The Ocean Engineering Committee

Final Report and Recommendations to the 26th ITTC

1. GENERAL

1.1 Membership and Meetings

The members of the Ocean Engineering Committee of the 26th International Towing Tank Conference were as follows:

- Prof. Wei Qiu (Chairman), Memorial University of Newfoundland, Canada
- Prof. Xuefeng Wang (Secretary), Shanghai Jiao Tong University, China
- Prof. Pierre Ferrant, Fluid Mechanics Laboratory, Ecole Centrale de Nantes, France
- Prof. Shuichi Nagata, Institute of Ocean Energy, Saga University, Japan
- Dr. Dong-yeon Lee, Samsung Ship Model Basin, Korea
- Dr. Ole David Okland, MARINTEK, Norway (joined the Committee in January 2011)
- Prof. Sergio H. Sphaier, Lab Oceano, Federal University of Rio de Janeiro, Brazil
- Prof. Longbin Tao, University of Newcastle upon Tyne, United Kingdom (joined the Committee in June 2010)
- Prof. Martin Downie (Chairman during the period from September 2008 to June 2010), University of Newcastle upon Tyne, United Kingdom.
- Dr. Rolf Baarholm (Secretary during the period from September 2008 to June 2010), Norwegian Marine Technology Research Institute, Norway.

Note that both Prof. Downie and Dr. Baarholm resigned from the Committee in June 2010.

Four Committee meetings were held respectively at:

- University of Newcastle upon Tyne, United Kingdom, March 2009.
- Memorial University of Newfoundland, Canada, October 2009.
- Shanghai Jiao Tong University, Shanghai, China, June 2010.
- Samsung Ship Model Basin, Daejeon, Korea, January 2011.

1.2 Tasks Based on the Recommendation of 25th ITTC

- Update the state-of-the-art for predicting the behavior of bottom founded or stationary floating structures including moored and dynamically positioned ships emphasizing developments since the 2008 ITTC Conference. The committee report should include sections on:

    - The potential impact of new technological developments on the ITTC
    - New experimental techniques, extrapolation methods
    - New benchmark data
    - The practical applications of computational methods to prediction and scaling
    - The need for R&D for improving methods of model experiments, numerical modeling and full scale measurements.

- Review ITTC Recommended Procedures relevant to ocean engineering (including procedures for uncertainty analysis)

- Identify any requirements for changes in the light of current practice, and, if approved by the Advisory Council, update them.
- Identify the need for new procedures and outline the purpose and content of these.

- Identify the parameters that cause the largest uncertainties in the results of model experiments, numerical modeling and full scale measurements related to ocean engineering.

- Conduct a study of numerical computations in comparison with existing benchmark data for
  - Wave run up on a fixed vertical cylinder,
  - Vortex shedding from a circular cylinder for forced oscillation

- Propose benchmark tests to investigate the hydrodynamic damping due to mooring lines.

- Develop guidelines for hydrodynamic testing of marine renewable energy devices.

- Write a procedure for the testing of dynamic positioning (DP) systems.

- Liaise with the ISSC and the Seakeeping Committee

1.3 Structure of the Report

The work carried out by the committee is presented as follows:

<u>2. State of the Art Reviews</u>

- Section 2.1: Predicting the Behaviour of Bottom-Founded Structures
- Section 2.2: Predicting the Behaviour of Stationary Floating Structures and Ships
- Section 2.3: Predicting the Behaviour of Dynamically Positioned Structures
- Section 2.4: Predicting the Behaviour of Renewable Energy Systems
- Section 2.5: Highly Nonlinear Effects on Ocean Structures
- Section 2.6: New Experimental Techniques

<u>3. Review of Existing Procedure</u>

Section 3 reviews the procedure on Uncertainty in EFD (7.5-02-01-01).

<u>New Documentation</u>

- Section 4 discusses parameters that cause the largest uncertainties in results.
- Section 5 presents the benchmark study of numerical computations and comparisons to existing experimental data for vortex flow induced by 2D cylinders
- Section 6 presents the investigation of hydrodynamic damping due to mooring lines
- Section 7 discusses the new guideline for testing of wave energy converters (WEC)
- Section 8 discusses the new procedure for testing of dynamic positioning (DP) systems

<u>Conclusions and Recommendations</u>

Sections 9 and 10 present the conclusions and recommendations, respectively.

2. STATE OF THE ART REVIEWS

2.1 Bottom-Founded Structures

Bottom founded structures are traditionally classified in terms of their typical size in relation to the characteristic wavelength, λ, of their wave environment. They present a wide variety of concepts and flow regimes, from small volume structures for which flow separation plays a dominant role in the fluid loading (commonly represented by the Morison equation) to large volume gravity based structures (GBSs) for which wave diffraction effects dominate.

Having been used for decades in the offshore industry, methods of estimating the fluid loading on bottom founded structures are well established. This category of structures has been extensively reviewed by the two previous ocean engineering committees. Thus the present review will concentrate on innovative approaches, or new application sectors, such as bottom-mounted marine renewable energy systems.

Morgan & Zang (2010) investigated the use of the open source Computational Fluid Dynamics (CFD) software suite OpenFOAM released for the simulation of focused wave packets interacting with a vertical bottom mounted cylinder. Wave elevation in the vicinity of the cylinder was compared to the experimental data. In a parent paper, Zang et al. (2010), higher-order diffraction effects in the loading were studied. In both cases, it was shown that a reasonable agreement with experiments could be expected, with affordable computing times on standard computers.

Bredmose & Jacobsen (2010) reported investigations on a similar cylinder arrangement, a typical bottom-mounted offshore wind turbine foundation, also using the OpenFOAM suite as numerical simulation tool. Special attention was paid to the wave generation process, while fluid loading obtained from CFD calculations in breaking wave events was compared to results given by a combination of Wheeler stretching technique for the incident wave kinematics, and Morison equation for the fluid loading. Comparisons were repeated for different wave focusing point locations. A fair agreement between both sets of results was demonstrated, although the comparison with experimental results was missing.

In Merz et al. (2009), the literature concerning the hydrodynamics of wind turbine support structures has been reviewed. Important phenomena not covered by the usual Morison equation approach are mentioned, including the interaction of structural vibration and vortex shedding, the impulse loading from steep waves and the damping of structural vibrations.

Yang et al. (2010) report on the experimental study of the scour around jacket offshore wind turbine foundations in shallow water, in different wave and current conditions. The effect of scour mitigation devices was investigated.

Johannessen (2011) revisited the problem of the high frequency resonant response of offshore structures in irregular waves, using state of the art approximate nonlinear diffraction models. The case of the Snorre GBS was especially addressed. The author concludes that provided the incident wave spectral properties are carefully represented, such models allow a good representation of the resonant response of the GBS structure.

Roos et al. (2009) and Roos et al. (2010) report on the experimental study of wave impacts on elements of a GBS composed of submerged storage caissons combined with four surface piercing vertical cylinders, in relatively shallow water. The wave in deck impact loads and the loads on vertical columns were successively investigated. The authors indicate that large impact loads, larger than those measured on the underside of the deck, may be recorded on the columns with heights substantially larger than the incident wave height.

2.2 Stationary Floating Structures and Ships

2.2.1 Spar Platforms

Spars continue to be a preferred industry solution for certain offshore deepwater developments. Research has been carried out to address the global motions of spar hulls in waves, current and wind.

The direct vertical access spar, Perdido, has been recently installed in the ultra deepwater of Gulf of Mexico. It is the deepest spar production and drilling facility in the world. The numerical prediction of the spar motions in waves, wind and current was carried out by Liapis et al. (2010) using COSMO/WAMIT and was compared with model test results. Special line members were included to take the viscous loads and damping into account. Several heave plate configurations were also studied to investigate their effect on the global spar motions.

Koo et al. (2010) studied the motions and loads for the float-over installation of spar topsides. The numerical analysis involved multi-body hydrodynamic interaction and simulation of impact forces. Validation studies were carried out by comparing the measured and predicted motions and loads. In the transportation analysis, it was found that the predicted catamaran barge global motion statistics were slightly conservative in comparison with those of the model tests. The predicted mooring line tension statistics for the highest loaded line agreed well with the model tests.

The predicted global topsides load statistics are slightly lower than that of the model test. For pre-mating analysis, the predicted maximum downward relative motion agreed well with those of model tests while the highest lashing line tension was somehow conservative. For load transfer, the maximum vertical impact forces on the mating units were in a good agreement with model test results.

2.2.2 TLPs

In the past three years, research has been carried out on experimental tests of TLP structures, numerical methods for the simulation of the behavior of TLP structures, and the design and the use of damper mechanisms to reduce the loads on the tendons.

Heidari et al. (2008) presented the design of a dry-tree FourStar TLP with 100,000 ton displacement structure and a payload of approximately 40,000 tons for 4300 ft water depth. Tests of the TLP model at 1:52 scale were performed at the Offshore Technology Research Center (OTRC) at Texas A&M University. The top-tensioned risers were included in the physical model in order to provide more realistic estimates of the hydrodynamic behavior of the TLP. The model tests have confirmed that the dry-tree FourStar TLP is a stable drilling and production platform.

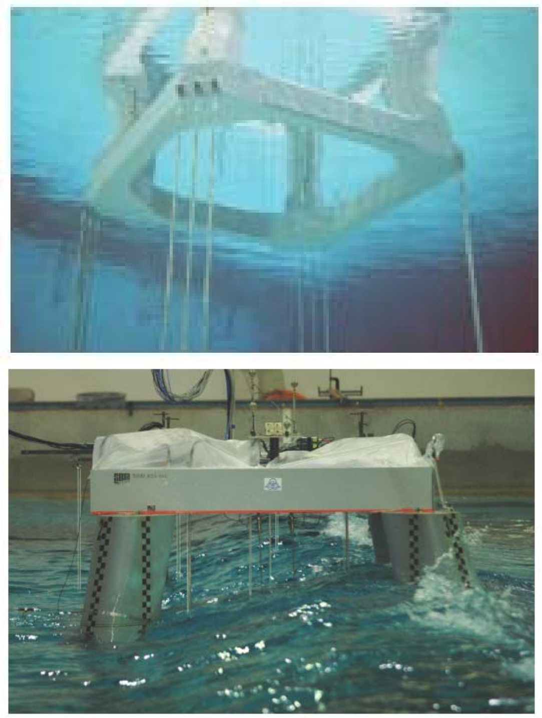

Figure 2.2.1: The Underwater View and Side View of the Dry-tree FourStar TLP (Heidari et al., 2008)

Bian et al. (2010) presented the design of an integrated ultra-deepwater TLP with an air spring type vibration absorber to suppress the vertical resonance motions. The vibration absorbers were calibrated against the results from the proof-of-concept model tests carried out at the OTRC. Figure 2.2.2 shows the 1:45 scale model of a SeaStar TLP variation tested in the OTRC wave basin. The tests were to investigate the effectiveness of the vibration absorber.

Figure 2.2.2: 1:45 Scale Model of a SeaStar TLP Hull (Bian et al., 2010)

Jayalekshmi et al. (2010) investigated the effect of tether-riser dynamics on the response characteristics of deepwater TLPs in water depths of 900 m and 1800 m and in random waves. The nonlinear dynamic analysis of deep water TLPs was performed using an in-house finite element analysis program. Results are reported in the form of statistical values of responses. It is indicated by the authors that the statistical values of responses increase with water depth and a significant increase was observed when risers were included in the analysis.

Yan & Ou (2010) studied the hydrodynamic parameters and dynamic responses of different types of TLPs: a classical TLP (CTLP), an extended TLP (ETLP, designed by ABB Co.), a minimum offshore surface equipment structure (MOSES, designed by MODEC Co.), and the Seastar TLP (Seastar, designed by Atlantia Co.), as shown in Figure 2.2.3 AQWA, based on the unsteady potential flow theory and the boundary element method, was used for the hydrodynamic computations and the analysis of flow field. The results showed that the dynamic responses of the four types of TLPs are observably different.

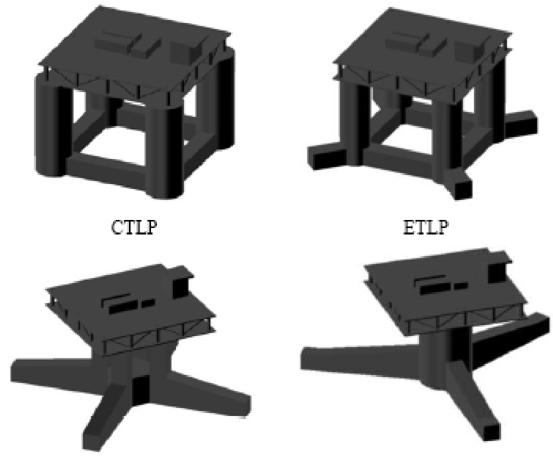

Figure 2.2.3: Schematic View of the 4 TLP Conceptions (Yan and Ou, 2010)

Yang et al. (2008) presented a numerical study of the transient effect of tendon disconnection on the global performance of ETLP in harsh environmental condition. WAMIT was used to calculate added mass, damping, and the first- and second-order wave excitation forces in the frequency domain. Time-domain simulations were carried out by using a hybrid model of potential theory and Morison's equation to take into account the viscous effects.

Taflanidis et al. (2008) explored the idea of using mass dampers for reduction of dynamic loadings. The use of both single and dual mass dampers per hull column was investigated for the protection of the platform. To achieve greater vibration suppression, appropriate tuning of the parameters of the dampers is necessary. A robust stochastic design approach is presented in their paper for this purpose.

Lee and Lim (2008) presented an advanced TLP hull form design which has a displacement of 35000 m^3 and is targeted for operation in a water depth of 1829m (6000ft) off the Gulf of Mexico. A fully automated hull optimization procedure was used and the fatigue damage to the most loaded tendon due to top tension was minimized. The authors argued that a better design can be achieved when the optimization is performed with an objective function based on the coupled analysis instead of linear approximation. They illustrated the dynamic behaviors of the optimized TLP by a fully coupled time-domain analysis for a survival condition, considering second-order wave forces and nonlinear viscous forces.

Yalpaniyan & Goodarzi (2010) studied the flow pattern around a TLP at three Froude numbers using inviscid, laminar and turbulent flow solvers. It was observed that, besides the generated surface waves, there was a pair of non-symmetric vortices behind each column and the vortex behind the first column significantly affected the flow pattern around the second one. The results showed that the generated waves using the inviscid flow solver were smoother than those by using the turbulent flow solver. Furthermore, the computed waves by the turbulent flow solver were smoother than those by the laminar solver, and the influence of the flow velocity on the wave heights was significant.

Srinivasan (2010) addressed the use of TLP in ultra deepwater to support dry-tree in oil and gas production. To reduce the effects of the wave loading, truss-pontoons were used. A technically feasible and cost-effective artificial sea-bed was used to ease the tendon design at such deepwater in harsh environment. A simple and slim hull, which is easy to design, fabricate, transport and install, was obtained.

Masciola & Nahon (2008) presented a non-linear 6 degree-of-freedom dynamics model for a TLP-type structure. The effect of random wave forces and a method to calculate the buoyant righting moment were included. First- and second-order forces due to waves were also considered. Morison's equation was used to account for the viscous effects.

2.2.3 Semi-Submersibles

Semi-submersibles are a subject of continuing interest studied by a number of authors by a variety of methods. Matsumoto et al. (2010) carried out wave basin tests for a large semi-submersible designed to operate in Campos Basin. They observed significant run-up effects on its squared-section columns for the steepest waves in several design conditions. Also, they found relatively large low-frequency motions in heave, roll and pitch, which affected the dynamic air gap measurements.

Williams et al. (2010) presented the development of SBM Atlantia's dry-tree semi-submersible platform suitable for deployment in non-hurricane/non-cyclonic environments worldwide. The verification of the FourStarTM concept through wave basin model testing was also discussed. The implementation of this concept has been illustrated through an example application of an integrated DTS-GAP-FPSO system in 2,100 m water depth offshore Brazil.

Hussain et al. (2009) discussed the requirement for a floating vessel designed to support top tensioned risers. They introduced the Extendable Semi-submersible (E-Semi) with a retractable Second Tier Pontoon (STP) to suppress heave motions in order to support top tensioned risers in the ultra deep water of central Gulf of Mexico. Numerical studies and model tests showed the effectiveness of the STP in suppressing the heave motion.

In the dry-tree semi-submersible, the upper sections of the risers are exposed to surface currents. In addition, most dry-tree semi-submersible designs have to support the keel joints similar to a Spar. Gupta et al. (2009) discussed a methodology for VIV suppression using a riser stem. They quantified the reduction in fatigue damage when the stem is used.

Mansour (2009) introduced the performance of a new conceptual semi-submersible design that provides motion response similar to a Spar. The invention introduces a new feature in terms of a Free-Hanging Solid Ballast Tank, and hence the semi-submersible is named as FHS Semi. The use of the free-hanging Solid Ballast Tank (SBT) significantly increases the heave natural period while controlling the heave response in the wave frequency range, and therefore, enables the use of the FHS Semi in dry tree applications.

Figure 2.2.4: Wave Run-up (Matsumoto et al., 2010)

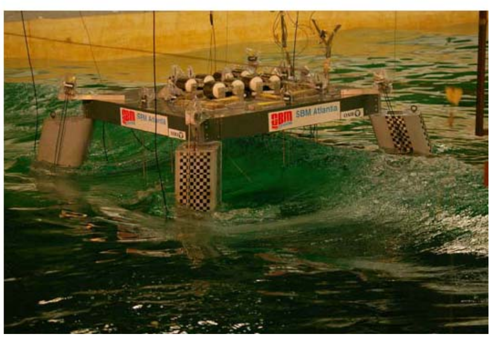

Figure 2.2.5: FourStar DTS Model (Williams et al., 2010)

Figure 2.2.6: E–Semi (Hussain at al., 2009)

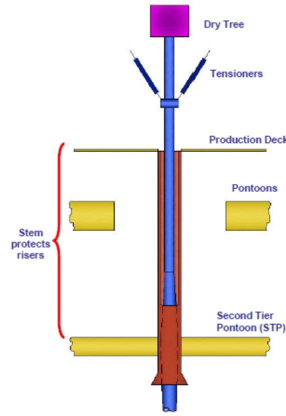

Figure 2.2.7: Riser Stem (Gupta et al., 2009)

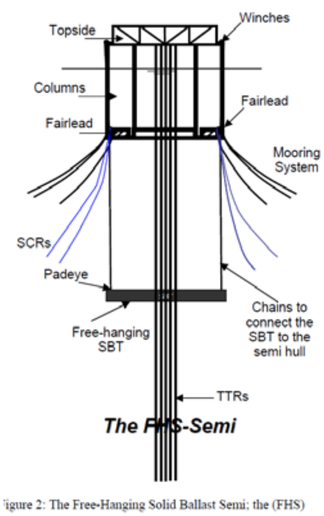

Figure 2.2.8: Free Hanging Solid Ballast Semi (Mansour, 2009)

Current loads on stationary vessels have been investigated by Vaz et al. (2009) as part of the Current Affairs Joint Industry Project (JIP). Model-tests, semi-empirical models and CFD methods were used to predict these loads. Two key issues affecting the modelling accuracy, the location of the transition to turbulent flow and the control of the numerical errors, were identified and discussed.

Vortex Induced Motion (VIM) of a deep draft semi with four square columns has been observed by Rijken & Leverette (2009) in model tests and in the field tests for a prototype configuration. The lock-in and post lock-in response characteristics have been observed. The lock-in response amplitudes are larger and more harmonic than the post lock-in response amplitudes, as observed in both field tests and model tests. Their field measurements indicate that the design guidance derived from model tests, as presented by Rijken & Leverette (2008), results in very conservative estimates of VIM. In the work of Rijken & Leverette (2008), it was also observed the flow field around the columns caused the vessel to oscillate along one of the vessel's main diagonals under particular conditions.

Hassan et al. (2009) presented the measured steady drift force and low frequency surge motions of a semi-submersible model. They found that the presence of current increases the damping ratio of the system for both horizontal and catenary moorings. Only in the cases of high sea states with the horizontal mooring system, it was found that the standard deviation of the surge motions is slightly larger than those obtained for waves and current separately.

Simos et al. (2009) showed that semi-submersible hulls may be subjected to second-order slow motions in heave, pitch and roll. These resonant motions are directly related to the large dimensions and relatively low natural frequencies of the floating systems. This paper discusses the evaluation of the 2nd order wave-induced motions of a large-volume semi-submersible platform using the WAMIT second-order module. It is shown that the hydrodynamic forces induced by the 2nd-order potential represents the prevailing effect in the resonant response.

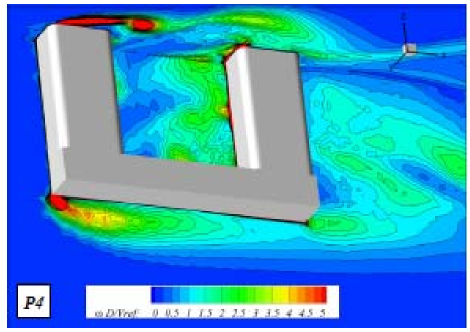

Figure 2.2.9: Current Affairs JIP (Vaz et al., 2009)

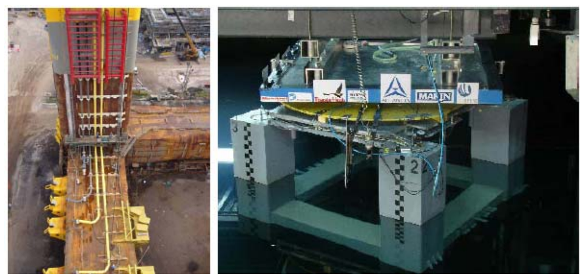

Figure 2.2.10: SBM Atlantia Deep Draft Semi-Submersible (Rijken & Leverette, 2009)

Figure 3 Major appurtenances on hull and SCR porches on pontoon

Figure 2.2.11: Semi Hull and SCR Porches (Rijken & Leverette, 2008)

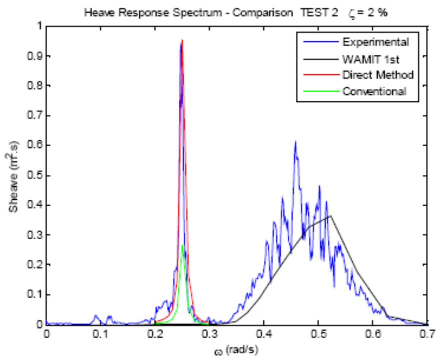

Figure 2.2.12: Heave Motion Spectra (Simos et al., 2009)

Matos et al. (2010) studied the scale effect of the slow drift motions in vertical plane of a large volume semi-submersible platform, PETROBRAS 52 (P-52). Slow drift motions in the vertical plane (heave, roll and pitch) were observed in the model tests. It was found that the 2nd order amplitudes from spectral analysis were greater than the first-order ones. They compared the full-scale measurements and theoretical predictions. The importance of considering the resonant roll and pitch motions in the seakeeping analysis of large-volume semi-submersible platforms was demonstrated.

2.2.4 FPSO Vessels

FPSO vessels have been operated in a variety of water depth due to their flexibility, reliability, and low cost. Efforts have been made to investigate the responses of FPSO vessels in waves. Studies have been addressing low frequency motion, the effect of internal liquid cargo, the hydrodynamic interaction when operated in a close proximity, the shallow water effects, and fully nonlinear analysis.

Yan & Ma (2008) presented a review on fully nonlinear modelling of wave-structure interaction. Yan et al (2009) studied the nonlinear responses of FPSO-like structures in waves.

Yan et al. (2010) conducted fully nonlinear analysis of a moored FPSO vessel in shallow water waves using the quasi arbitrary Lagrangian-Eulerian finite element method. The paper presents the observations of motions and forces on the FPSO and the relative run-up at bow and stern. Investigations were also carried out on the effects of water depth on motions, forces and wave run-up. The numerical results suggest that the induced forces decrease while the nonlinear components may be more significant as the water depth decreases. The transient translational motions and relative run-up increase as the water depth decreases.

2.2.5 Floating LNG Production Storage and Offloading Vessels

Park et al. (2010) studied the motions of a LNG-FPSO considering the effect of sloshing effect. The methodology is based on a coupled model of sloshing and motion in the time domain. The coupled motion program was validated by comparing the frequency-domain motion results of a LNG-FPSO. It was confirmed that the sloshing impact pressure depends on wave period, the number of filled tanks and the tank filling level.

Ryu et al. (2010) studied sloshing loads in partially filled LNG tanks for a floating offshore LNG vessel at different headings and sea states. They described the effect of wave heights on the sloshing loads, especially for partial filled LNG tanks, and also load assessment results.

Lee et al. (2010) calculated motions of two floating bodies (FSRU and LNGC) in shallow water. They found that the horizontal surge motion is significantly affected by the wave deformation. Particularly, the surge motion is considerably amplified in low frequency waves by nonlinear wave-wave interactions. It implies that shallow water effects must be included in the motion and mooring system analysis of floaters in shallow water.

2.2.6 Coupled Hull/Mooring/Riser Systems

The floating structure, mooring and riser system dynamically responds to environmental loads due to waves, wind and current in a complex way. Motions of a floating structure may include the components of (1) mean response due to mean wave drift, mean wind load and mean current load, (2) wave-frequency response, (3) low-frequency response, (4) high-frequency response, especially for TLPs, and (5) vortex induced motion on Spar like hulls. The dynamic system responses can be obtained using the decoupled analysis method or the coupled analysis method. The coupled analysis is to accurately predict the motions of the floater and the detailed dynamic response of mooring lines and risers at design conditions such as extreme conditions, fatigue load cases, accidental conditions as well as temporary conditions.

The coupled analysis typically treats the floater as a rigid body and models the mooring lines and risers by the finite element method. Appropriate boundary conditions are applied at the points connecting mooring lines/tethers/risers to the floater. The coupled equations of the system are solved in time domain using a non-linear integration scheme and the coupling effects are automatically included in the solution.

The coupled analysis requires extensive computational efforts. More efficient computation schemes are needed for use in practical design analyses. Efforts have been made to develop highly efficient frequency domain approach in which the drag forces are linearized. Studies have showed that provided the geometric nonlinearity of the moorings/risers is insignificant, which often holds for ultra-deepwater systems, the mean-squared responses yielded by the time and frequency domain methods are in close agreement (Low & Grime, 2011). Since the practical design is concerned with the extreme response, for which the mean upcrossing rate is a key parameter. The crossing rate analysis based on statistical techniques is complicated as the total response occurs at two timescales, with the low frequency contribution being notably non-Gaussian. In the work of Low & Grime (2011), they applied statistical techniques in conjunction with frequency domain analysis to predict the extreme responses of the coupled system, in particular the modes with a prominent low frequency component. It was found that the crossing rates for surge, sway and yaw obtained agree well with those extracted from time domain simulation, whereas the result for roll was less favourable.

Over the past three years, many researchers have contributed to the application of the coupled analysis in practical engineering design.

Chan & Ha (2008) used a fast time-domain coupled analysis along with a frequency-domain mooring analysis to predict the first-order and slowly-varying drift motions of a FPSO in a design extreme weather condition. The line tensions predicted in the time domain were compared with the frequency domain solutions

Chen et al. (2008) used the coupled analysis to assess the effect of two different top tensioned riser configurations, one with buoyancy cans and one with tensioners, on the motion responses of a Truss Spar in ultra deepwater. Nonlinear spring properties of tensioners and hydrodynamic loadings on the risers and mooring are included in the fully coupled analyses. A semi-coupled analysis considering only the riser and mooring stiffness was also performed to evaluate the effect of mass and damping of risers and mooring on the Spar responses.

Lee & Lim (2008) optimized a TLP based on the coupled analysis. In the optimization, the fatigue damage was assessed based on the frequency domain coupled dynamic analysis including first-order wave forces, mean drift forces and linearized viscous forces. The optimization led to a hull form with remarkably improved dynamic performance and minimized top tension of the tendon. The dynamic responses of the optimized TLP were then illustrated by a fully coupled time domain analysis for a survival condition, where second order wave forces and nonlinear viscous forces were considered.

2.3 Dynamically Positioned Systems

2.3.1 Recent Development

The offshore activities for exploration and production of oil and gas have strongly stimulated the development of dynamic positioning systems for vessels. More than 2000 DP vessels operate all over the world with a large variety of DP systems. Many researchers have contributed to the scientific and technological development of DP systems (Sorensen, 2010).

Simulation systems, CFD application and model tests have been used to evaluate the performance of DP systems. The use of the theory of nonlinear control, robust control, reliability, and simulation of interference between thrusters has also been addressed by researchers.

Li et al. (2009) presented a model to simulate the path following of marine surface vessels using the rudder control. A back-stepping nonlinear controller was used. Simulation results were presented to verify and illustrate the effectiveness of the resulting control against rudder saturation and rate limits and delays in the control execution. The control design was validated by model tests of a ship model.

Sørensen & Smogeli (2009) showed that significant reductions of undesired thrust, torque, and power fluctuations in the dynamic operating conditions encountered in waves can be achieved by applying control strategies. Open-water model test experiments validated the analysis and demonstrated the performance of the proposed controllers.

Using experimental results for a ducted propeller with varying submergence and loading at low advance velocities, Smogeli et al. (2008) presented a simulation model for propellers subject to ventilation and in-and-out-of water effects. They introduced the anti-spin control concept and showed that it gave increased control of the thruster performance in extreme seas.

Tannuri et al. (2010a) and Tannuri & Agostinho (2010) applied Higher-Order Sliding Mode Control (HOSM) theory to the problem of dynamic positioning. A simulation model was developed and experiments were carried out with a model in a towing tank of 1.5m deep, 5m wide and 21m long.

Tannuri et al. (2010b) present numerical and experimental results from a research program supported by Petrobras and the Brazilian government. A numerical simulator developed through this research program was used to evaluate the behavior of a DP crane-barge operating close of a FPSO (Tannuri et al, 2010e).

Jenssen et al. (2009) discussed the problems involved in the model tests of a DP system operated in ice conditions.

A method of improving DP accuracy using only sensors and control algorithms was presented by Hughes et al. (2010). The method is based on the estimation of wave drift forces using the wave elevation measured by the sensor. A wave feed forward control method was employed.

Cozijn et al. (2010) investigated the wake flow behind a ducted azimuthing thruster. The velocity in the wake was measured by a PIV system. The results helped to improve understand the thruster-interaction effects.

The analysis of the installation of two top-side modules using a dynamically positioned crane vessel was presented by Cozijn et al. (2008). The purpose of the analysis was to determine the operational limits of the offshore installation. The model of the crane barge was equipped with a DP system, including the controller, Kalman filters and azimuthing thrusters.

Moratelli et al. (2008) performed a reliability analysis of the design of a DP system in the preliminary stage for a shuttle tanker using the failure mode and effect analysis (FMEA).

The wind, waves and current fields of a shuttle tanker can be disturbed by the presence of a FPSO. The wake effects of the environmental forces on the DP system of a shuttle tank, when offloading a FPSO, was investigated by Illuminati el al. (2009) and Tannuri et al. (2010c).

A multi-body time-domain simulation program with 6 degrees of freedom was presented by Serraris (2009) to simulate a DP system including Kalman filter, PID controller and a Lagrange optimized allocation algorithm.

Many vessels with DP system involved in offshore activities usually use multiple azimuth thrusters. Once the thrusters are positioned in close proximity, their performance may suffer due to thruster-thruster interactions. Bosland et al. (2009) developed a robust numerical flow solver to predict the interaction effects.

A methodology based on fully nonlinear dynamic simulations was used by Tannuri et al. (2010d) to evaluate the downtime of offloading operations. It was employed to compare the use of conventional non-DP tankers assisted by a tugboat and DP tankers operated in typical Brazilian environmental conditions.

Waals (2010) commented that a few cases have been reported where the DP system became instable during the installation. A method was proposed using the actual tension measurement in the hoist wire to enhance the DP system and to correct the additional forces in the horizontal plane due to the hoisting wire. The proposed method was investigated in a series of model tests.

Fang et al., (2009) presented a nonlinear mathematical model, including seakeeping and maneuvering characteristics to simulate dynamic motion behaviors of a barge using the outboard hubless thrusters as the DP system in random waves. The mathematical model included nonlinear drifting forces.

Yang et al. (2009) investigated the maneuvering performance of an Arctic shuttle tanker with a twin azipod system. A mathematical model was developed. To obtain the hydrodynamic characteristics, captive model tests and pod open-water tests were carried out at the Samsung Ship Model Basin.

Tanaka et al. (2009) conducted captive model tests to investigate the hydrodynamic force characteristics of a ship with twin azimuthing podded propeller in maneuvering motions. Podded propeller open-water tests in pusher and puller modes were performed. Forces and moments were measured on a hull and podded propellers behind hull. Using a mathematical model, they concluded that the lateral force open-water characteristics of podded propeller and the hydrodynamic interaction between hull/podded propellers affect the course stability of ship.

Full-scale measurements of a DP offloading operation were presented by Tannuri et al. (2009a). Vessel motions and thruster forces were measured. A time-domain offshore system simulator was used to simulate the same operational conditions. It was indicated by the authors that good agreement between numerical results and full-scale measurements was obtained.

Zakartchouk Jr. & Morishita (2009) presented a comparison of numerical and experimental results of a dynamic-positioned shuttle tanker model, using a back-stepping controller.

Morishita et al., (2009) presented an experimental set-up for tests of scaled models with DP systems. Details of the experiment and components of the system were described. Preliminary experimental results were given and compared with results by a numerical model.

A complex system for the ship motion control in confined waters was presented by Gierusz et al. (2007) using two different controllers connected in parallel. One controller is based on the robust control technology while another is based on the fuzzy logic technique. The choice of controller is determined by the velocity of the vessel. The control system was implemented first in a nonlinear multi-variable simulation model and then in a real-time autonomous model of a VLCC.

Mahfouz (2007) presents a new method to predict the Capability-Polar-Plots for offshore platforms using the combination of the artificial neural network and the capability polar plot program. A trained artificial neural network was designed to predict the maximum wind speed at which the thrusters are able to maintain the offshore platform in a station-keeping mode in the field site. Results were presented for the case study of a scientific drilling vessel with four azimuth thrusters of a maximum deliverable thrust of 3.6 ton each.

Using a hybrid controller, Nguyen and Sørensen (2009) developed a high-level control of dynamic positioning systems to extend the operational weather window for marine operations in harsh environments. Numerical simulations and experiments were conducted to verify the proposed system operating in various environmental conditions.

A nonlinear model including a dynamic partial differential equation formulation for dynamic positioning and low-speed maneuvering was developed and applied to a pipe laying operation by Jensen et al. (2010).

Nguyen et al. (2010) modeled a system consisting of a vessel, mooring lines and a drilling riser with the objective of minimizing the rigid riser angles at the well-head and at the top joint. The model was based on the control of the vessel's position by changing the tensions in the mooring lines to ensure that the riser end angles are within safe limits. The paper includes numerical simulations and experiments of a moored vessel.

Kuehnlein (2009) described the major challenges of dynamic positioned vessels in ice-covered water. As the forces acting on vessels in ice and their response are substantial different from the behavior in open waters, new philosophies and strategies have to be developed. The paper summarized where we are and what still need to be done.

de Wilde et al. (2010) discussed the first investigation of LNG stern-to-bow offloading with dynamic positioned shuttle tankers, based on a model test program. The shuttle tanker was controlled by a full closed loop DP system which is largely identical to the real DP system, including extended Kalman filtering, PID control and thruster allocation. The modeling of the azimuthing thrusters, rudder and main propeller as well as the modeling of the relative position between the two ships are discussed in the paper.

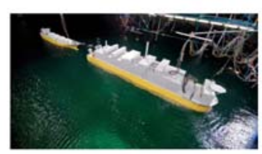

Figure 2.3.1: Examples of Side-by-side and Tandem LNG Offloading

Tannuri et al. (2009b) presented a detailed analysis of a crane and pipelaying barge. A DP system is installed in the barge to improve the position control ability, for both pipe-laying and crane operations, with no loss of safety, to enhance the operational time schedule and to make the operation economically feasible. For the simulations of the DP-Mooring operational mode, two mooring lines at the bow were considered, in order to counteract the force of the pipe being launched (Figure 2.3.2).

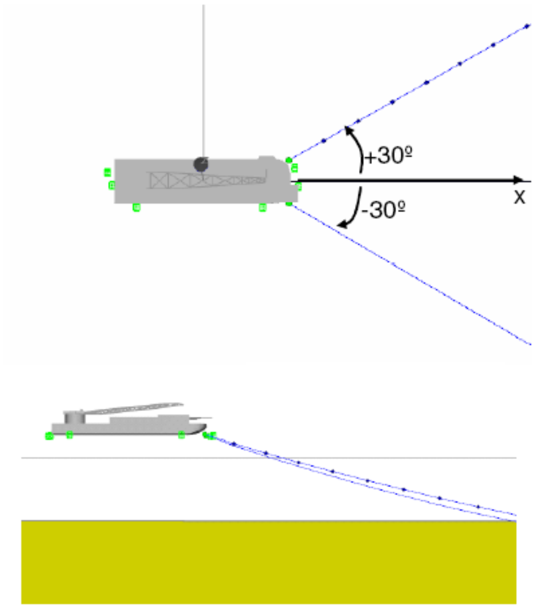

Figure 2.3.2: Mooring Lines Used in the DP-Mooring

2.3.2 Operation of Thrusters

Using a model test of deepwater semi-submersible platform in the scale of 1:50, Wang et al. (2009a) analyze the hydrodynamic interaction characteristics of a dynamic positioning thruster system, the thruster-thruster interaction caused by the propeller race and the thruster-hull interaction caused by the Coanda phenomena.

Wang et al. (2009b) studied the hydrodynamic interaction characteristics of a DP thruster system, including the thruster-thruster interaction caused by the propeller race from one thruster on the neighboring thrusters and the thruster-hull interaction caused by the Coanda effort. A set of hydrodynamic curves for the system in the current flow and in the calm water were presented. In the studies, some feasible ways to reduce interaction so as to improve the capability of DP systems were also presented.

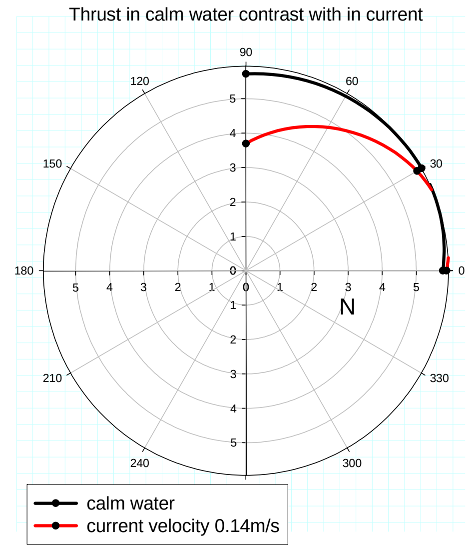

Figure 2.3.3: Thrust Comparison (Wang et al., 2009b)

2.3.3 Ventilation and Ingestion of Air

Koushan (2007) carried out the model test in order to obtain insight into the dynamics of propeller blade and duct loading fluctuations and ventilation phenomenon of thrusters in dynamic positioning mode involving dynamic model tests of a ducted pushing thruster and an open pulling thruster. Ventilation affects both the dynamic and static loadings on thrusters. Variations in relative blade torque are almost identical to variations in relative blade thrust under ventilated conditions. When a thruster undergoes heave motion, it is the ventilation mainly causing loading fluctuations rather than the heave motion, although the heave motion induces ventilation. Ventilation inception leads to highest dynamic fluctuations. It results in sudden large drop of blade thrust.

2.4 Renewable Energy Systems

2.4.1 Wave Energy

Wave energy converters (WECs) can be broadly classified into three types: oscillating water columns (OWC), moving bodies and wave overtopping devices. Falcão (2010) summarized technologies for WECs including hydrodynamics of wave energy absorption, power take-off (PTO) systems, control, and mooring. A variety of theoretical and experimental studies have been carried out. The potential-flow theory has been mainly used to evaluate the performance of WECs.

A summary of approaches based on the potential flow theory was presented by Mei (2005) and Falnes (2002). In order to evaluate the efficiency of the wave power absorption for a fixed OWC type device, numerical models based on linear potential theory in frequency and time domains were proposed, for example, by Cruz (2008) and Falnes (2002). Lopes et al. (2009) examined experimentally the effect of latching control to the airflow of fixed OWC type WEC by turning a shut-off valve and verified the numerical method for the dynamics of the system. Liu et al. (2010) evaluated the efficiency of the power absorption for a fixed OWC device by using 2D mixed-Eulerian-Lagrangian boundary integral equation approach based on potential flow theory.

Oscillating Water Columns (OWC)

For the floating OWC type devices, Suzuki et al. (2009b) proposed a 2D numerical method in frequency domain considering the radiated waves by oscillating dynamic air pressure in air chamber based on the linear potential-flow theory. The authors studied the optimum profile of the floating OWC, "Backward Bent Duct Buoy", including wells turbine with guide vanes, in irregular waves. They assumed that the air pressure is proportional to the square of vertical velocity of average water surface in air chamber, and used the measured proportionality. Nagata et al. (2009) presented the equations of motion of a floating OWC-type WEC in the time domain using the impulse response matrix for body velocity and air pressure in air chamber. The retardation functions for the air pressure in the equation of motion are expressed by the hydrodynamic coefficients for air pressure and its derivatives in frequency domain. A method for reducing the free surface elevation in air chamber at resonance frequency was employed to calculate the radiation and diffraction potentials.

CFD has also been used in evaluating the performance of OWC device. Liu et al. (2008) and Yin et al. (2010) evaluated the efficiency of the power absorption for a fixed OWC device by using two-phase VOF model for the two phase flow in air chamber using the commercial CFD code, Fluent.

Moving-body Type WECs

Moving-body type WECs can be broadly classified into five categories, such as point absorber systems, fully submerged heaving systems, pitching devices, bottom-hinged systems and multiple-body systems. Various suitable PTO systems, such as a linear generator system with direct drive conversion and an oil-hydraulic system etc. are typically used for these WECs.

Frequency and time-domain models have been developed for predicting motions of the floating devices in waves in order to evaluate the performance of moving type WECs. For a single-body heaving buoy type WEC, Backer et al. (2009) carried out tank tests in irregular waves for a device with mechanical brake as damping system, and compared the test results with numerical solutions in time domain based on the potential theory. Ricci et al. (2008) also conducted the time-domain simulation for same type WEC with two kinds of PTO models, a linear PTO and a hydraulic PTO. In the hydraulic PTO model, they used four kinds of ordinary differential equations to describe the dynamics of a hydraulic circuit including a hydraulic cylinder, a high-pressure gas accumulator, a low-pressure gas reservoir and a hydraulic motor.

For two-body heaving buoy type WECs, Gomes et al. (2010) conducted the geometry optimization of the IPS wave power buoy with linear PTO in irregular waves of a specific wave site. In their work, frequency domain models based on potential theory and the stochastic method were used. The optimization criterion was to maximize the ratio of the annual average of the absorbed power to the submerged volume of the device. Cândido and Justino (2008) developed a time-domain model for evaluating the efficiency of wave power absorption of a WEC with two concentric axisymmetric heaving bodies. They used a non-linear PTO model with a hydraulic circuit including a number of pairs of cylinders, high-pressure and low-pressure gas accumulators and hydraulic motor.

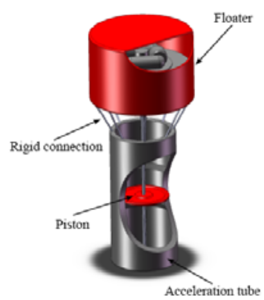

Fig.2.4.1: IPS Wave Power Buoy

Justino et al. (2008) proposed frequency and time domain models for a two-body WEC that extracts energy from sea waves by relative pitch motion between their two independent parts, and has a hydraulic PTO with non-linear characteristic. Fonseca et al. (2008) calculated wave drift forces acting on this device and examined the effect of damping of linear PTO on the drift forces.

In order to enhance the wave energy absorption of moving body type WECs with hydraulic PTO, research has been carried out on the PTO force control. Falcão (2007) modelled a hydraulic circuit composed of a hydraulic cylinder, high-pressure and low-pressure gas accumulators and hydraulic motor. The effect of latching control for a single-body heaving buoy in regular and irregular waves was also examined by using theoretical time-domain modelling. Babarit et al. (2009) also carried out a multi-degree of freedom simulation in time domain for the floating WEC 'SEAREV' with hydraulic PTO. They demonstrated the effectiveness of declutching control, i.e., the PTO force is set equal to 0 during some parts of the cycle, in regular and irregular waves.

Overtopping WECs

For overtopping WEC, Victor (2010) conducted experiments on average overtopping discharges for smooth linear-slope single-level structures with a slope extending to the bottom. They compared their results with those based on empirical formulae from the literature. Tedd & Kofoed (2009) measured the overtopping flow of the 1:4.5 scale 'Wave Dragon', which is an offshore floating WEC of overtopping type in an inland sea in Northern Denmark.

WEC Farm

Concerning a wave farm with many WECs, the research on hydrodynamic interactions between floating bodies and mooring design has been carried out. One of the key considerations on mooring design of WEC is to maintain the position of the WEC under extreme loading conditions, while allowing efficient conversion of wave energy by increasing the motions of floating body in operation conditions. Vicente et al. (2009) calculated the behaviour and the power performance of triangular-grid arrays of identical WECs, absorbing energy using heaving buoys from regular and irregular waves. The WECs are spread-moored to the bottom through the bordering elements and are inter-connected with lines under tension provided by weights. They showed that the behaviour and the power performance are significantly affected by the presence of the mooring system. Garnaud and Mei (2009) proposed a new method in the frequency domain to evaluating the energy extraction by a periodic array of small heaving buoy type WECs with similar separation compared to the typical wavelength. They used a method of homogenization (multiple scales) to derive the equations governing the macroscale behaviour of the entire array. Taghipour and Moan (2008) studied a multi-body WEC which consists of a semi-submersible platform and 21 buoys. They used a mode expansion method, with total number of 27 modes, to formulate the dynamic motions, and assumed that the PTO force acting on each buoy has linear damping characteristics.

New WEC Types

Many experiments have been carried out in the development of new WEC devices. Howard et al. (2009) carried out the tank tests for 'Oyster', which is a seabed mounted WEC that consists of a buoyant flap freely oscillating about a pivot, under extreme sea conditions. They measured the foundation loads by using a five-degree-of-freedom load transducer.

Buchner et al. (2010) carried out pilot model tank tests on the 'Green Water Concept' floating WEC. This device is a weathervaning vessel with a small freeboard and a water reservoir in the centre based on the concept of 'heaving' or 'pitching' and 'overtopping'. They conducted the tank tests on linear and hydraulic PTOs.

Pecher et al. (2010) carried out the experimental tests for an oscillating wave surge converter, 'Langlee' floating WEC, which extracts the wave energy using a number of hinged flaps positioned under the water surface.

Kanki et al. (2010) have developed a floating WEC using the gyroscopic moment by the rotation of large flywheels and the swing of a float excited by wave motion. A field test for a 45kw prototype system was carried out in Japan. Salcedo et al. (2009) also proposed a gyroscopic WEC of the same type, named 'OCEANTEC' and carried out wave tank tests and sea trials.

Chiba et al. (2008) proposed a single buoy type WEC using Electroactive Polymer Artificial Muscle (EPAM) which is a rubbery material that can generate electricity by simply being stretched and allowed to return to its original shape. They carried out the sea trials off the coast of Florida and showed that this device were able to generate a peak power of 1.2W and an average power of 0.25W using EPAM of 300g.

2.4.2 Current Energy

Many concepts of tidal and marine current energy converters have been proposed since 2008. Hardisty (2009) and Khan et al. (2009) summarized the technologies for tidal and marine current energy converters. These devices can be broadly classified into two types: devices using turbine and devices not using turbine. Horizontal-axis turbine systems and vertical-axis turbine systems are typically used in turbine type converters. Oscillating hydrofoils and devices making use of vortex induced vibration are employed in non-turbine systems. Numerical methods and experiments have been carried out to evaluate the performance of turbines or hydroplanes of these converters.

Clarke et al. (2009) developed a horizontal axis contra-rotating marine current turbine system which can be tuned to extract energy over a wide range of water depths by 'flying' a neutrally-buoyant device from a flexible, tensioned mooring. They conducted the stability trial of a 2.5m diameter prototype turbine in a towing tank and at sea.

Kyozuka et al. (2009) proposed a hybrid turbine, consisting of a Darrieus turbine with a Savonius rotor to improve its starting torque. They also examined the effect of the attaching angle between the Darrieus wing and the Savonius rotor in circulating water channel.

Blunden et al. (2008) tested the thrust and torque characteristics of a $1/20^{th}$ scale model rotor for a 16m diameter horizontal axis tidal turbine under yawed flow conditions in a towing tank in order to assess the performance of the device in non rectilinear currents. They also calculated the annual power output at some design cases for the turbine using measured data and tidal analysis results in three locations of the English Channel.

Many numerical methods such as RANS-CFD, BEM and vortex method have been developed for design and performance evaluation of the devices. The commercial RANS-CFD codes such as FLUENT, ANSYS CFX and SC/Tctra are typically used.

O'Doherty et al. (2009) compared numerical solutions by FLUENT with experimental results of torque and power output for a three-bladed horizontal axis turbine. They examined the numerical accuracy of five turbulence models: Spalart-Allmaras, Standard k-ε,RNG k-ε, Realizable k-ε and RSM. Alidadi et al. (2008) studied the effect of ducting on the performance of a vertical axis tidal turbine using the FLUENT code and a discrete vortex method. Harrison et al. (2009) compared numerical solutions by ANSYS CFX with experimental results for the thrust coefficient of a horizontal axis tidal turbine which was simplified as an actuator disc. Dai et al. (2010) also used the ANSYS CFX code to optimize the efficiency of a Darrieus-type marine current turbine. Using the Tetra code, Jo et al. (2009) investigated the interaction between rotating rotors of a multi-arrayed tidal current power device by considering axial, transverse and diagonal arrangements.

Baltazar & Falcão de Campos (2008) analyzed the flow around the blades of a horizontal axis current turbine using the BEM. In their work, an empirical vortex model was assumed for the turbine wake which includes the pitch variation of the helicoidal trailing vortices behind the blades.

Kinnas et al. (2010) proposed a blade design procedure for a horizontal axis, three-blade tidal turbine. It combines a lifting line approach with the vortex lattice analysis method and a nonlinear optimization scheme. This design procedure starts by specifying the number of blades and the turbine operating conditions. The vortex lattice method was used to predict the turbine performance.

Wang et al. (2010) used the Lattice Boltzmann Method to analyze the performance of a blade hydrofoil and compared the numerical results with other numerical solutions.

Fabrice et al. (2008) calculated the wake behind a three-bladed horizontal axis turbine in a uniform current by using the 3D vortex method. McCombes et al. (2009) presented a numerical model for unsteady wake modelling for marine current turbines based on a finite volume solution of the Navier-Stokes equations in the form of vorticity conserving.

2.4.3 Wind Energy

The offshore floating wind turbines can be classified into four main categories, Spar-buoy type, TLP type, Semi-submersible type, and Barge-type. Wang et al. (2010) conducted a literature survey of research and development on floating wind turbines and summarized future work.

To study offshore floating wind turbines, it is important to understand the coupling between the support structure and the wind turbine subjected to combined wind and wave loading. Cordle (2010) studied the numerical design codes in time domain for floating wind turbine such as FAST, ADAMS, Bladed, HAWC2, 3Dfloat, SIMO, and Sesam/deepC. In the study, the wind inflow, aerodynamics, elasticity and control of the wind turbine, and hydrodynamics of floater and mooring dynamics in waves was considered. In these numerical codes, the combined blade element and momentum theory was used to model the aerodynamic forces acting on a wind turbine rotor, and Morison's equation and linear potential theory were used to model the hydrodynamic forces acting on floater.

Jonkman (2009) explained the FAST code. Jonkman et al. (2010) conducted code-to-code comparisons of these codes for the NREL 5-MW three-bladed horizontal axis wind turbine on the OC3-Hywind spar.

For Spar-buoy type floating wind turbines, Utsunomiya et al. (2009) carried out experiments to measure motions of a stepped SPAR-type floating wind turbine under regular and irregular waves, and steady horizontal wind force using a 1:22.5 scale model. These experimental results were compared with the numerical results based on Morison's equation for fluid forces. Utsunomia et al. (2010) also conducted on-sea experiments using a 1/10 scale model of the prototype with 2MW horizontal-axis wind turbine of down-wind type in Japan. Karimirad & Moan (2010) carried out structural dynamic response analyses of a Spar-type wind turbine in the extreme survival condition by using HAWC2 code. Suzuki et al. (2009a) developed an analysis method of progressive drifting and evaluated the risk of a generic Spar type wind farm. They showed that optimal wind farm arrangement will be determined by the trade-off between the risk of wind turbine drift and the installation cost of power cable on the sea bed.

For TLP-type floating wind turbines, Shin & Kim (2008) and Bae et al. (2010) carried out the fully coupled dynamic analysis of an offshore floating wind turbine system in time domain, including blade-rotor dynamics and control, mooring, and platform motions. Their analyses were based on the FAST code, an aeroelastic analysis program for two and three-bladed horizontal axis wind turbines, the WAMIT code, a 3D diffraction/radiation panel program for floater hydrodynamics, and the CHARM3D code, a floater-mooring coupled dynamic analysis program. They applied these numerical codes to a three-bladed horizontal axis and mini-TLP-type floating offshore wind turbine. Jagdale & Ma (2010) examined the effect of change in platform configuration for TLP type floating offshore wind turbine on its response in waves by using a numerical model in time domain.

For Semi-submersible type floating wind turbines, Phuc & Ishihara (2009) developed a numerical model to predict the dynamic response of a floating wind turbine in the time domain, considering the interactions between wind turbines and the floaters. They also carried out model tests to study the dynamic response of system in winds and waves by using the pulsating wind tunnel with water tank at NMRI. It was shown that the predicted responses by the proposed numerical model were in good agreement with experimental results.

Figure 2.4.2: Semi-sub Type Floating Wind Turbine (Phuc & Ishihara, 2009)

Roddier et al. (2010) summarized the feasibility study of the 5MW semi-submersible type floating wind turbine 'WindFloat' with a three-legged floating foundation. A computer program was developed to model the coupled dynamic aero-hydro-servo-elastic response in wind and waves. Model tests in wind and waves were also conducted to validate the numerical analysis tools.

Figure 2.4.3: WindFloat

For barge-type floating wind turbines, Iijima et al. (2010) presented a numerical method for the fully coupled aerodynamic and hydroelastic analysis of a floating wind turbine in wind and waves. The wind turbine system comprised of two parallel longitudinal box girders connected at forward and aft ends as well as amidships by transverse box girders. They used the FAST code for the aerodynamics analysis of the wind turbine system.

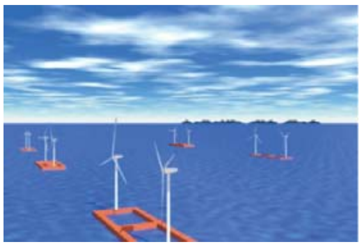

Figure 2.4.4: Barge Type Floating Wind Turbine (Iijima et al., 2010)

Korogi el al. (2009) carried out the resistance tests and the oblique towing tank tests with a 1/100 scale model of a very large mobile offshore structure sailing-type wind farm in order to improve the navigation simulation and to investigate the interactions among the wind shaped struts or between the lower semi-submersible hull and the struts.

With respect to the standard for the design of floating wind turbines, Ronold et al. (2010) introduced 'DNV Guideline for Offshore Floating Wind Turbine Structures' which covers floater concepts, design principles, site conditions, loads, structural design, station keeping and stability.

2.5 Highly Nonlinear Effects on Ocean Structures

2.5.1 Slamming

Slamming is a complex nonlinear problem. It has been continuously studied by many researchers using the Wagner approach, methods based on the potential-flow theory, and CFD methods such as SPH, VOF and CIP.

Tassin et al. (2010) proposed a fast numerical method based on the Wagner approach and the displacement potential formulation to solve the 3D water impact problems. The predicted wetted surface has been verified against analytical results for an elliptic paraboloid. The predicted slamming forces were validated by comparison with other numerical results and experimental data by Constantinescu et al. (2009).

Investigations have been conducted as part of the MARSTRUCT network of excellence to compare predictions of pressure distribution during impact of two-dimensional sections obtained using a range of two-dimensional numerical methods with available experimental measurements (Brizzolara et al., 2011). The numerical methods employed include BEM, the LS-DYNA code, the volume of fluid (VOF) method and Lagrangian solid modeling, commercial CFD software packages, FLUENT and FLOW-3D, and the SPH method. It was found the pressures predicted by various numerical methods show great differences, especially for the BEMs. The agreement between the predicted and measured pressures is in general reasonable. The CFD approaches, such as SPH and Flow-3D, appear to result in the best predictions provided the kinematics of the problem is modeled accurately.

Based on the CIP method, Yang and Qiu (2008) studied the water entry of 2D wedges with small deadrise angles considering the compressibility of air. In 2010, they further solved the slamming problems for 2D and 3D bodies, including wedges, sphere, cylinder, and a catamaran section, with constant water-entry velocities and free-fall motions. Validation studies showed that the predicted slamming forces are generally in good agreement with the experimental data.

2.5.2 Green Water/Air Gap

The highly non-linear nature of wave elevation around large structures in steep waves makes it difficult to accurately predict wave field under the deck and wave run up along the columns. Liang et al. (2010) adopted a Navier-Stokes solver with the VOF technique for violent free surface capturing and DNV/Seasam to predict motions of a moored semi-submersible platform.

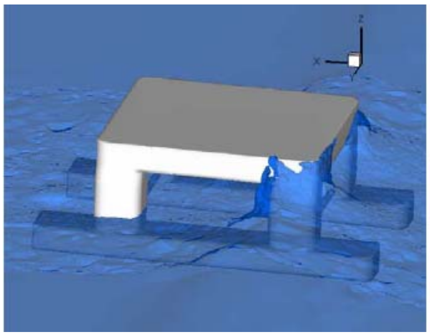

Figure 2.5.1: Wave Run-up along the Fore Column (Liang et al., 2010)

Using the Smoothed Particle Hydrodynamics (SPH) method, Rudman et al. (2008) carried out the three-dimensional simulation of the impact of a rogue wave on a semi-submersible platform, a TLP and a Taut Spread Mooring (TSM) system.

Figure 2.5.2: Wave Run-up for TLP (Rudman et al., 2008)

2.5.3 Sloshing

The problem of the sloshing of liquid cargo in tanks is especially important in the case of Liquefied Natural Gas (LNG). The liquid is stored at atmospheric pressure in insulated tanks at -161° Celsius. Due to the insulation system, tanks cannot be partitioned. As a result, important liquid motions in the tanks, excited by the vessel motions, may be observed. The design of LNG ships or storage units is thus very complex. The state of the art methodology is based on the use of seakeeping computer codes to estimate ship or platform motions. Then experiments on tank models are performed in order to estimate global and local fluid loadings in the tanks. New estimation of the ship motions may then be necessary in case significant deviations between predicted and measured global loads are observed.

Moirod et al. (2009) present two different coupled approaches for evaluating the effect of the motion of the LNG cargo on the motion of LNG terminals. A time domain approach in which nonlinear sloshing effects are evaluated using a CFD code was compared to a more conventional approach combining a linearized sloshing model and a frequency domain seakeeping code. Different LNG FPSOs or LNG FSRUs configurations were studied. Numerical simulation results were analyzed together with dedicated experiments, either on the forced motion of LNG tank models, or in wave basin tests where hull and tank are modeled.

Similar numerical tools are used by Bunnik & Veldman (2010). In their study, the most advanced model combining linear diffraction theory for ship motions and CFD for the internal flow is shown to perform significantly better than the fully linearized one, although not incorporating boundary layer effects.

Lee et al. (2009) compared a pulsating Green function approach, a desingularized Rankine source method an a simplified sloshing model based on CFD, for the prediction of sloshing global force and moment due to liquid sloshing in partially filled tank. Good agreement between the three methods was found.

Cao et al. (2010) simulated 2D sloshing flows in rectangular tank using three different

CFD codes based on the SPH method, a Finite Element model (FeFLO), and a Volume of Fluid (VOF) methods (OpenFOAM), respectively. Potential flow solvers with different approximation levels for the free surface modeling were also included in the comparative study. Results are compared with experiments previously conducted in Marintek. The three CFD codes show very convincing results, while semi nonlinear and fully nonlinear potential flow models are shown to be capable of correctly estimating the fluid loading for non-breaking internal waves.

Another key problem is the estimation of the effect of impact loads on the insulation system. The integrity of the insulation system is vital, as any massive leakage of liquefied gas at very low temperature may lead to dramatic consequences for the ship, due to the fragility of steel at such temperatures. The estimation of actual impact pressures on the insulation system indeed involves the solution of a strongly coupled fluid-structure interaction problem, with the additional difficulty of multiphase flow and mass transfer between liquid and gas phases. This problem is numerically very challenging and the availability of accurate numerical models for the estimation of actual impact pressure in 3D insulated tanks is still ahead. Regarding the experimental approach, the situation is also very complicated, for a number of reasons: scaling effects, influence of pressure sensors during impacts, difficulty to work with actual fluids, model scale reproduction of the insulation system, etc.

Due to these difficulties, the methodology has long been widely based on the correlation between experiments on model scale tanks, using water and air as liquid and gas phases, and the feedback from the behavior observed on board ships in service. However, this methodology is valid only when *gradual* changes are made in the design of ships and on the operational conditions. With projects of very large LNG ships, and the development of floating storage and regasification units (FSRUs) operating with arbitrary filling ratios, the situation has changed, leading to massive R&D efforts to improve the methodology for assessing LNG ships and storage units designs.

Industries, classification societies and academics are contributing to this R&D effort. A noticeable example of collaborative research related to sloshing is the SLOSHEL Joint Industry Project (JIP), initiated by MARIN, Gaztransport and Technigaz (GTT), Bureau Veritas and Shell with six other participants, aiming at developing a methodology to assess membrane systems by direct comparison of the loads and the structural capacity. The project involved full and small-scale tests, numerical developments and validation studies. A global overview of the project is given in Brosset et al. (2009). One of the outstanding tasks within this project was related to the first impact experiments on full scale real containment system elements, subjected to water wave impacts produced by focusing waves. These tests, performed in the Delta flume operated by Deltares, are reported in Kaminski & Bogaert (2009). Among conclusions drawn from these experiments, it was noticed that the flip-through type of sloshing impact caused the most intensive action on the impacted structure and was very sensitive to small variations of the wave shape, which led to analyzing results based on a stochastic approach. NO96 samples sustained 110 impact tests with 2.6 MPa maximum local pressure recorded. These experimental results were further exploited to assess the direct Finite Element fluid-structure interaction approach adopted by ABS (Wang & Shin, 2009).

Within the project, tests at reduced scale were performed in Ecole Centrale Marseille, Kimmoun et al. (2009), with the aim of providing reference results for the validation of numerical models in the case of breaking waves impacting a flexible wall.

Figure 2.5.3: Full Scale Impact Tests on NO96 Elements in the Delta Flume (Kaminski & Bogaert, 2009)

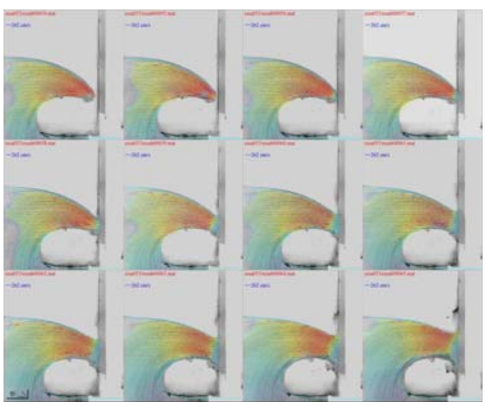

Figure 2.5.4: PIV Measurements of Fluid Velocities during Wave Impacts on a Flexible Wall (Kimmoun et al., 2009)

Regarding the development of numerical methods for the simulation of the complex fluid-structure interaction effects occurring during impacts on the containment systems, Oger et al. (2009) report on the development of a 2D Smooth Particle Hydrodynamics (SPH) model with applications to hydro-elastic impacts. Especially, the impact of an idealized NO96 2D model on a free surface is simulated, showing significant influence of the plywood structure deformation on the impact pressure field. Chen et al. (2009) developed a compressible two-fluid flow model for the simulation of liquid sloshing in 2D LNG tanks. Wemmenhove et al. (2009) report on the extension of a Volume of Fluid method to incorporate a compressible two-phase flow model for more accurate simulation of LNG tank sloshing.

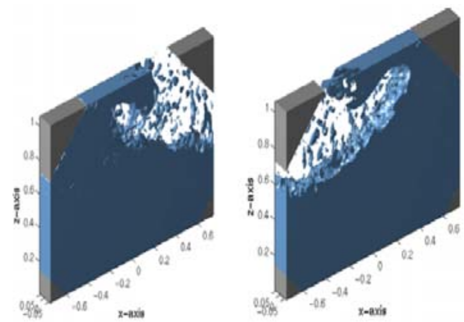

Figure 2.5.5: Fluid Configurations during Two Phase Sloshing (Wemmenhove et al., 2009)

Iwanowski et al. (2010) compared CFD calculations using the Comflow software, with large scale experiments carried out in MARIN and reported in Bunnik and Huijsmans (2007), using statistical analysis tools.

Braeunig et al. (2010) analyzed the effect of phase transition between the liquefied gas and its vapor on the impact pressure during sloshing.

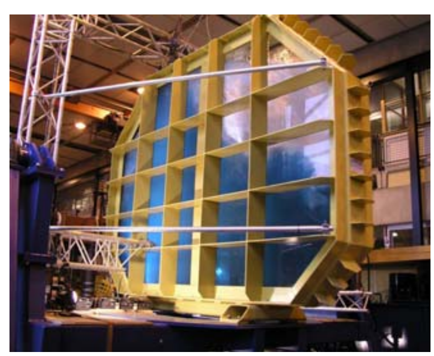

Figure 2.5.6: Large Scale Sloshing Facility (Bunnik & Huijsmans, 2007)

The research activity about sloshing is nowadays so active that a complete bibliographical review would be out the scope of the present report. Thus, for more information, analyses or references, we refer to the book by Faltinsen and Timokha (2009), and to the numerous papers presented since 2009 in the sloshing symposium of the ISOPE conferences.

2.5.4 Wave Run-up

Research has been carried out in the past years on the study of the wave run-up on cylindrical vertical structures, such as columns of TLPs, semi-submersible platforms, wind turbine structures, and vertical piles. The work has been focused on the use of mathematical models to account for nonlinear effects. Second-order potential theory and the CFD solutions have been explored along with experimental studies. The research has indicated that the developed numerical methods give results in a reasonable agreement with experimental data. Furthermore, studies have also been conducted on the probability distribution functions for events of the wave run-up phenomena.

Iwanowski et al. (2009) computed wave run-up on a semi-submersible's columns and under-deck fluid impact by using a CFD tool, ComFLOW, which solves Navier-Stokes equations by an improved Volume of Fluid (iVOF) method on high-accuracy computational grids. The computed wave run-up and fluid pressures at various locations were validated against the experimental results for a range of incoming wave heights.

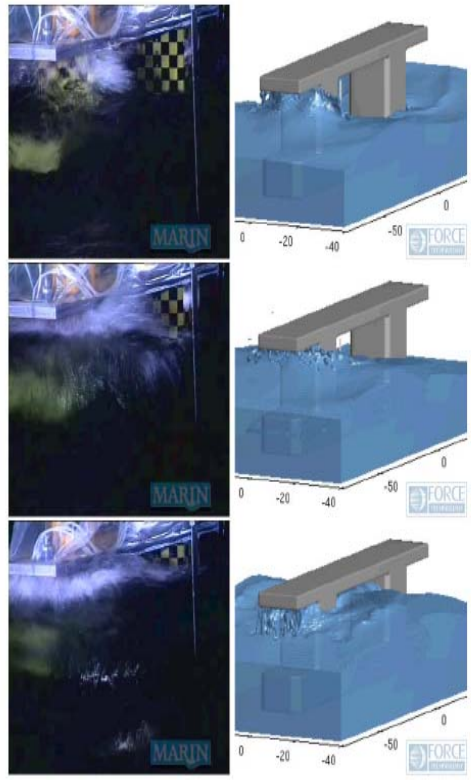

Figure 2.5.7: Wave Run-up. Videos from Tests with Short, Medium and Long Waves are Synchronized with Simulation Using ComFLOW (Iwanowski et al., 2009)

Myrhaug & Holmedal (2010) presented a practical method to estimate the wave run-up height on a slender circular cylindrical foundation for wind turbines in nonlinear random waves. The approach was based on the velocity stagnation head theory and the Stokes second-order wave theory. They assumed that the wave motion is a stationary Gaussian narrow-band random process. The results were compared with experimental results of de Vos et al. (2007). Some of the predicted highest wave run-up events agree with the experimental results.

Morgan & Zang (2010) presented the numerical simulation of non-linear wave interactions with a circular cylinder. The computed time series of free surface elevations were compared with experimental data for the impact of non-linear waves on a cylindrical column in shallow water. The rasInterFoam

CFD code, part of the OpenFOAM library, was used in the numerical simulation. They also presented two photos of the experimental test conducted at the Danish Hydraulic Institute's shallow water basin.

Izadparast & Niedzwecki (2010) carried out experiments with a mini-TLP model to develop a three-parameter probability distribution function for nonlinear wave run-up amplitudes. This study demonstrated that the new empirical model and the Weibull distribution are more robust in representing the probability distribution of nonlinear run-up amplitudes, especially for the weakly nonlinear cases with moderate steepness. The sea states investigated included the relatively benign sea conditions of West Africa and the more extreme sea environments of the Gulf of Mexico.

Zang et al. (2008) presented both numerical and experimental studies on the non-linear wave interaction with a circular cylinder in shallow water and examined the effect of non-linearity on the wave run-up. In the numerical simulation, the second-order wave diffraction theory was employed. The time-history of the wave run-up on the cylinder and the wave response from the diffracted waves were presented and compared with the experimental data from the model tests conducted in a wave tank. The authors concluded that the second-order wave diffraction solution works well for steep waves in shallow water, while the linear diffraction theory incorrectly predicts the peak water levels and the response spectrum.

Huang & Chen (2010) developed a numerical wave model to simulate the run-up and overtopping of a solitary wave near a real seawall. The unsteady Reynolds Averaged Navier-Stokes (RANS) equations were solved. The hybrid particle level-set method was applied to capture the complex free surface evolution. An immersed boundary method was adopted to mimic the irregular solid boundary. Numerical results were compared with experimental data of the wave run-up and overtopping near a real seawall located at the east coast of Taiwan.

Considering that nonlinear effects on the incoming and scattered waves are usually relevant and sometimes non-linear effects on the motions of the floating hull may also play an important role in estimating the air gap, Matsumoto et al. (2010) developed a numerical solution to determine the air gap for a large semi-submersible production platform. Their numerical results were obtained using WAMIT which accounts for second-order diffraction effects, and the CFD code COMFLOW. Numerical results were compared with the experimental data from the model tests of a large semi-submersible designed to operate in Campos Basin. The authors indicated that the use of second-order effects improved the predictions as the wave-steepness increased. The numerical results presented are in good agreement with the experimental data.

For the prediction of wave run-up around a gravity based structure in intermediate water depth, Danmeier et al (2008) evaluated two computational tools, the panel program WAMIT and the Volume-of-Fluid (VOF) program ComFLOW. Predictions of maximum wave run-ups in irregular waves based on linear and second-order diffraction theories were compared to the model basin results. The importance of including nonlinear effects has been illustrated. As indicated by the authors the differences between the predictions from the second-order diffraction theory and model test results are presumably due to the highly nonlinear phenomena, such as jet-like wave run-up (see Figure 2.5.8) and interaction effects with the submerged caisson. The ComFLOW simulations revealed that the wave run-up was sensitive to the incident wave and that the maximum amplification occurred when the incident wave was nearly breaking (see Figure 2.5.9).

Andersen et al. (2011) carried out model tests to develop a design procedure on estimating wave run-up and the induced loads on platforms for offshore wind turbines. They investigated the effects of the water depth to pile diameter ratio, the wave height to water depth ratio and wave steepness. A design method to consider the interaction of waves with offshore wind turbine was presented. It was based on the stream function theory for wave kinematics and the velocity stagnation head theory with the inclusion of an empirical factor on the velocity head. The method has been evaluated against data from other published results. The authors considered that the method is reliable and accurate.

Figure 2.5.8: Wave Run-up Around a GBS (Danmeier et al., 2008)

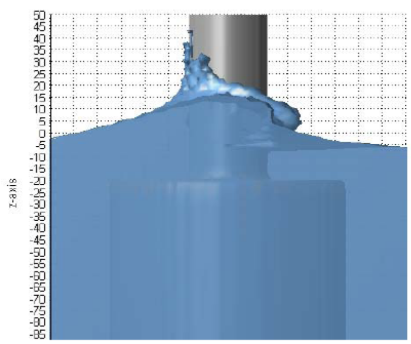

Figure 2.5.9: Wave Run-up around a GBS (Danmeier et al., 2008)

2.6 New Experimental Techniques

The collision scenario when a semi-submersible is struck by a containership was studied by Hu et al. (2010) through model tests. Two special devices were designed to fulfil the model tests. One is the Ship Launching Device (SLD) which launched the striking ship with the controllable velocity in any horizontal direction. The other one is the Energy Absorbing Device (EAD), which can simulate the buffer effect of the column structure and collect the collision force as well. The collision force dominates the collision moment and the tension force of the mooring lines lags behind.

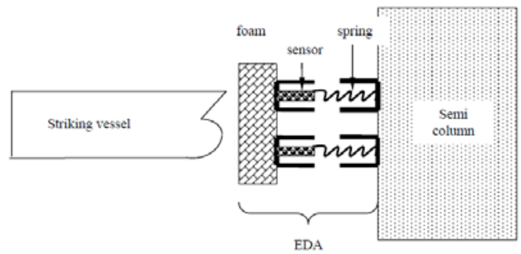

Figure 2.6.1: Energy Absorbing Device (Hu et al., 2010)

Fernandes et al. (2009) presented a methodology to be used in model tests to overcome the limitation of ocean basins to simulate the ocean depth. For instance new oil field discoveries, Tupi and Jupiter in Brazil, are over more than 3000m water depth. They suggested the use of magnetic bases to avoid problems with lines truncation, so that the same full scale properties such as restoring forces and also the same viscous dissipation are obtained.

3. REVIEWING THE EXISTING PROCEDURE

The committee reviewed the existing procedure 7.5-02-01-01 on the uncertainty assessment methodology for the uncertainly analysis in EFD. This procedure introduces a general methodology for estimating the uncertainty in an experimental result at a 95% confidence level.

The committee recommended including clear definitions for the precision error, the bias error, the random error and the systematic error. It is also recommended to include the application of the methodology to complex seakeeping and ocean engineering experiments.

Two references were added related to the evaluation of measurement data and the expression of uncertainty in measurement.

4. PARAMETERS CAUSING LARGEST UNCETAINTIES IN OCEAN ENGINEERING TESTS

4.1 Introduction

There are many parameters causing uncertainties in ocean engineering tests and numerical simulations. A list of parameters has been identified. The parameters causing largest uncertainties in ocean engineering experiments involving mooring lines and dynamic positioning systems are discussed in Section 4.2 and Section 4.3.

The parameters causing uncertainties in general ocean engineering model tests, full-scale tests and numerical simulations are listed below according to the categories of physical properties of fluid, initial conditions, model definition, environments, scaling, instrumentation and human factors.

Model Tests:

- Physical properties of the fluid
  Viscosity
  Water density
  Temperature
  Surface tension
  Seeding or contamination
  Aeration

- Initial conditions
  Remaining waves from previous tests
  Remaining circulation from previous tests
  Remaining turbulence from previous tests
  Initial model motion

- Model definition
  Bottom friction for mooring lines
  Truncation of mooring lines
  Length of mooring lines
  Diameter of mooring lines and risers
  Weight distribution of mooring lines and risers
  Stiffness distribution of mooring lines and risers
  Structural scaling
  Friction in bearings etc.
  Location of anchor point
  Fairlead position
  Hull geometry
  GM values with and without mooring lines
  Inertia properties
  Stiffness properties
  Pretension of mooring lines and risers
  Surface roughness
  Topside geometry
  Speed and heading

- Environment
  Wave condition, usually only measured at defined points
  Parasitic waves on shallow water
  Variation of current in time and space
  Wind (homogeneity, profile)
  Wave maker control
  Wave reflection from beaches and model
  Interaction between wind and wave
  Refraction due to uneven seabed on shallow water
  Wave-current interaction
  Test duration which affects the quality of generated environments.

- Scaling
  Scaling of parameters in different regimes

- Instrumentation
  Accuracy of gauges
  Calibration of gauges
  Stability
  Parasitic vibrations
  Noise

- Human factors

Full scale experiments:

- Physical properties of the fluid
  Viscosity

Water density
Temperature
Surface tension
Contamination
Aeration
Salinity

- Environment
  Wave condition, usually only measured at defined points
  Variation of current in time and space
  Wind (homogeneity, profile)
  Wave reflection from beaches and model
  Interaction between wind and wave
  Refraction due to uneven seabed on shallow water
  Wave-current interaction

Numerical modelling:

- Modelling errors
  Choice of method
  Equations to describe real physics
  Level of approximation
  Turbulence models
  Grid generation (volume or geometry correct)
  Rounding error
  Budget
  Introduction of empirical parameters
  Understanding of the physical model by the practician

4.2 Uncertainties in Tests Involving Mooring Lines and Risers

When testing structures with mooring lines, risers or other submerged lines, the primary requisite is to correctly model the system quasi-static characteristics, i.e., forces and moments due to linear and angular offsets of the moored structure. Many uncertainties are involved in this stage, especially when the truncation of lines is needed, since it is difficult to scale the elastic and mass characteristics of prototype lines. To scale the elasticity (EA and EI, when it is important) and mass (density) in the same time, it is often required to change the specified segments configuration of each line, or even bundle some very thin lines in groups. This leads the addition of spring segments, the partial or total substitution of original segments, and sometimes the addition of floaters or clump weights in some segments to correct submerged weight.

The instrumentation of mooring lines also causes some uncertainties, for example, in-line load cells are often used to measure line tensions. The geometry and the weight of such sensors change the properties of the line segment where the sensors are located.

Other source of uncertainty is the location of an anchor point on the basin bottom. Special care has to be paid to the correct marking of anchor points and water depth of mooring lines. The bottom friction coefficient also contributes to the uncertainty.

For model tests with truncated mooring lines/risers, it is important to keep the correct geometrical parameters of the system, i.e., top angles and lines elongation during excursion. This may lead to other distortions on the original specified characteristics of segments. In some cases, a totally different mooring system from the prototype one may be used.

Having assessed the quasi-static issues on the design of scaled submerged lines, the next step is to check the hydrodynamic loads on the lines. The drag of the segments may play an important role in the behavior of the floater, especially when the number of mooring lines and riser is large and/or the floater damping is small compared to the lines damping. In this case, the truncation will lead to more uncertainties due to geometric differences on segments and great changes of the configuration of the mooring lines. To assess the drag of the modeled lines, an analysis of the Reynolds number on each segment will be necessary and some distortion on diameters may be needed to correct the drag effects.

4.3 Uncertainties in Tests Involving DP Systems

There are many factors causing uncertainties in model tests involving DP systems. The first issue is on the floater itself which is usually tested in low velocities. This will lead to great scale effects due to friction forces acting on the hull. The second issue is the modeling of thrusters and propellers whose hydrodynamic characteristics are not necessarily well described by the Froude scale law. Even if the thrust forces are correctly modeled according to the Froude scale, other uncontrolled effects on the flow of each propeller and on the thruster-thruster and thruster-hull interactions may affect the behavior of the overall system.

The third issue is on the modeling of the electronic control system. Usually the parameters used in the DP system of a prototype are tuned in a very empirical way and based on the experience of the DP system manufacturer. These parameters are often not available for the model tests. Even when they are known, they will have to be adapted to the model system. As the control parameters are directly related to the behavior of the system, special care is needed. There are also uncertainties associated with the feed values of model position which is usually measured by an optical tracking system and other parameters, e.g., wind velocity and wave heights. It is desirable that these values are treated to give correct levels of input noise to simulate the same uncertainty observed in prototype, i.e., the GPS and other equipment errors. It is also beneficial to assess the influence of the uncertainty on the behavior of the control system by changing the level of noise on the feed values.

Based on the issues discussed above, the main factors affecting the uncertainties in DP tests are listed below:

- Scale effects on model friction forces due to low Reynolds number;
- Hydrodynamic effects due to propellers interaction;
- Hydrodynamic effects due to thruster/hull interaction;
- Propeller air suction effects;
- Propeller emersion effects;
- Greater rpm of the propellers;
- Control parameters of model and prototype;
- Bundling propellers or changing of propeller/thruster position due to space limitation of model;
- Quality of feed values used in the control system of the model different from those of the prototype.

5. BENCHMARK STUDIES - VIV

5.1 Benchmark Data

The benchmark data for the VIV of a circular cylinder was provided by MARIN. The rigid circular cylinder is 200mm in diameter and 3.52m in length (Figure 5.1.1). The cylinder was suspended from the carriage about 1.7m below the calm water surface. The VIV test apparatus is shown in Figure 5.1.2. The towing tank is 4m deep, 4m wide and 210m long. The cylinder was kept fixed in the flow and towed by the carriage at various speeds. Details of the tests can found in de Wilde & Huijsmans (2001) and de Wilde et al. (2003, 2004 and 2006).

Figure 5.1.1: Smooth Cylinder of MARIN

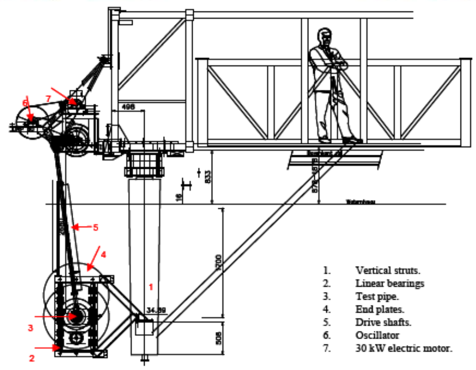

Figure 5.1.2: High Reynolds VIV Test Apparatus

For the numerical computations, six (6) Reynolds number are selected as follow:

6.31E+04, 1.26E+05, 2.52E+05
3.15E+05, 5.06E+05, 7.57E+05

The measured drag coefficient for the smooth stationary cylinder is presented in Figure 5.1.3.

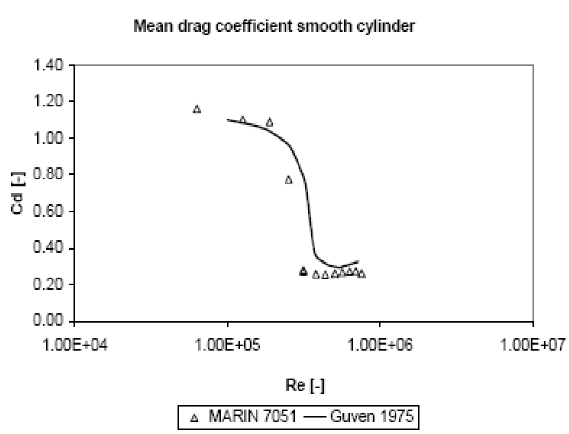

Figure 5.1.3: Drag Coefficient for Smooth Cylinder

5.2 Participants and Numerical Methods

Various organizations and individuals have been invited to participate in the benchmark studies. A list of participants is given in Table 5.2.1. The numerical methods and computational details are summarized in Table 5.2.2.

Table 5.2.1 Participants for the VIV Benchmark Studies

Affiliation	Nationality
China Ship Scientific Research Center (CSSRC)	CHINA
Seoul National Univ. (SNU)	KOREA
Samsung Ship Model Basin (SSMB)	KOREA

Table 5.2.2 Numerical methods Used by the Participants

Participant	Code name	2D/ 3D	Steady/ Unsteady	RANS/ LES/ etc
A	FLUENT (Commercial Code)	2D	Unsteady	RANS
B	In-house Code	2D	Unsteady	RANS
C	FLUENT (Commercial Code)	2D	Unsteady	RANS

	Number of Grid	Type of Grid	Convection term	Δt
A	87223	Structured	Upwind	0.001/0.0005
B	32280	Structured	Upwind	0.001/0.0002 /0.0001
C	43820	Structured	Upwind	0.001

	y^+	Wall function (Use / No use)	Turbulence model	Transition model (Use / No use)
A	59	U	k-w SST	N
B	2	N	k-w SST	N
C	10	N	k-w SST	N

5.3 Numerical Results

In the benchmark studies, the mean C_D, the mean C_L, the RMS of C_L, and the Strouhal number were compared to experimental data measured by MARIN. Vorticity contour (at Re=6.31E+04, 7.57E+05) from numerical simulation were also presented.

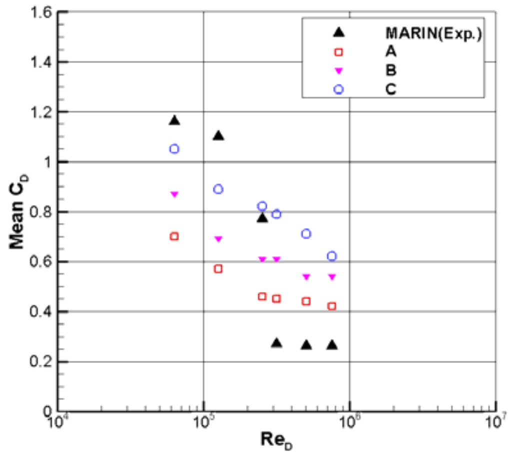

Figure 5.3.1: Mean Drag Coefficient

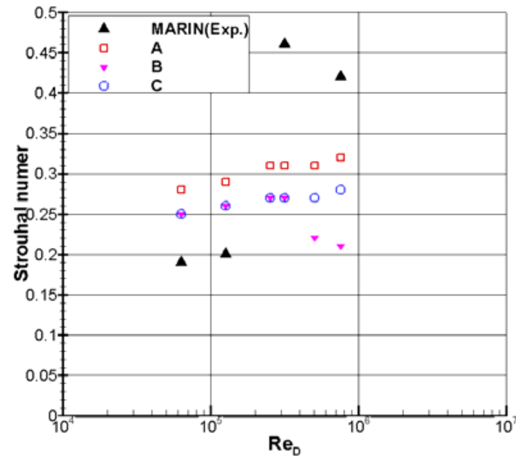

Figure 5.3.4: Strouhal Number

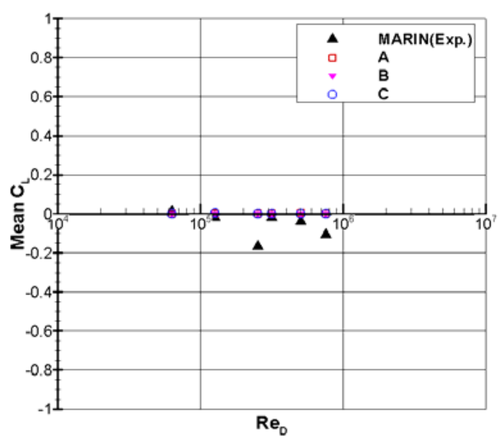

Figure 5.3.2: Mean Lift Coefficient

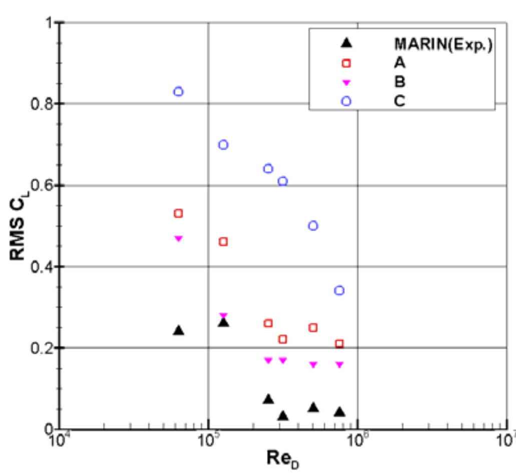

Figure 5.3.3: RMS of Lift Coefficient

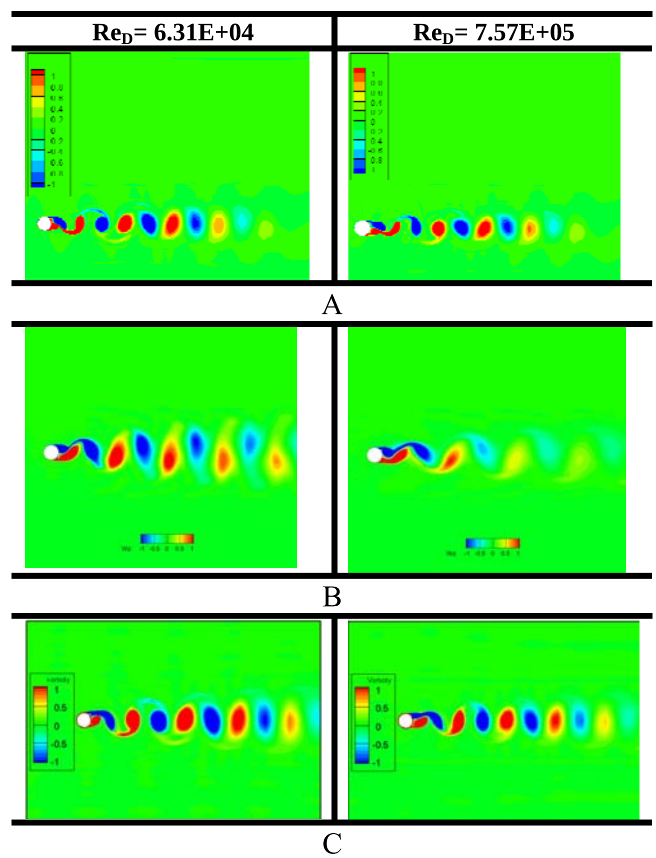

Figure 5.3.5: Vorticity Contour

5.4 Conclusions and Recommendations

In this benchmark study, all participants selected two-dimensional unsteady RANS methodology. The k-ω SST turbulence model is used with the assumption that the flow is fully developed to the turbulent status.

It is concluded that the drag crisis phenomenon on the stationary smooth cylinder was not predicted in the numerical studies. It is well known that the drag crisis is caused by the instability of separated shear layer in critical range ($3\text{x}10^5 < Re_D < 3.5\text{x}10^5$). At the critical Reynolds numbers, the transition point is located very close to the point of flow separation. As a result, the shear layer eddies cause the mixing of flow in boundary layer so that the flow is energized and the flow separation is delayed. The delay of separation point leads to the reduction of the drag coefficient (Singh & Mittal, 2005). The methodology based on two-dimensional, unsteady RANS with turbulence models is not sufficient to simulate the physical phenomenon. It is necessary to predict the complicate flow phenomenon using LES or DNS method.

6. MOORING LINE DAMPING

6.1 Introduction

The dynamics of mooring lines are complicated and challenges still exist in understanding the behaviors of the system and its interaction with the moored vessels and floating structures. The Committee was tasked to propose benchmark tests for mooring line damping. A literature review was first conducted to identify existing model-scale and full-scale tests. In the review, focus was put on the low-frequency mooring line damping forces exerted on moored structures.

The use of model tests to understand the mooring system damping is expensive and technically challenging. A comprehensive parametric study on mooring line damping dynamics was conducted by Webster (1995). In his work, Webster identified 15 factors involved in mooring dynamics and obtained an expression for non-dimensional tension of a mooring subjected to sinusoidal forced motion at the top end using dimension analysis.

$$\frac{T}{wH} = f\left[\frac{t}{\tau}, \frac{l}{H}, \frac{T_o}{wH}, \frac{a}{H}, C_d\frac{D_h}{D_s}, C_m\frac{A_h}{A_s}, \frac{I_s}{A_s^2}, \frac{\tau}{2\pi}\sqrt{\frac{g}{H}}, \frac{\rho fg}{w}, \frac{wl}{E_sA_s}, \frac{A_s}{H}, \frac{\rho_f}{2}\frac{U_c^2}{wD_s}\right]$$

where:

- a = amplitude of sinusoidal motions
- A_h = effective cross-sectional area for computing added mass
- A_s = structural cross-sectional area
- C_d = cross-flow drag coefficient based on D_h
- C_m = added mass coefficient based on A_h
- D_h = effective diameter for computing drag
- E_s = modulus of elasticity
- g = gravitational acceleration
- H = water depth
- I_s = moment of inertia in bending
- l = length of line from fairlead to anchor
- ρ_f = mass density of sea water
- τ = period of sinusoidal motions
- t = time
- T_o = pretension
- U_c = current velocity
- w = wet weight per unit length of line

In a dynamic analysis, some of these terms may be neglected for simplicity. For instance, the added mass term may be neglected since mooring lines possess relatively small diameters. In addition, the term (Ds/H) may be neglected since the diameter is always much smaller than the water depth. With these assumptions, the mooring induced damping, *D*, may be expressed as the amount of energy absorbed per cycle by the mooring line.

$$D = \int_t^{t+T} T_n(q_n)\frac{dq_n}{dt}dt = \oint T_n(q_n)dq_n$$

where T_n is the component of tension in the **n** direction and q_n is the instantaneous displacement in that same direction. Non-dimensional damping is obtained by *D/(awH)*.

$$\frac{D}{awH} = f\left[\frac{l}{H}, \frac{T_o}{wH}, \frac{a}{H}, C_d\frac{D_h}{D}, \frac{\tau}{2\pi}\sqrt{\frac{g}{H}}, \frac{E_sA_s}{wl}, \frac{\rho_f}{2}\frac{U_c^2}{wD_s}\right]$$

These parameters were varied, one at a time, to examine their impact on the dynamic response and damping of mooring lines. Webster presented the results on the response to horizontal and vertical forced motions, as well as the influences from drag coefficient, excitation period, stiffness, and current.

In the physical modelling of mooring system, the most important property is the weight per unit length of the line. The size and material of the model line must be chosen to match the weight at a small scale. Another important property is the elasticity of the line at the desired scale. The most difficult property to model; however, is the geometry of the line. As indicated in the work of Chakrabarti (2002), the difficulties in modelling the properties of mooring lines lead to challenges and inaccuracy in studying the mooring damping at model scale.

6.2 Existing Tests

A few model and field experiments have been identified in the review.

Model-Scale Tests

Huse (1986) conducted model tests on mooring line hydrodynamic damping at MARINTEK. The experiments consisted of two models of semi-submersibles moored by 3-inch chain in a spread mooring configuration. The tests were first conducted with a model of the spread moor configuration, and then some tests were repeated with the models attached to horizontal lines and springs. Both models were tested at 1:50 scale. As shown in the surge spectrum (Figure 6.2.1), the drag forces on mooring lines provide a great source of surge damping for moored semi-submersibles. Based on the analysis, it was shown that a 20-25 percent damping was noticed in surge and sway directions. Huse's work has proved that the inclusion of mooring line damping for offshore structures is vital to the prediction of motions of these vessels.

Huse & Matsumoto (1988) further conducted two sets of experiments to verify a simplified approach for estimating mooring line damping. The first set of experiments involved calm water surge decay tests and irregular sea tests that measured motion responses of a ship. The tests were conducted with catenary mooring lines and repeated with horizontal lines and springs. The spring stiffness was selected to achieve the same surge natural frequency in both cases. In the second set of experiments, a pendulum-induced motion was excited on mooring lines and the damping energy of model mooring lines was measured.

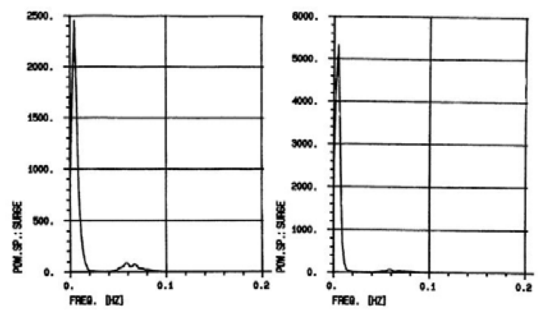

Figure 6.2.1: Surge Spectrum for Platform A. Left: Complete Modelling of Catenary Mooring System. Right: Model Suspended in Horizontal Lines and Springs (Huse, 1986).

Another set of experiments on mooring line damping were conducted by Huse & Matsumoto (1989). The purpose of the experiments were to evaluate the various contribution to surge damping by (1) viscous forces on the hull in calm water, (2) mooring system in sinusoidal LF surge, and (3) mooring system with combined LF surge and superposed HF motions. The first item above was measured accurately using surge decay tests with the model moored in horizontal lines and springs. The second contribution was determined from conducting a calm water surge decay test with the complete mooring system at model scale. The energy dissipation obtained from this experiment was the sum of the contributions from the first two items. Subtracting the measured result from the viscous force effect (item 1) gives the contribution from the mooring system. Huse and Matsumoto explained that the third item was difficult to determine just by model testing in waves. Hence they utilized an exciter mechanism to excite the top end of the mooring system relative to the model. Performing the calm water decay tests with the excitation at the same time gives the damping energy dissipation that is the sum of the first three items above. Again, subtracting the measured energy from the first two items, the contribution from item 3 was obtained.

Wichers & Huijsmans (1990) conducted the low-frequency oscillation tests to obtain the mean chain damping values of a turret-moored tanker. The lower end of the chain being tested was mounted onto a "false bottom" which was fixed to the carriage. The top end of the chain was connected to a force transducer that was attached to an oscillator also mounted on the carriage. The chain force, horizontal force and displacement were measured. The effect of current was taken into account by simply towing the chain through the basin. The scale used in the experiment was 1:82.5.

Matsumoto (1991) focused on the theoretical and experimental aspects of the three main contributions to the low-frequency surge motion of moored vessels - the drag and friction damping on the moored vessel, wave drift damping, and drag forces on mooring lines. The experiments were performed on a ship-shaped, turret-moored floating production system. The first part of the experiments was to find out the contributions to low-frequency surge damping from the three factors mentioned above. In doing so, three types of surge decay tests were conducted, including (1) model moored in horizontal lines and spring, tests conducted in still water, (2) model moored by same lines and spring system as above, tests conducted in five different regular waves, and (3) model moored in modelled catenary mooring system, tests conducted in still water. The second part of the experiments was to measure the low-frequency motions in irregular waves. Two kinds of measurements were taken: one with horizontal mooring lines and springs and the other with catenary mooring system. Measurements from the former include effects from viscous damping and wave drift damping on the hull. The latter includes the effects from viscous, wave drift, as well as mooring line damping. Based on these two measurements, the effect of mooring line damping on low-frequency surge motion was found.

Bauduin & Naciri (2000) developed a quasi-static approach for computing mooring line damping. In verifying their approach, results from his approach were compared to the experimental results obtained from experiments conducted for two field developments (the Teal and Guillemot Fields in Central North Sea and the Aquila Field in the Adriatic Sea.) Note that the Anasuria FPSO is used in the production in the Central North Sea while the Firenze FPSO operates in the Adriatic Sea.

The Anasuria FPSO mooring system was tested in the MARIN ocean basin. The FPSO operates in 89.2 meters of water depth, and is kept in station by a mooring system that consisted of 12 mooring lines. The experiment was conducted at a scale of 1:80. The mooring line damping was determined from a decay test in calm water by subtracting the viscous hull damping component. The viscous hull component was obtained by performing a calm water decay test in which the model was suspended in horizontal lines and springs.

The Firenze FPSO mooring system was tested at MARINTEK at a scale of 1:120. The mooring system on the FPSO consisted of 8 mooring lines. The test program consisted of decay tests in calm water, current, irregular waves, and irregular waves with current.

Sales and Sphaier (2009) carried out an investigation on mooring line damping using two sets of tests: (1) a semi-submersible moored with 20 lines and (2) an FPSO moored with 4 equivalent spread mooring lines. For the first set of tests, taut mooring tests were conducted on the semi-submersible with the following configurations: horizontal mooring tests, truncated tests and full depth tests. For each of the configurations above, static offset, surge and sway decay tests, regular and irregular wave tests were conducted. Some of the results from this set of experiments are shown below:

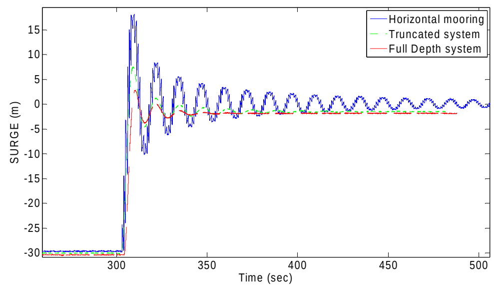

Figure 6.2.2: Surge Decay for Different Test Configurations (Semi-submersible)

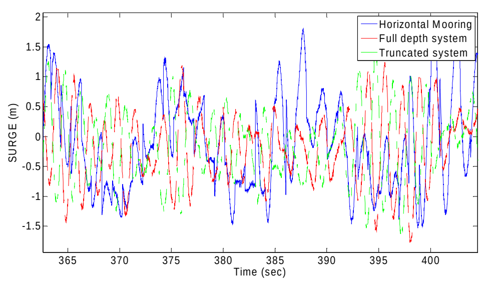

Figure 6.2.3: Surge Response from Irregular Wave Tests for Different Test Configurations (Semi-submersible)

Figures 6.2.2 and 6.2.3 present the surge decay and the responses due to irregular waves, respectively, for the three configurations. Largest responses were recorded for the horizontal mooring case, as this configuration excludes the effect due to mooring line damping. When mooring line effects are included (truncated and full depth systems), the responses are reduced due to mooring system damping.

For the second set of tests, mooring tests were conducted on an FPSO model with the following configurations: (1) horizontal mooring tests, (2) four lines mooring system tests (thin wire), (3) four lines, increased diameter tests (tube around wire), and (4) four lines, additional increase in diameter (another tube around wire). For each of the above configurations, static offset, surge and sway decay, and regular and irregular wave tests were conducted.

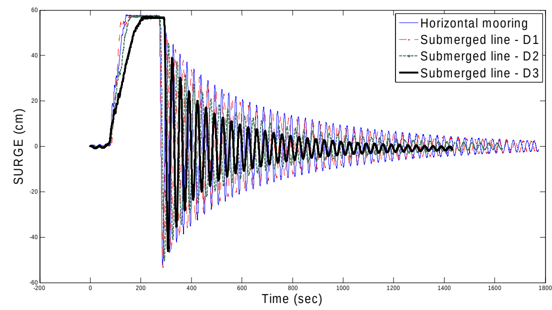

Figure 6.2.4: Surge Decay Responses for Different Mooring Configurations

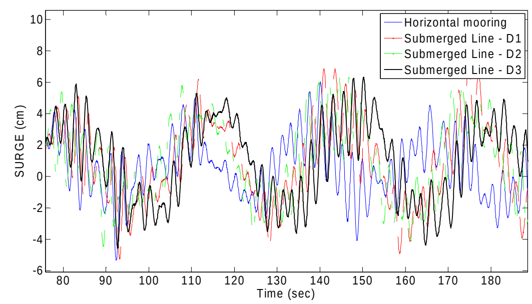

Figure 6.2.5: Surge due to Irregular Wave Tests

Figures 6.2.4 and 6.2.5 show the surge decay responses and those due to irregular waves. Mooring line damping effects were noticeable in decay tests. However, it was concluded that the effects of mooring line damping was insignificant in wave-only tests, further investigation is needed to perform tests with current.

Full-Scale Tests

Full-scale free-oscillation field experiments were carried out by Triantafyllou et al. (1994) through a Joint Industry Project (JIP), entitled "Mooring Line Damping and Current Loads", led by Noble Denton & Associates Inc. The full-scale experiments were conducted on the "Jack Bates", a 4th generation semi-submersible. The mooring system was an 8-point spread mooring system (3-9/16 in x 2,000 ft RQ3 chain, and 3-3/4 in x 7000 ft six-strand wire). The semi-submersible has dimensions of L x B x D (370 x 255 x 140) feet, an operating draft of 75 feet, and a displacement of 103,000 kips. The rig was operating in 2,800 feet water depth in the Gulf of Mexico. During the field measurements, the weather condition was described as calm/moderate, with a wind speed of 17 knots, and wave heights of 4-6 feet. The field test consisted of the following steps: (1) an initial offset was induced by the thrusts onboard, (2) thrusters were then shut off, (3) time-history of rig motion and mooring line tensions were recorded, and (4) the LF damping based on observed oscillation attenuation was estimated. The test program gave an indicative measure of LF damping in calm to moderate sea states. However, a rigorous field measurement is needed to correlate field observations with analytical or experimental predictions for severe storms.

Another full-scale experiment was conducted during the October of 1995 on the ALAGOAS tanker. At the time, the tanker was moored in the southern part of the Brazilian coast. The tanker is 168 m in length, 25 m in breadth, a draft of 7.6 m, and a displacement of 27,428 cubic meters. The environmental conditions were fairly calm, with wind speed of 7 knots, wave height of 0.5 m and current speed of less than 0.2 m/s. The full scale tests were conducted in 185 meters of depth. The mooring system consisted of eight mooring lines, each with a diameter of 0.095 meter, a unit weight of 58 kgf/m, and a drag coefficient C_D of 1.8.

Two sets of data were analyzed and presented in the work of Nishimoto et al. (1999). The first set of data was obtained from a decay test in which the tanker was pulled with 70 tonf of force and then released, while the second set recorded a pulling force of 100 tonf. The instantaneous positions of the ship were recorded by a DGPS every 3 seconds, and transformed into surge and sway motion. Figure 6.2.6 presents the results collected from the first decay test, with a pulling force of 70 tonf. The top plot shows the positions of the tanker as recorded by the DGPS, and the bottom plot is the analyzed sway motion over time. Figure 6.2.7 shows the position and sway motion data collected for the 100 tonf case. The surge motion for both cases is shown in Figure 6.2.8.

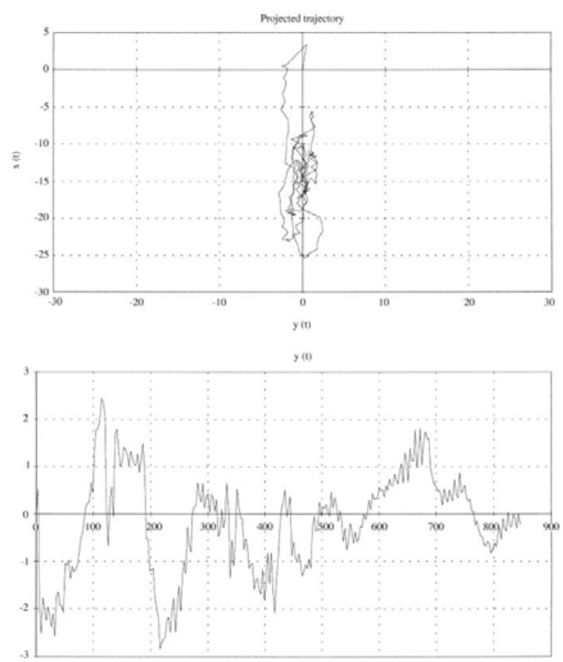

Figure 6.2.6: 70 tonf Pulling force. Top: Ship's Position in xy Plane. Bottom: Sway Motion

The experiments described above were mainly concerned with surge and sway damping due to the mooring system. Huse (1991) carried out investigations of heave damping due to mooring systems. It was concluded that heave damping effects from mooring systems may be negligible for moored ships, but important for semi-submersibles, and dominating for spar buoys.

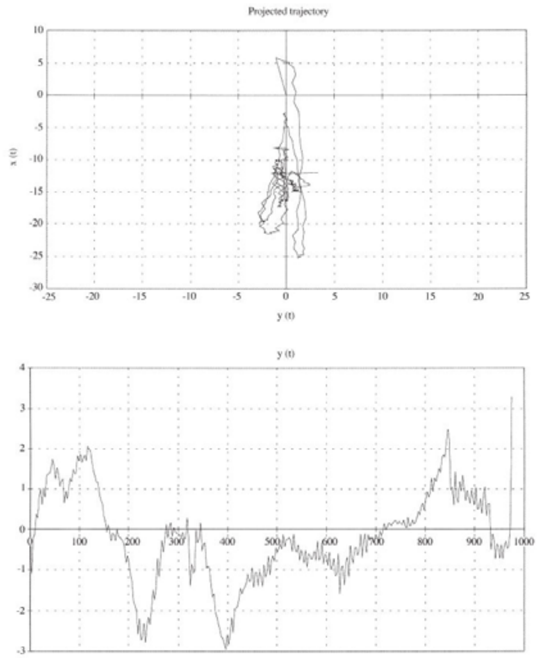

Figure 6.2.7: 100 tonf Pulling Force. Top: Ship's Position in xy Plane. Bottom: Sway Motion

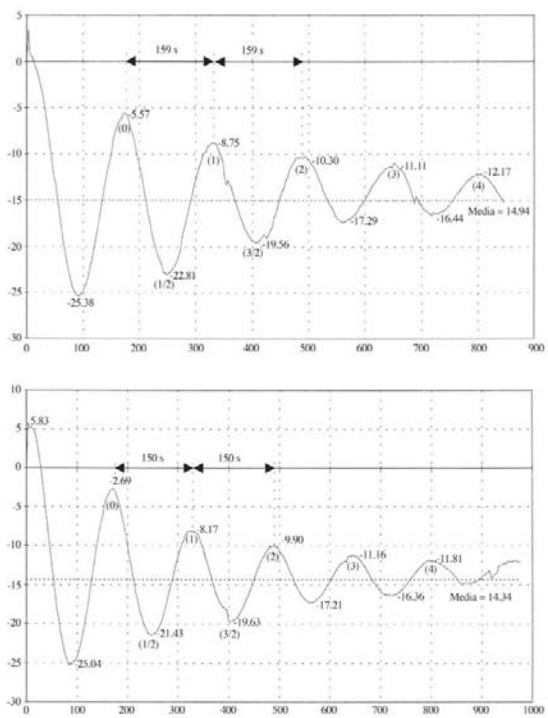

Figure 6.2.8: Surge motions for cases of 70 tonf and 100 tonf

6.3 Challenges

A literature review has been conducted for mooring line damping. Existing model and full-scaled tests have been reviewed. As discussed above, the three most significant contributions to damping of a moored vessel are from the viscous hull effects, mooring system damping, and drift force. The most practical approach to obtain the mooring system damping is to perform calm water decay tests. The decay test is first carried out with a complete modelling of the vessel and its mooring system, and then the same decay test is conducted for a model suspended by horizontal lines and springs. From the first type of calm water decay tests, one may obtain the total damping energy from both viscous hull effects and the mooring system. The second type of calm water decay tests produce the damping energy from viscous hull effects. Subtracting the damping energy obtained from the second type of experiments from the first type of experiments, one obtains the mooring system damping in calm water.

For the mooring damping due to the low-frequency motions in regular and irregular waves, two measurements can be taken: one with horizontal mooring lines and springs and the other with a mooring system. Based on these two measurements, the effect of mooring line damping on low-frequency motion can be found.

The main challenges for obtaining the mooring damping in model tests lie on the geometry modelling of lines and scale effects. With the water depth increased, the scale effect becomes more severe. In addition, it is difficult to obtain the mooring line damping with scaled model testing for platforms operated in ultra-deepwater due to the limitation of today's testing facilities.

The desirable approach is to determine the mooring damping from the full-scale tests. There are very limited test results available for use. A rigorous field measurement is needed. However, it is very difficult to get the full-scale tests carried out due to financial and operational reasons.

6.4 Recommendations

It is recommended to conduct large-scale model tests of a semi-submersible in a lake and in a model basin to study the scale effect on determination of the mooring line damping.

7. GUIDELINES FOR HYDRODYNAMIC TESTING OF RENEWABLE ENERGY DEVICES

The Committee focused on the development of the guideline for wave energy converter (WEC) experiments. The guideline (7.5-02-07-03.7) has been developed by considering the main differences and challenges between the WEC tests and the offshore structure tests as follows:

- The inclusion of a simulator of the power take-off (PTO) mechanism in WEC tests. One of the important objectives in WEC tests is to evaluate the device's ability to capture and convert wave energy.

- Involvement of various experimental stages, such as the concept validation stage, the design validation stage, the system validation stage, and the prototype and demonstration stage. The model scale depends on the test stage.

- Tests of multiple device models corresponding to a farm of WECs.

The purpose of this guideline is to ensure that wave energy converter (WEC) experiments are performed according to the state of the art. In general, model tests on WECs are employed to validate the device concept, quantify the technical performance variables, acquire information on power take-off (PTO) and data for optimized performance design, confirm survivability characteristics, and validate numerical models.

8. PROCEDURE FOR DYNAMICALLY POSITIONING SYSTEMS

Before proposing the procedure for model tests of dynamic positioning systems, questionnaires were sent to ITTC members. Responses from nine organizations (Table 8.1.1) have been received. The questionnaires included the following subjects:

- Purpose of DP model tests
- Parameters for DP tests
- Model scale
- Environmental parameters
- Actuators
- Measuring systems
- Control system
- Filtering system
- Thrust allocation logics
- Feed forward
- Test duration
- Procedures for DP tests
- Environmental calibrations (wave, current, wind and combined environments)
- Actuator calibrations
- Thrust loss tests
- Measuring motion and velocity
- Measuring actuator's parameters
- Validation procedure for DP tests
- Uncertainty analysis
- Validation numerical models
- Validation against full scale data
- Benchmark test

A procedure (7.5-02-07-03.6) for model tests of dynamic positioning systems has been developed. The practices used by the organizations have been reflected in the procedure.

Table 8.1.1 Participants of DP Questionnaire

No.	Affiliation	Nationality
1	China Ship Scientific Research Centre (CSSRC)	China
2	FORCE Technology (FORCE)	Denmark
3	Institute for Ocean Technology (IOT)	Canada
4	Lab Oceano and Sao Paulo University	Brazil
5	MARIN	Netherland
6	MOERI	Korea
7	Samsung Ship Model Basin (SSMB)	Korea
8	AKISHIMA Laboratories (MITSUI ZOSEN) Inc.	Japan
9	Shanghai Jiaotong University	China

9. CONCLUSIONS

9.1 State of the Art Review

Bottom-Founded Structures

Experimental and numerical design procedures for bottom founded structures (BFS) are well established, but significant challenges remain, concerning unusual geometries, and/or extreme conditions for which direct numerical simulation methods may take the advantage over standard fluid loading estimation methods based on Morison's equation. This is especially the case for structures supporting marine renewable energy systems which introduce elements to the design problem not normally encountered in conventional mainstream offshore BFSs. The most significant effort in this category concerns the numerical modeling of offshore wind mills foundations in harsh conditions.

Stationary Floating Structures and Ships

Experimental and numerical procedures for predicting motions of floating structures are in general well established. There is still a need of research in predicting second-order slow motion and force. Studies have been carried out on novel structures, for example, dry tree semi-submersible and devices for VIV suppression.

Relative motions between two floating bodies became very important research topics since they concern the safe operation of a floating offshore LNG vessel. Hydrodynamic effects of liquid in partially filled tanks are considered in the ship motion and sloshing analysis. In shallow water, the low-frequency component induced by nonlinear wave interactions is important for the low frequency motion of two floating bodies. The hydrodynamic effects of tank fluid and the gap phenomena between two floating bodies still need to be studied further.

Dynamic Positioning Systems

Simulation systems, CFD application and model tests have been used to evaluate the performance of DP systems. The use of the theory of nonlinear control, robust control, reliability, and simulation of interference between thrusters has also been addressed by researchers. Further studies are needed in the areas of thruster-thruster interaction, thruster-hull interaction, ventilation and ingestion of air.

Renewable Energy Systems

The state of the art research for wave energy, current energy and wind energy has been comprehensively reviewed. Research in this field has progressed rapidly. Appropriate experimental techniques and procedures should be developed for this expanding field.

Highly Nonlinear Effects on Ocean Structures

Green water and air gap, representing the highly nonlinear effects, becomes important for the design/operation of offshore structures in extreme sea conditions. Accurate measurements of relative wave and impact load are important for the determination of design values and the development of reliable numerical method. To predict the wave field under the deck and the wave run-up, Navier-Stokes solvers with the VOF techniques and the Smooth Particle Hydrodynamics (SPH) techniques and other numerical tools have been adopted. The development of the relation between the measured pressure and the design pressure for structures need to be studied further.

Sloshing

The very important increase in the size of LNG ships in recent years, together with development of floating storage and regasification units (FSRUs) operating in arbitrary filling conditions, have boosted a number of R&D projects aiming at improving the design methodologies and the scientific knowledge about the physics of hydroelastic impact problems involving a complex containment system and the two phase flow of a liquefied gas together with its gaseous phase. Significant progress have been reported at three different levels: (i) global simulation of the ship and liquid cargo coupled behavior, (ii) numerical simulation of local fluid-structure interaction effects during two-phase impacts, (iii) large scale impact tests.

9.2 Review of the Existing Procedure

The committee reviewed the existing procedure 7.5-02-01-01 on the uncertainty assessment methodology for the uncertainty analysis in EFD. The committee recommended including clear definitions for the precision error, the bias error, the random error and the systematic error.

9.3 Parameters Causing Largest Uncertainties in Ocean Engineering Tests

There are many parameters causing uncertainties in ocean engineering tests and numerical simulations. A list of parameters has been identified. The parameters causing the largest uncertainties in ocean engineering experiments involving mooring lines and dynamic positioning systems are discussed.

9.4 Benchmark studies on VIV

In the VIV benchmark studies, three participants chose the two-dimensional unsteady RANS methodology. It is concluded that the drag crisis phenomenon on stationary smooth cylinder was not predicted from this numerical study. It is necessary to investigate the application of other methods such as LES and DNS or to develop a new method to predict the complex flow phenomenon.

9.5 Mooring Line Damping

A literature review has been conducted for mooring line damping. Existing model and full-scale tests have been reviewed. The main challenges for obtaining the mooring damping in model tests lie on the geometry modelling of lines and scale effects. The desirable approach is to determine the mooring damping from the full-scale tests. A rigorous field measurement is needed. It is recommended to conduct large-scale model tests of a semi-submersible in a lake and in a model basin to study the scale effect on the mooring line damping.

10. RECOMMENDATIONS

The Ocean Engineering Committee would like to make the following recommendations to the 26th ITTC:

- Adopt the new procedure 7.5-02-07-03.6, "Dynamic Positioning System, Model Test Experiments"

- Adopt the new guideline 7.5-02-07-03.7, "Wave Energy Converter, Model Test Experiments"

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