix are taken into consideration, which is critical for the reasonable prediction of the dynamic responses involving hydrodynamic interactions. Mechanical couplings or mooring system are then modelled.

Scenarios with two barge parallel arranged are firstly studied in terms of hydrodynamic excitation forces, and added mass as well as damping values considering viscous effects; then another barge perpendicular to the first two barges are incorporated, mechanical couplings are also introduced; four barge system is introduced consequently; at last, a large tank mooring by fender system is simulated in the four barge frame, and the results are compared with single large tank case without any interference by the barge system. The barge dimensions are shown in Table 1.

Table 1. Barge dimensions

	Length [m]	Breadth [m]	Height [m]	Draft [m]
BARGE 11/12	145.6	30	6	4
BARGE 21/22	110	20	6	4

Energy dissipation zone is deployed between the bodies, covering the space among the barges. The layout studied in this work is shown in Figure 3. The time domain simulation is carried out in SIMA [22] code developed by Sintef Ocean (Previously MARINTEK). Barge 11 and barge 12 are moored by two pile foundations, to provide horizontal stiffness. The pile foundations are simply modelled by a stiffness relationship. On each pile, two contact points are distributed in the vertical direction to provide restoring moment on the barge. The stiffness for each contact point is 1×10^5 kN/m in the pile modelling. In the three and four barge configurations, the barge 21 and barge 22 are connected to barge 11 and barge 12 through mechanical couplings. In the mechanical couplings, there are two coupling points for each connection, with the stiffness of 1×10^4 kN/m for each point. A large empty tank is employed in the last configuration moored by marine fender system, with fender stiffness of 1×10^4 kN/m. In addition, a single large empty tank moored by fenders without the barge frame interaction is also investigated. The stiffness parameters are not the optimum values, but are the reasonable values based on the trial and error iteration. Water depth is assumed to be 20 m. Incoming wave direction of 0 degree is investigated.

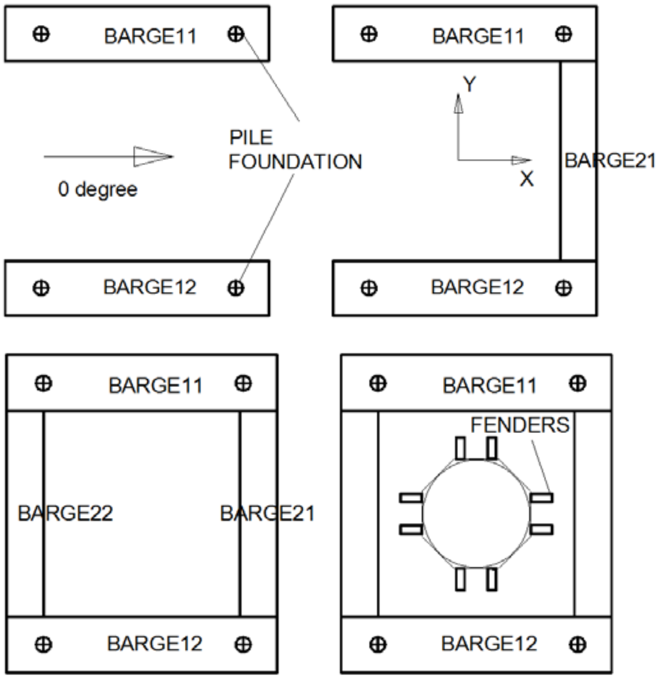

Figure 3. Scenarios with different barge layouts: two-barge (top left), three-barge (top right), four-barge (bottom left), four-barge with large tank (bottom right)

The 100 year return period wave condition is used with Hs=2m, Tp=6s, and JONSWAP spectrum is applied. Under this condition, 1 hour steady state simulation is carried out. Dynamic motion results are the focus of this study. Statistical results and time series show hydrodynamic interaction effect and mechanical coupling effect.

HYDRODYNAMIC AND MECHANICAL INTERACTION EFFECT IN BARGE SYSTEM

A single-barge case, two-barge case with no dissipation zone, and two-barge case with dissipation parameter ε of 0.05 and 0.1, respectively are investigated, and the added mass in surge and heave directions, as well as the wave damping in heave direction for barge 11 are shown in Figure 4, Figure 5 and Figure 6 to investigate the hydrodynamic interaction effects. It can be seen that the heave added mass and wave damping are significantly influenced by the existence of barge 12, especially in some specific periods which are considered as the different resonant periods of fluids between the barges. With the damping factor applied, the oscillation peaks are suppressed. For wave periods larger than 13s, the A33 and B33 are significantly different between single-barge and double-barge cases. These differences will affect the responses of the barges to various extends.

Time domain simulations of cases in Figure 3 are investigated in sequence. With the variation of damping parameter, the barge 21 motion statistical results (maximum, minimum and standard deviation) of the three-barge system case is shown in Figure 7. The viscous parameters are 0, 0.05 and 0.1 respectively. It can be seen that with the viscous parameter variation, the barge dynamic responses are also changed; however, the difference is not as significant as the variation in added mass and damping. One reason could be that the most significant variation occurs in some specific wave period, while the statistical values show results in an average sense under sea state basis.

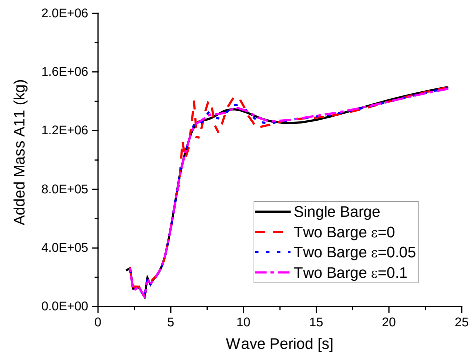

Figure 4. Surge added mass A11 of barge 1 under different conditions

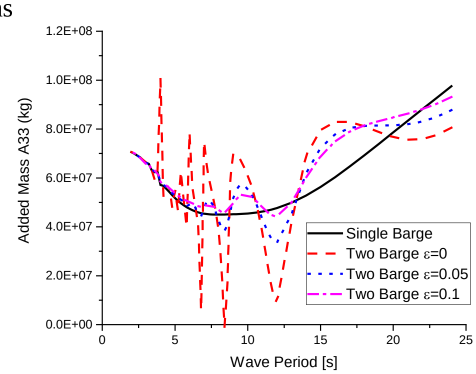

Figure 5. Heave added mass A33 of barge 1 under different conditions

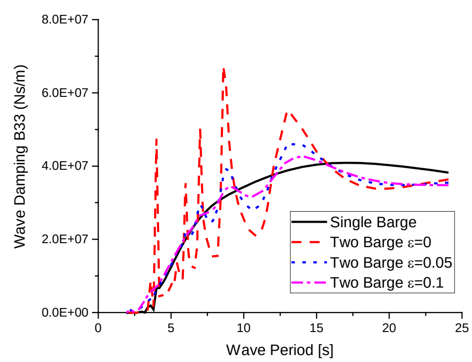

Figure 6. Wave damping in heave B33 of barge 1 under different conditions

For different barge configurations shown in Figure 3, due to different number of barges and mechanical coupling applied between them, the dynamic responses also show different features. The surge and heave motion statistical results of barge

11 in different barge cases with viscous parameter of 0.1 are shown in Figure 8 and Figure 9. The influence of the other barges on barge 11 is significant, especially in heave. With the increase of the barge number, the significance of influence is also larger. This is due to the hydrodynamic interaction and mechanical coupling forces introduced by the additional barge in y direction, i.e., barge 21 and barge 22. For the four-barge case, the time history of the four barges, i.e., barge 11, 12, 21 and 22 are shown in Figure 10. It can be seen that the motions of barge 11 and 12 are the same due to symmetry. The motions of barge 21 and 22 are larger than that for barge 11 and 12, and are different due to the phase difference of wave.

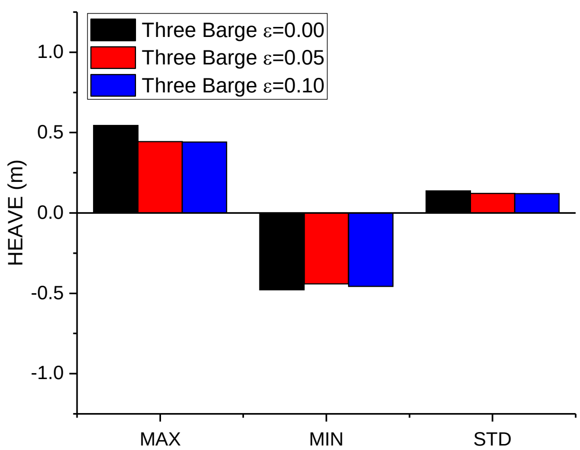

Figure 7. Barge 21 motion statistical results of the three-barge system case under extreme sea state

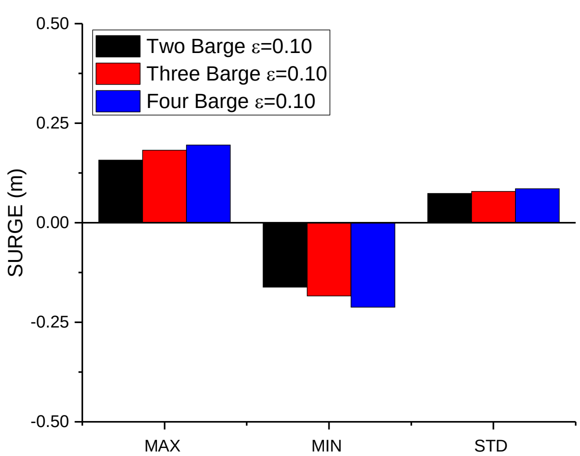

Figure 8. Surge motion statistical results of barge 11 in different barge cases with viscous parameter of 0.1

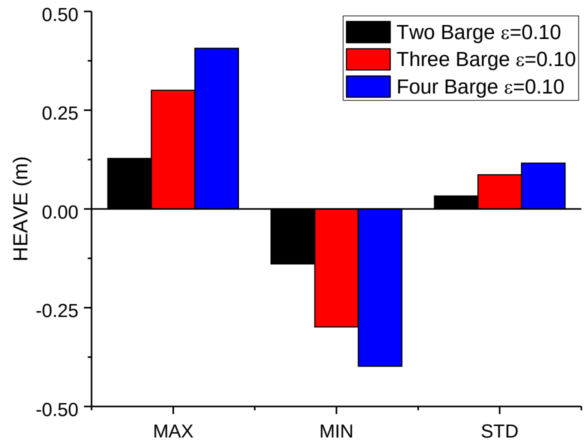

Figure 9. Heave motion statistical results of barge 11 in different barge cases with viscous parameter of 0.1

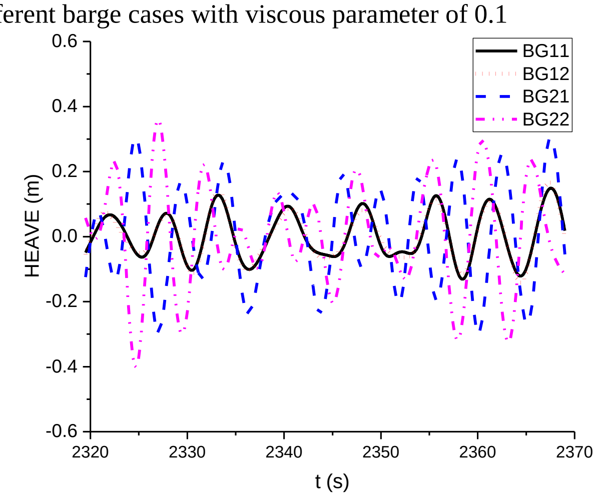

Figure 10. Time history of heave for barge 11, 12, 21, and 22 under the four-barge case with damping parameter of 0.1

BARGE FRAME EFFECT ON THE TANK DYNAMIC PERFORMANCE

In the proposed concept, the tanks are enclosed by the barge frame. Due to the hydrodynamic interaction, the tank dynamic performance should be different than the case with single tank which no hydrodynamic interaction. For the consistent comparison of tank dynamic responses, the tank fender system is assumed to have the same boundary condition. For both single tank and tank enclosed by the barges, one end of the fenders is fixed in space, which means they are not connected to the barges for the latter case, while the other end of the fenders is in contact with the tank. For the case of single tank and the case of tank enclosed by barge frame, the tank motion statistical values are shown in Figure 11, Figure 12 and Figure 13. It is seen that with the hydrodynamic interaction, the tank motion is smaller compared with single tank case. However, it should be noted that in real cases, one end of the fenders should be installed onto the barge, which means the barge motion will have influence on the fender boundary conditions and further on the tank dynamic motions. This influence is only related to the fender friction forces and contact position variation, which is assumed to be limited.

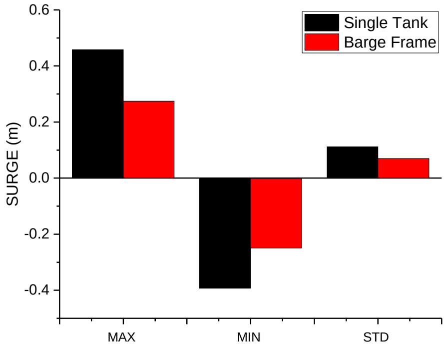

Figure 11. Surge motion statistical results for cases of single tank and tank enclosed by barge frame.

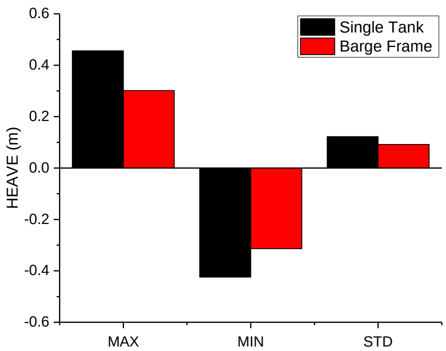

Figure 12. Heave motion statistical results for cases of single tank and tank enclosed by barge frame.

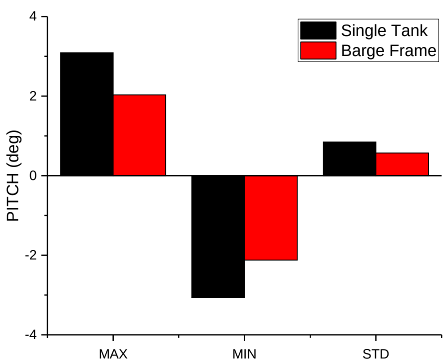

Figure 13. Pitch motion statistical results for cases of single tank and tank enclosed by barge frame.

CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

In this work, some basic scenarios are studied for the proposed floating storage tank system. Single-barge, two-barge, three-barge and four-barge systems are investigated to study the hydrodynamic interaction and mechanical coupling effect. In addition, the tank enclosed by the four-barge frame are studied and compared with the case of single barge. In all the simulations, extreme sea conditions with 0 wave incoming direction are used.

From the study, it can be concluded that the hydrodynamic interaction between the barges have influence on the barge dynamic responses. However, by changing the viscous parameter, the variation is not so significant, especially under sea state basis. By changing the number of barges, due to the hydrodynamic interaction and mechanical coupling, the dynamic responses are strongly affected. It is also concluded that when the tank is deployed inside the barge frame, the dynamic motions are significantly smaller than the single tank case.

In the near future, tank fender system should be connected to the barge and the fender boundary conditions should follow the barge motion. Sloshing should be considered if the tank is filled with fluid. In addition, more detailed analysis is needed to study the dynamic performance under different regular wave conditions, which can reveal more pronounced hydrodynamic interaction effects.

ACKNOWLEDGEMENT

The author gratefully acknowledges the financial supports from the Multi-Purpose Floating Structure (MPFS) project, from the JTC through the Center for Offshore Research & Engineering (CORE), National University of Singapore. The funding support from Newcastle Research & Innovation Institute Pte Ltd (NewRIIS), Newcastle University in Singapore is also acknowledged.

REFERENCES

[1] E. Watanabe, C. Wang, T. Utsunomiya, and T. Moan, "Very large floating structures: applications, analysis and design," CORE Report, vol. 2, pp. 104-109, 2004.

[2] S. Ohmatsu, "Overview: Research on wave loading and responses of VLFS," Marine structures, vol. 18, pp. 149-168, 2005.

[3] L. Wan, A. R. Magee, Ø. Hellan, W. Arnstein, K. K. Ang, and C. M. Wang, "Initial design of a double curved floating bridge and global hydrodynamic responses under environmental conditions," in Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2017-61802, June 25-30, 2017, Trondheim, Norway, 2017.

[4] M. Lwin, "Floating bridges," Bridge Engineering Handbook, vol. 22, pp. 1-23, 2000.

[5] J. E. Huguenin and F. J. Ansuini, "A review of the technology and economics of marine fish cage systems," Aquaculture, vol. 15, pp. 151-170, 1978.

[6] M. Shainee, H. Ellingsen, B. Leira, and A. Fredheim, "Design theory in offshore fish cage designing," Aquaculture, vol. 392, pp. 134-141, 2013.

[7] S. Ueda, "Floating Oil Storage Base," in Large Floating Structures, ed: Springer, 2015, pp. 91-105.

[8] B. Buchner, A. Van Dijk, and J. De Wilde, "Numerical multiple-body simulations of side-by-side mooring to an FPSO," in The Eleventh International Offshore and Polar Engineering Conference, 2001.

[9] R. Huijsmans, J. Pinkster, and J. De Wilde, "Diffraction and radiation of waves around side-by-side moored vessels," in The Eleventh International Offshore and Polar Engineering Conference, 2001.
[10] B. Koo and M. Kim, "Hydrodynamic interactions and relative motions of two floating platforms with mooring lines in side-by-side offloading operation," Applied Ocean Research, vol. 27, pp. 292-310, 2005.
[11] S. Hong, J. Kim, S. Cho, Y. Choi, and Y. Kim, "Numerical and experimental study on hydrodynamic interaction of side-by-side moored multiple vessels," Ocean Engineering, vol. 32, pp. 783-801, 2005.
[12] Y. Liu, C. Kim, and X. Lu, "Comparison of higher-order boundary element and constant panel methods for hydrodynamic loadings," International journal of offshore and polar engineering, vol. 1, 1991.
[13] Kevin Markeng, Torgeir Vada, and Z. Y. Pan, "Investigation of free surface damping models with applications to gap resonance problems," in Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering,OMAE2017-61288, June 25-30, 2017, Trondheim, Norway, 2017.
[14] B. VERITAS, "Hydrostar for experts user manual," 2016.
[15] J. Eskenazi and J.-h. Wang, "Analysis of angular side berthing against a rubber Cone Fender," Journal of Shanghai Jiaotong University (Science), vol. 20, pp. 571-583, 2015.
[16] L. Wan, Z. Gao, and T. Moan, "Nonlinear local structural modelling and analysis of the interface for a hybrid wind and wave energy converter concept," presented at the Proceedings of the 26th International Offshore and Polar Engineering Conference, June 26 - July 1, Rhodes, Greece, 2016.
[17] L. Wan, M. Han, J. Jin, C. Zhang, A. R. Magee, and Ø. Hellan, "Global dynamic response analysis of oil storage tank in finite water depth: Focusing on fender mooring system parameter design," Ocean Engineering, vol. 148, pp. 247-262, 2018.
[18] L. Wan, A. R. Magee, J. Jin, M. Han, C. Zhang, K. Ang, et al., "An innovative mooring system for floating storage tanks and stochastic dynamic response analysis," Submitted to Ocean Engineering, 2018.
[19] L. Wan, Z. Gao, and T. Moan, "Experimental and numerical study of hydrodynamic responses of a combined wind and wave energy converter concept in survival modes," Coastal Engineering,, vol. 104, pp. 151-169, 2015.
[20] W. Cummins, "The impulse response function and ship motions," SchiffStechnik,, vol. 47, pp. 101-109, 1962.
[21] J. Jin, A. R. Magee, M. Han, J. R. Hoff, E. M. Hermundstad, Ø. Hellan, et al., "Internal fluid effect inside a floating structure: From frequency domain solution to time domain solution," Proceedings of the ASME 2017 36nd International Conference on Ocean, Offshore and Arctic Engineering. Trondheim, Norway, 2017.
[22] MARINTEK, "SIMO User's Mannual Version 3.6," 2007.