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Keynote Paper

Recent Advancement in Numerical Modeling of Various Ocean Systems

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ABSTRACT

One of the biggest problems related to the ultra-deepwater development is that there is no wave basin in the world that can model the system in correct scale. Similar problem also happens due to a great expansion of the entire system in the horizontal scale to make relevant model testing more difficult. One example is multi-well development, for which several floating units are tied together by several-mile-long flow-line bundles. Recently, many innovative systems for harnessing clean and renewable energy from ocean wind, wave, and current have been suggested, for which both Reynolds and Froude numbers are relevant and the scale effects in model testing are yet clearly understood. In this regard, the role of reliable numerical simulation tools becomes more and more important nowadays for various ocean-engineering projects. Other examples that are hard to be tested in wave basin include (i) FOWTs (Floating Offshore Wind Turbines) due to the complicated aero-elastic-controller-floater-mooring interactions, (ii) safety of mooring-riser system with internal waves due to the difficulty related to the generation of internal waves in physical wave basins, and (iii) multiple floating units with liquid tanks due to the difficulty in correctly scaling the sloshing and structure/dynamics parameters. These examples, however, can more straightforwardly be modeled in numerical simulation tools by using BEM (Boundary Element Method) for floater motions, FEM(Finite Element Method) for line/tower dynamics, and CFD(Computational Fluid Dynamics) for liquid sloshing.

1. INTRODUCTION

During the past two decades, offshore industry has been moving into deeper and deeper waters and can now produce oil/gas from about 9000-ft (2743-m) water depth. This trend has continuously posed never-experienced challenges in developing innovative, robust, and cost-effective ultra-deepwater systems. One of the biggest problems related to the ultra-deepwater development is that there is no wave basin in

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the world that can model the system in correct scale. Recently, offshore industry also experiences a great expansion in the horizontal scale for multi-well development, for which several floating units are tied together by several-mile-long buoyant-flow-line bundles. The dynamic interactions among many floating units and flow-lines are considered to be significant but it is hard to be physically tested with correct or reasonable scale even in the world largest wave basins due to its vast horizontal scale. Similar example is VLFSs (very large floating structures) such as floating offshore airport and mobile offshore base. To physically model such cases, the system has to be truncated in vertical or horizontal direction, and therefore, the uncertainty related to model testing is greatly increased and the model test alone cannot be so reliable. Therefore, in such ultra-deepwater and ultra-horizontal-scale problems, physical model test has to be supported by reliable numerical-simulation tools, which is called “physical-numerical hybrid model testing” i.e. the model testing with truncated system is validated and tuned by numerical simulation program and then the computer program is used for the extrapolated (non-truncated) real system. In this regard, the role of reliable numerical wave tanks becomes more and more important nowadays for various offshore projects.

There are also many important offshore-engineering problems, for which physical experimental testing is intrinsically difficult. One of such cases is the testing of floating wind- or current-energy converters, for which both Reynolds and Froude numbers are relevant and the scale strategy in model testing is yet clearly understood. Other examples that are hard to be tested in wave basins include (i) FOWTs (Floating Offshore Wind Turbines), WECs (wave energy converter), and smart offshore platforms due to the complexity with regard to control systems and multi-component interactions, (ii) safety of mooring-riser system with internal waves due to the difficulty related to the generation of internal waves in the physical wave basin, and (iii) floating units with multi-phase liquid tanks due to the difficulty in correctly scaling the sloshing-related conditions and parameters. These examples, however, can more straightforwardly be modeled by numerical simulation tools by using BEM (Boundary Element Method) for floater motions, FEM (Finite Element Method) for line/tower dynamics, and CFD(Computational Fluid Dynamics). After sufficiently verified against experimental and field-measurement results, those numerical simulation tools can be repeatedly used for a variety new applications with much less limitation by the scale. Several example simulation tools and the corresponding sample results are introduced in the following sections.

2. EXAMPLES & SAMPLE RESULTS

2.1 MULTI-HULL/MOORING/RISER COUPLED DYNAMICS ANALYSIS TOOL

During the past two decades, a commercial-level multi-hull-riser-mooring fully coupled dynamic analysis computer program CHARM3D/HARP has been developed by Prof. M.H. Kim’s research group (Kim et al., 2001; Tahar and Kim, 2003; Yang and Kim, 2010). The developed CHARM3D/HARP can solve a full dynamic coupling among multiple surface platforms, mooring lines, multiple risers, flow lines, hawsers/fenders, and cables/umbilicals, which is vital for the design/development of the whole offshore system.

To run this time-domain program, one preprocessor is needed. It is WAMIT (Wave Analysis at MIT), which is a well-established commercial diffraction/radiation 3D panel program based on the linear potential theory. WAMIT includes the second-order sum- and difference-frequency wave loadings, which are important for the accurate prediction of motions of moored floating platforms. The WAMIT is good for frequency-domain wave-structure interaction problem including hydro-elasticity and also provides all the necessary hydrodynamic coefficients for the ensuing time-domain simulations by HARP/CHARM3D.

The commercialized version of the time-domain program with various pre and post processors and GUI (graphics user interface)/animation tools is called HARP (Hull And Riser Program) and the research version of the program with file-based inputs is called CHARM3D (Coupled Hull And Riser Mooring 3 Dimension). The program has been commercialized and is currently being used by more than 20 offshore companies worldwide for their real projects related to the design of offshore oil/gas platforms and mooring/riser systems. The mooring/riser program of the HARP/CHARM3D was developed by using an elastic-rod theory and global-coordinate-based high-order FE (finite element) technique. The floater dynamics of the HARP is based on the Cumming's time-domain equation with the hydrodynamic coefficients provided by a preprocessor like WAMIT. The nonlinear viscous drag forces at the instantaneous body position up to instantaneous free surface are also included in the HARP/CHARM3D. The program solves the full interactions among multiple floaters by time marching with mooring/riser dynamics (Kim et al., 2001; Tahar and Kim, 2003; Yang and Kim, 2010). In this regard, the hull and lines are dynamically fully coupled and simultaneously solved without using iteration technique, which is a unique feature compared to other competing commercial programs up to this level. The coupled dynamics of floaters and risers/mooring lines are simultaneously solved at each time step as an integrated system by using the combined equations of motions. The developed floater-mooring coupled dynamic analysis program has been verified by numerous comparisons against model-test results and field data (e.g. Kim et al., 2005; Tahar et. al. 2006). The developed mooring/riser program can also be used as a stand-alone program for various types of mooring lines and risers with any combinations of materials. In addition to wave loadings, the HARP/CHARM3D can include steady storm-induced currents and loop currents from different directions as well as dynamic wind loading (from any directions) for the given wind spectrum i.e. non-collinear wind-wave-current conditions can be simulated in time domain. The CHARM3D has recently been further extended to include coupling with sloshing CFD programs, hydro-elastic capability (Kang et al., 2013), and coupling with active control scheme (Kang et al., 2013). One example of modeling a complicated 2-body system (TLP and a tender drilling barge) with many mooring lines, risers, and hawsers is shown in Fig.1. The whole system dynamics are solved simultaneously in a combined matrix at each time step, and thus the fully coupled effects among many dynamic components can be accurately assessed. This kind of example is hard to be studied by experiment with correct scale.

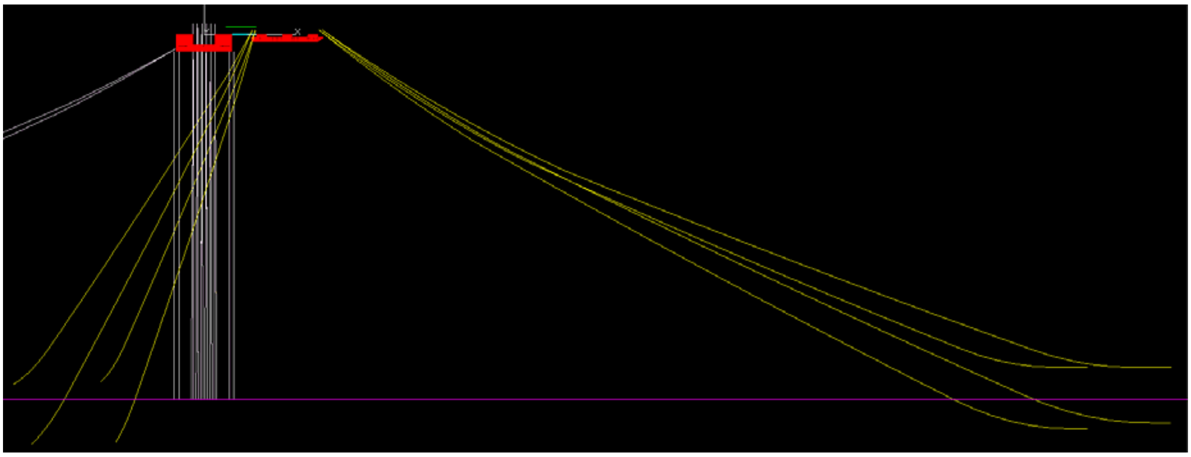

Fig.1 TLP and a tender drilling barge with many mooring lines, risers, and hawsers

Fig.2 shows another multi-body simulation example including a big containership docked (through two bow hawsers) at a single-point post and two catamaran-type mobile harbors for offloading operation on both sides (Kang and Kim, 2012). There are fenders and hawsers between the ship and mobile harbor. A sea state (random wave-wind and steady current) can be inputted to simulate and assess the global performance of the complicated system for the given environmental condition.

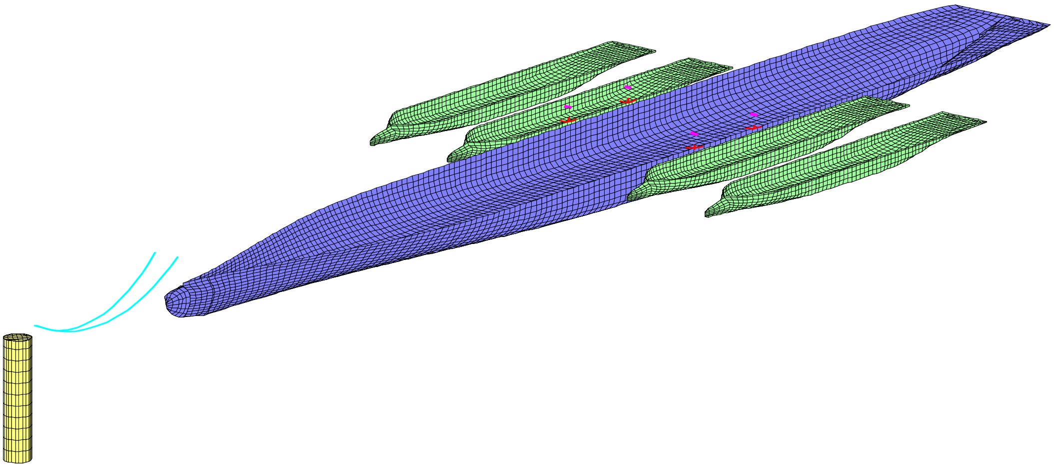

Fig.2 A big containership and two catamaran-type mobile harbors for offloading operation

2.2 FOWT (Floating Offshore Wind Turbine)

Recently, several countries started to plan and install FOWTs (floating offshore wind turbines). Although they are considered to be more difficult to design compared to fixed type, FOWTs in deeper waters are in general less sensitive to space availability, noise restriction, visual pollution, and regulatory problems. They are also exposed to much stronger and steadier wind fields to be more effective. The whole units can be constructed at quay side and towed to connect to the preinstalled mooring system, and thus the installation process may be much simpler compared to the fixed type. On the other hand, possible disadvantages of floating type wind turbines include the complexity of blade controls due to body motions, a larger inertia loading on the tall tower caused by greater floater accelerations, survivability in harsher environments etc.

In designing those floating wind farms, the existing technology and experience of offshore industry used for petroleum production is still useful but cannot be directly applied. The major reason is that the floater is connected to a very tall and flexible tower with flexible blades, the wind loading is continuously changing due to blade pitch control, there may be a possibility of extra resonance between the floater and control mechanism, the whole system is yaw weathervaning etc.

As a result, a new fully coupled-analysis simulation program needs to be developed including all those coupling elements, which has been developed by the author's research group during the past 5 years (e.g. Bae and Kim, 2011; Bae et. al., 2012). The computer program integrates rotor dynamics and control, aero-dynamics, tower elasticity, floater dynamics, and mooring-line dynamics to investigate the full dynamic coupling among those components in time domain. For the dynamics and control of blade and tower, the primary design code of wind turbines, FAST, developed by National Renewable Energy Laboratory (NREL), is employed (Jonkman and Buhl Jr, 2004). A portion of the FAST algorithm is implemented into the floater-mooring coupled dynamic analysis program, CHARM3D, and vice versa so that the tower-floater coupling can accurately be achieved. The developed fully coupled dynamic analysis program for FOWTs is applied to three different types of FOWTs, Hywind spar, Windfloat semisubmersible, and mono-column TLP. The simulations correlate well against observed data and phenomena in scaled experiments. With this kind of numerical tool available, various scenarios of different designs can be simulated and tested with minimal cost. One example is shown in Fig.3 for the greatly reduced pitch motion and power fluctuation by an optimally designed control system in case of 5MW-Hywind spar compared to the typical control strategy used for fixed OWTs.

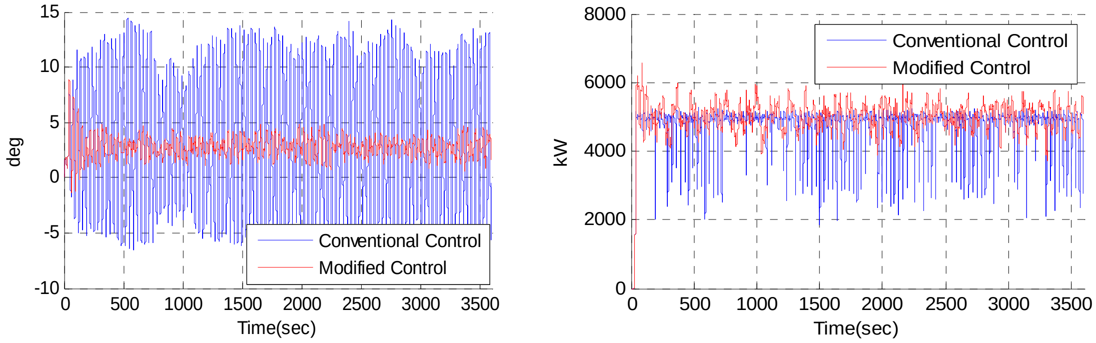

Fig.3 Time series of pitch motion and produced power for two different control strategies

This kind of reliable numerical tool can also be used for the optimal design of a health-monitoring system for FOWTs. For example, a sudden damage of blade portion and mooring lines and malfunction of control system can be detected by observing the corresponding abnormality of sensor signals. Recently, the simulation program is further extended to be able to handle multiple FOWTs in a single gigantic floater (Fig.4) so that the full coupling among all those multiple components can be accurately analyzed. (Bae, 2013)

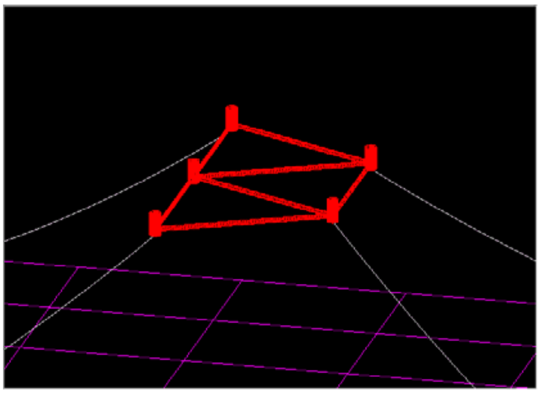

Fig.4 A numerical model of a FOWT with 5 wind turbines mounted on a single floater

Since HARP/CHARM3D is a time marching program, coupling with various time-domain control algorithms is relatively straightforward. One example is the use of DP (dynamic positioning) control along with vessel-response simulations. Another example is smart offshore platforms or WECs with active control (e.g. Kang et al., 2013).

2.3 VESSEL MOTION & MULTI-PHASE-SLOSHING INTERACTION

Many new floating offshore platforms, such as FPSO, FSRU, and FLNG etc. are planned to be installed in the coming years. Those floating platforms possess many large liquid tanks for storage. Recently, its size becomes larger and larger so that the dynamics of inner fluid significantly influences the vessel motions. On the other hand, the vessel motion also causes violent inner liquid motions that lead to sloshing impact. The sloshing impact often causes damage to the tank wall. In this regard, the dynamic interaction analysis between floating vessels and inner liquids is important in the design of such vessels and downtime estimate of side-by-side offloading operation between FLNG/FPSO and LNGC (LNG carrier). An example of a numerical simulation for FPSO/LNGC side-by-side offloading operation for various fill ratios (Lee and Kim, 2010) is shown in Fig.5. The numerical simulations of the motion-sloshing interactions agreed well against model-testing results (Lee and Kim, 2010; Kim et al., 2011). When the inner fluid motion is highly violent, a reliable CFD method, such as MPS (moving particle simulation), needs to be used to reliably predict the corresponding impact load (Kim et al., 2011; Kim and Kim, 2013).

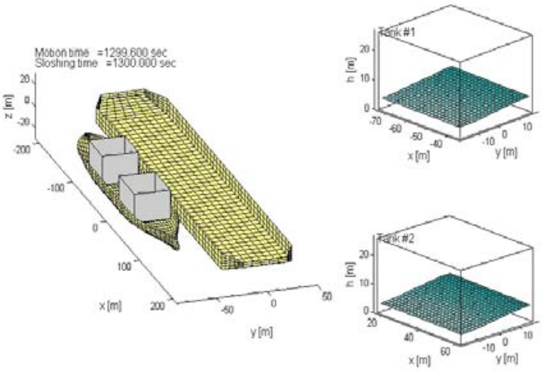

Fig.5 Simultaneous simulation of vessel motions and inner-tank-liquid motions for FPSO/LNGC side-by-side offloading operation

Those floating production platforms are also equipped with many processing units on the deck or inside the hull. One example is oil-gas-water separator. Its functionality depends critically on vessel responses. To increase the processing efficiency, many new ideas are suggested. For instance, subsea separators are newly introduced for maximizing production efficiency for new types of deepwater oil wells. Usually, separators are placed on deck and separate oil, water, and gas from produced mixed fluids. Recently, a new idea of larger-scale “wash tank” is also suggested as a pre-processor for conventional separators. It is for initial separation of oil and sea water with the help of emulsion fluid in simply shaped storage tanks inside hull for maximizing process efficiency. Thus, one or two large-scale wash tanks of three liquid layers can be positioned inside the FPSO hull, and thus the corresponding inner fluids motions can become an important issue (e.g. Molin et al., 2012). At the design stage, it is important to confirm that undesirable resonant motions of the multiple interfaces do not occur under the typical operational environmental conditions. Therefore, a consistent dynamic analysis including the coupling effect between the vessel motion and the sloshing of multiple inner fluids needs to be developed. In particular, the internal resonance or sloshing at the inner interfaces needs to be predicted in a reliable manner to check whether the separation process is well functioning. This kind of scenario is very hard to be studied by experiments.

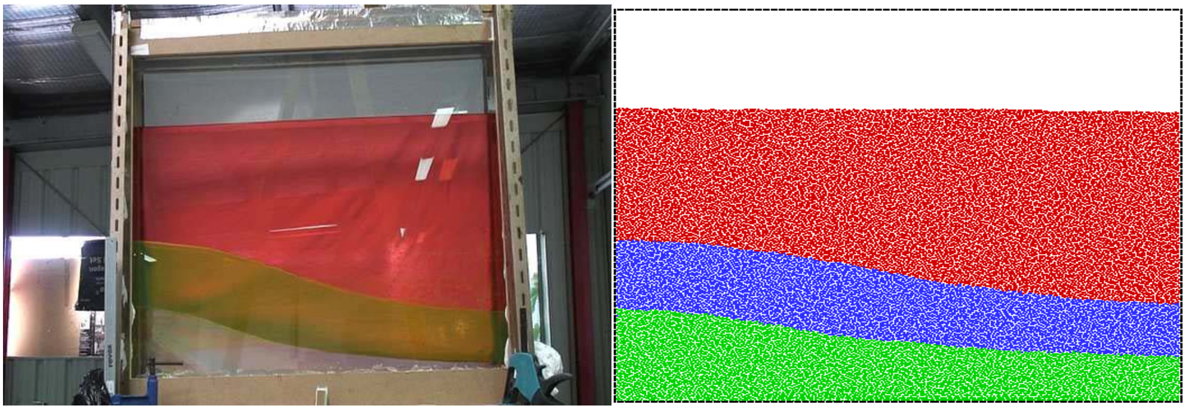

Fig.6 3-phase liquid layers and generation of internal waves by forced roll motion. Experiment vs. numerical simulation by MPS (Kim and Kim, 2013).

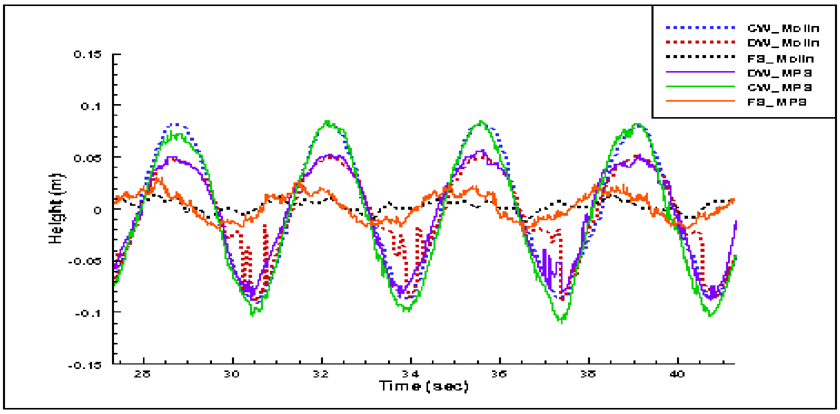

Fig.7 Comparison of Kim & Kim's (2013) numerical simulation with Molin et al's (2012) experiments for the interfacial motions of three liquid layers inside a rectangular tank under forced oscillation

The internal waves generated at the interfaces of different densities are hard to be realized in the large-scale physical model testing. Recently, large internal waves have been observed in the South China Sea and that up to 200-m amplitude has been reported. This kind of internal wave can seriously challenge the riser/mooring design for drilling and production units in the area. Only numerical simulation tool is a useful source to assess the performance and risk (Kurup et al., 2012).

3. CONCLUDING REMARKS

There are many ocean-engineering problems that are hard to be tested with a correct/reasonable scale without using truncation due to vast scales in horizontal and vertical directions. There are also other problems for which model testing is intrinsically difficult. In this case, the availability of reliable numerical simulation program is essential to solve the problem. Even when experiments can easily be done, numerical simulation program is still valuable in that it can be repeatedly used to find optimal design conditions and parameters, which is to be drastically expensive by experiments. In this paper, several of those examples are illustrated, which includes (i) multi-hull/mooring/riser coupled dynamics, (ii) actively controlled FOWTs (Floating Offshore Wind Turbines) including complicated aero-elastic-controller-floater-mooring interactions, and (iii) multiple floating units with multi-layer-liquid tanks. The use of those reliable numerical simulation tools with ever-increasing computer power is expected to be greatly increased in the future after fully verified in many real ocean projects.

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