Integration of Model Tests and Numerical Analysis for Deepwater FPSOs

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Abstract. Model testing of floating systems is still considered a key part of system design and validation, even with the improvement of numerical tools and analytical solutions of various fluid-structure interaction issues. However, as we continue to develop systems for ultra-deepwater, the integration of both numerical tools and physical model testing needs to be properly implemented.

Proper design of a model test program requires the understanding of the physics of the system, the limitations and benefits of scale-modeling and the numerical analysis, and the development of a program that allows the development of good input and output datasets that can be used in design and validation. Numerical models represent many portions of the system accurately but can be limited both by the lack of sufficient analytical development of solutions, and the implementation of the actual physics.

The paper provides a philosophy and methodology used in developing model test programs for deepwater with a focus on integration with the numerical analysis. This requires designing the model test program to provide the best datasets for design and validation, at the same time ensuring that the key physical processes are captured to allow proper benchmarking of the numerical tools. The paper demonstrates the use of this methodology with examples from various sets of model test data and numerical models conducted for several systems.

INTRODUCTION

Model testing, as a means of understanding the complex physics and to provide a basis of design, has been synonymous with offshore engineering from the initial stages of development in the 1950's. Today, based on the activities at several ocean basins and laboratories it still plays a major role in offshore system development.

In the 1980's the advent of the personal computer, development of analytical understanding of the physics of the complex interaction of the environment with structures, and the development of numerical tools to analyze such systems the general trend was to move away from model testing and focus on analysis. In fact in the late 1980's research funding for the development of laboratory facilities was hard to come by with an increased focus on "numerical wave tanks," computation fluid dynamics, and higher order expansions of analytical models.

However, in the 21st century we see that laboratory and model testing is still a major component of analysis and design of offshore systems with increasingly complex programs, and complex systems. As offshore systems are being deployed in deeper water and harsher environments, and with the advent of many new concepts and systems, laboratory and model testing has still been a major component of the development as the optimism of the 1980's has failed to develop as projected.

It is also important to keep in mind that there have been some major advances in physical understanding, analytical methods, and numerical tools, and with the increased processing power available today many systems can be analyzed and designed without the need to resort to model tests as has been quite common in our industry. In fact there are cases where model tests are performed where many of the tenets of model testing are ignored or not valid, leading to datasets of results that are either misrepresentative or incorrect results.

This paper provides a brief overview of the author's philosophy towards model testing and its integration with the analysis and design process from a global analysis and mooring design perspective. Note that it is not all encompassing of all types of laboratory and ocean basin tests. The paper will also provide comparisons of simulation data and model test results to show the accuracy of today's tools for global analysis. Finally the paper will also present some results of integrating model test and numerical models for accurate response prediction.

WHY MODEL TEST?

Model testing is a generic term that covers all aspects of laboratory testing of physical phenomena and global system response. Thus the question is open ended as there are many reasons, some of which are listed below:

- Concept development and evaluation
- Identification and understanding of the complex physics
- Input data for global analysis, e.g. wind and current load coefficients, etc.
- Provide an independent verification of the system global analysis:
    - Vessel motions, line tensions, system loads, etc.
    - DP/thruster system performance
    - Installation engineering

- Study and analyze phenomena that are difficult/inaccurate to model analytically or numerically:
  - Green water and slamming
  - Pack-ice and iceberg loads
  - Multi-body dynamics
  - VIV
- Primary means of detecting "new" phenomena
  - Computer models and global analysis methodologies are only as good as the understanding and implementation of the physics
- Preferred "third party" evaluation of system performance

This list is not too different from what would have been drawn up in the early days of offshore engineering so it is interesting to examine why some of these are still considered necessary. In the past when analytical development and numerical tools were in their infancy, model tests were performed to serve as the basis of design of such systems. System characteristics were changed methodically to provide a database of design parameters and responses to allow for the use of such data in the design of similar systems. This type of model testing was quite commonly performed for some of the early single point mooring systems (SALMs and CALMs) and the databases are still in use today. Based on the model test database conservative designs were developed and many of these systems are still operating 30 years later. Most of these systems were in shallow water and thus a strong knowledge of shallow water hydrodynamics was also established in the databases, leading to the development (for example) of OCIMF current coefficients for tankers that are still in use today.

Specific tests were also performed to develop coefficients for Morison's equation (drag and inertia coefficients for slender bodies) that resulted in large databases for use with simple numerical programs for offshore structures. Several tests were also conducted to provide insight in to vortex induced vibration for land-based structures, heat exchangers, and offshore pipelines.

Analytical and numerical tool development has progressed in parallel and for specific systems and structures has been validated to provide response estimates suitable for engineering design. These tools have been validated against model test data (both focused and global) and when used within the range of applicability by qualified engineers can be used in lieu of model tests. It is interesting to note that even with today's numerical tools and processing power that the design schedule of many of these systems have not been shortened and in fact may be more labor intensive given the level of analysis performed today.

However, in time many systems have progressed beyond the range of model tests conducted in the past. This is especially true for floating systems which are being considered in extremely harsh environments like the Arctic and the North Atlantic, and in extreme water depths up to 3000 meters or more. In addition the interface to the subsea is increasingly more complex with a large number of risers and umbilicals that requires focus on both the individual response and the global system response of the system. The floating unit is growing increasingly larger and operations like offloading (both in tandem and side-by-side) take place at a much higher frequency, requiring accurate assessment of feasibility and response.

The design of these systems demand high reliability and low maintenance with a major focus on the design of the subsea systems and thus increased focus on the global analysis. In many of these situations design specifications have generic requirements for model testing that may not reflect the true requirements of the specific project leading to a generic model test program without a lot of value. As with all laboratory tests it is important to develop clear objectives and requirements that also consider the limitations of a model test program.

As an example consider the requirements for an FPSO model test in 2,200 meters of water. The FPSO is moored with 20 – 24 anchor legs and may support up to 50 risers. With the current maximum available model test facility depth of 10 – 15 meters a true scale model would require a scale of 1:150 – 1:200. Model testing at this scale results in very small waves and other environmental data, poor Reynold’s similitude and the large scale effects coupled with poor input (and output) would result in a misrepresentation of system response in most cases. The “standard” approach to such a system is to develop an equivalent mooring and riser system that would allow “truncation” of the actual system allowing the model test to be conducted at a large model test scale of say 1:100 or smaller. This use of a “distorted” model typically has increasingly larger errors as the scale of the distortion increases and will only satisfy a few of the physical requirements of the system.

This method implicitly implies that in developing a truncated model the designer has a good physical and analytical model of the mooring and riser system changes certain parameters to maintain the system response (for the parameters of interest) to be similar to the original un-distorted system. The model test results are then compared to a numerical model of the model test set-up and once the appropriate “calibration” or validation is obtained the numerical model is then used to predict the actual system response. This approach allows one to continue to use the traditional methods of model testing for these systems.

Figure 1 schematically shows the problem at hand – for 2,200 meters of water the anchor radius is around 2,000 meters, with anchor leg and riser lengths of approximately 3000 meters. In comparison the FPSO is about 350 meters long with a beam of 60 meters. By focusing on water depth and the mooring and riser system truncation, the scale at which the wave, wind and current interaction with the floater occurs is compromised. Depending on the objectives of the test it may be worthwhile to focus on the scale for the wave-floater interaction rather than the mooring, especially if a model the model approach is being used for design. Proper design of a model test program based on surface interaction scaling and response measurement rather than strict focus on the anchor leg and riser system may lead to more accurate and meaning full results. One example of such an approach shall be shown later in this paper.

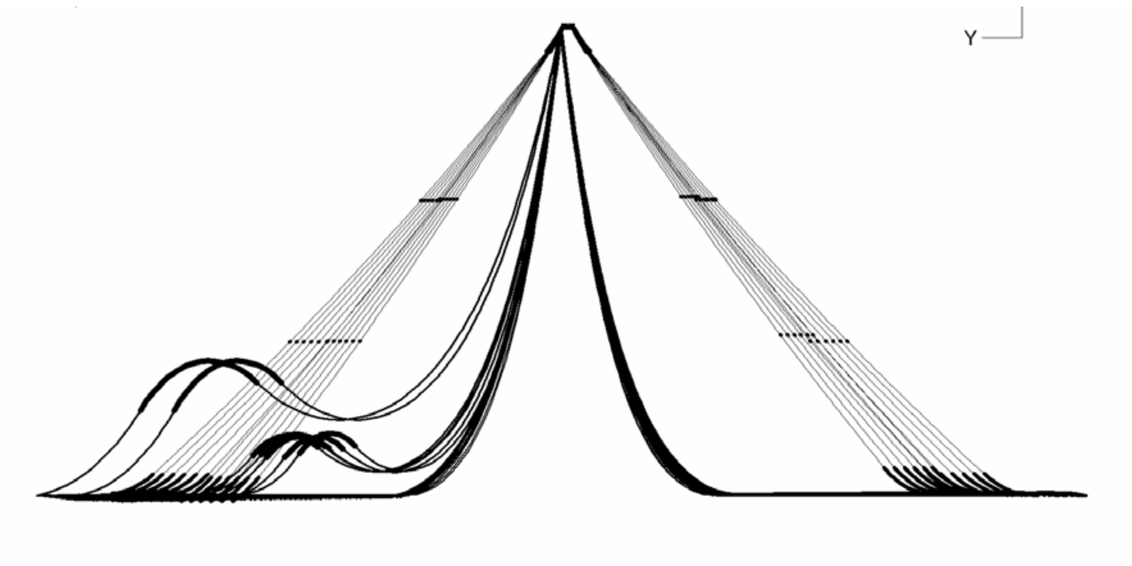


Figure 1. Elevation view of FPSO with mooring and risers in 2,200 meters water depth.

Of course laboratory and model testing of fluid-structure interaction phenomenon shall always play a role in the foreseeable future – both for fundamental research and for validation of data extraction. Several examples of such types of tests are VIV of slender structures in currents and waves, wave run-up and greenwater on large floaters and other objects at the splashzone, flow separation at various interfaces, etc.

Ice loading on floating systems is a relatively new area of research and development as floating systems for drilling and production are being considered for harsh Arctic environments. Though there has been a history of development in Arctic conditions from the 1970's, the large drop in interest in the 1980's and 1990's has resulted in a generation of offshore engineers with little exposure to ice loading and the resultant responses. Over the past 10 years there have been a few production systems in ice regions, the Terra Nova FPSO [1] being one example, but currently there is increased interest in development in the Arctic using floating systems, and model tests in ice basins have been extremely useful in developing both a physical understanding of ice interaction with FPSOs (for example) and the resulting loading and response.

Model tests have also been useful in studying multi-body responses e.g. offloading both in tandem and side-by-side and the performance of disconnectable FPSOs in terms of disconnect and reconnect of the mooring and riser buoys. Examples of this shall be shown later in the paper.

WIND AND ICE-TANK TESTS

Wind loads are an important input parameter for determining the system response. For simple F(P)SOs one can make use of the published OCIMF coefficients with correction for additional structures on the deck or use a software program developed for estimating wind loads on systems. An alternative is to perform wind tunnel tests on the hull and topsides for various drafts and headings to determine the wind loads and then allow the derivation of wind load coefficients by using an appropriate formulation. These wind load coefficients can then be used as input to the analysis and for a given FPSO and topsides reduce some of the uncertainty associated with these loads.

Figure 2 shows the Terra Nova FPSO in the wind tunnel (scale of 1:200) and Figure 3 presents the estimated wind coefficients plotted against preliminary estimates made using a software package. Similar tests can be performed for determining current loads on the hull though care must be made in correcting the loads for the boundary layer effects and blockage. Current loads from wind tunnel tests are only suitable for deep water applications as influence of the seafloor boundary condition is not modeled.

Figure 2. Wind tunnel tests on the Terra Nova FPSO.

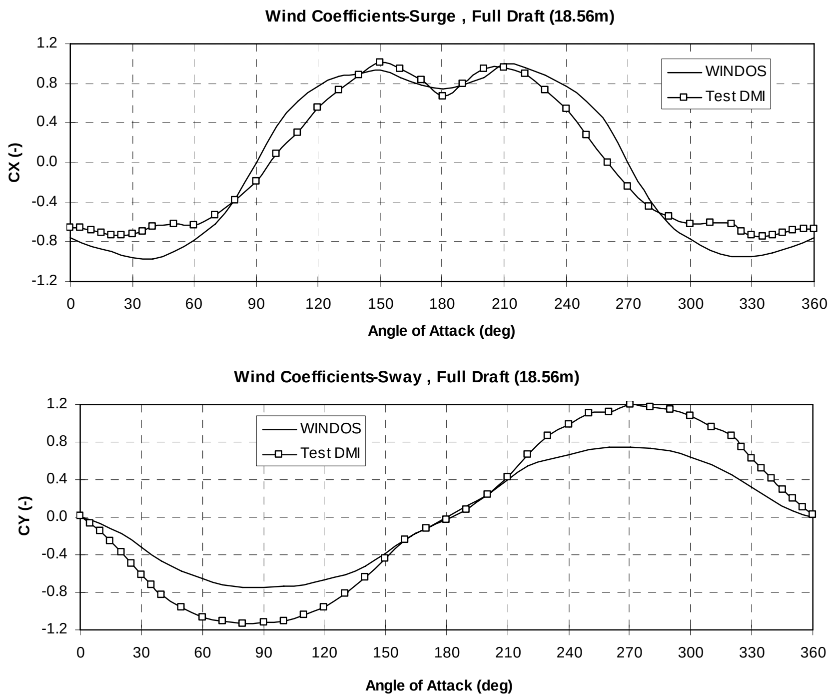


Figure 3. Comparison of wind load coefficients from wind tunnel tests and numerical simulation.

Pack-ice loading on floaters is another important interaction that can be modeled in an ice tank. Of paramount importance are the mechanical properties of the model ice which can be different at each laboratory depending on how the ice is modeled. Both crushing strength and bending stiffness of the ice needs to be modeled as well as the friction between the ice and the structure. These parameters are also driven by model scale and thus most ice tests are scaled based on the model test ice properties and the physical dimensions of the basin. Model test facilities can also develop formations like ridges and multi-year ice though the estimation of prototype properties is more difficult to control. However, testing at model scale is an effective method for understanding the physics of the interaction as well as developing design responses and loads.

Figure 4 shows model tests of the Terra Nova FPSO in pack-ice at the Institute of Marine Dynamics Ice Basin in St. John's, Newfoundland. Tests were performed in pack-ice conditions of different thicknesses and percentage coverage. The tests were performed at a scale of 1:27.5 with care taken to ensure that the ice mechanical properties were properly modeled at this scale. The FPSO model included a representative turret mooring to allow passive weathervaning of the FPSO in the ice field. Tests were performed with different ice thicknesses, percentage coverage, velocity, and vessel initial position to study ice drift reversal. Figure 5 presents a summary of some key results obtained that showed that shows the influence of pack-ice coverage percentage and drift reversal on turret-mooring loads. For Terra Nova the loads and response obtained from these tests were directly used for design.

Figure 4. Pack-ice model tests for the Terra Nova FPSO

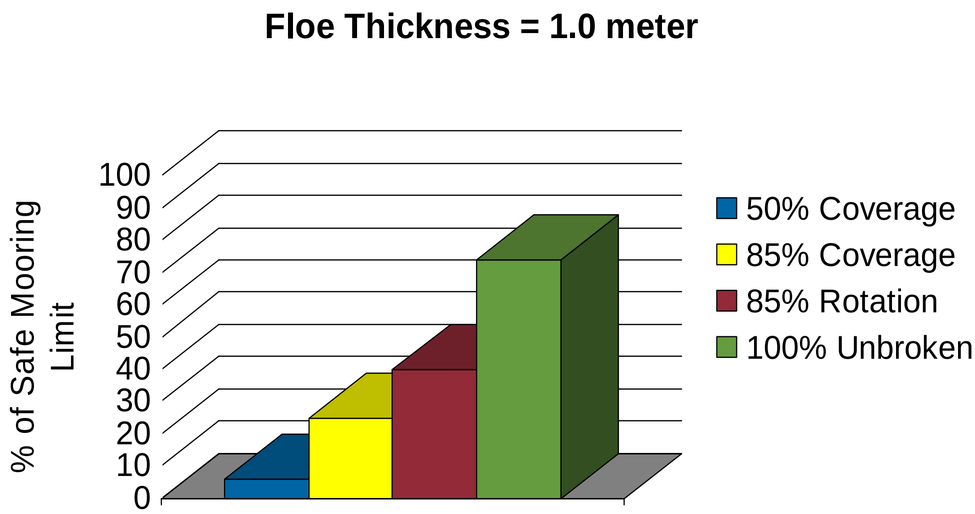


Figure 5. Sample pack-ice loads on the FPSO.

NUMERICAL MODELING AND MODEL TESTS FOR A DISCONNECTABLE FPSO

To design an FPSO with a Disconnectable Turret-Mooring (DTM) system, four main design cases must be addressed: (1) spider buoy connected to FPSO, (2) transient spider buoy disconnection from FPSO, (3) spider buoy reconnection, and (4) spider buoy survival in extreme cyclone environment. This section presents some results on the modeling of the DTM system for the various stages of disconnection and reconnection for the Stybarrow FPSO and validation with model test data.

The Stybarrow FPSO [2] is located in an average water depth of 825 meters offshore North Western Australia. The environment is characterized by strong swells from the south west, and severe cyclones during the months of January through April. The nine anchor legs for the FPSO vessel are arranged in three groups of 3 anchor legs each. The riser system consists of 10 lazy-wave risers and 2 umbilicals.

The analysis of the DTM system uses both time and frequency domain numerical models. The vessel and spider buoy hydrodynamic analysis is performed using the program WAMIT. Global analysis of the FPSO and mooring / riser system is primarily performed using the Seasoft software suite. Time domain analysis is conducted with the program OrcaFlex. Model tests at two scales were conducted in an ocean basin to derive some hydrodynamic coefficients of the spider buoy during disconnection, and to provide data for verification of the numerical models for the disconnect and reconnect operations.

Hydrodynamic model of FPSO and spider buoy

Calculation of hydrostatic coefficients, added mass and potential damping coefficients, first-order wave exciting forces/moments, motion RAOs, and drift forces/moments were performed by using a radiation/diffraction program WAMIT. WAMIT is also used to calculate the hydrodynamic pressure field and corresponding total hydrodynamic loads on the spider buoy both connected and disconnected from the FPSO. Figure 6 shows an FPSO panel mesh for hydrodynamic calculations. Figure 7 illustrates the normal vectors of each panel with pressure strength in size around the spider buoy connected to the FPSO.

Calculation of the hydrodynamic forces on the spider buoy when connected to the FPSO is important for the turret mooring system design as these forces can be of similar magnitude to the combined mooring and riser load. This has a large impact on the structural and mechanical design of the turret mooring system for both extreme and operational seas. In addition to diffraction and radiation loads drag loads on the buoy and hull were also considered.

The drag and inertia coefficients of the spider buoy when dropping from the turret were estimated by performing a series of experiments with and without the turret at two different scales (1:35 and 1:81) as shown in Figure 8. This allowed determination of the scale effects and also “tuning” of the 1:81 model of the turret and spider buoy (including flow into the lower turret) for later use in the ocean basin tests with the FPSO and complete mooring and riser system.

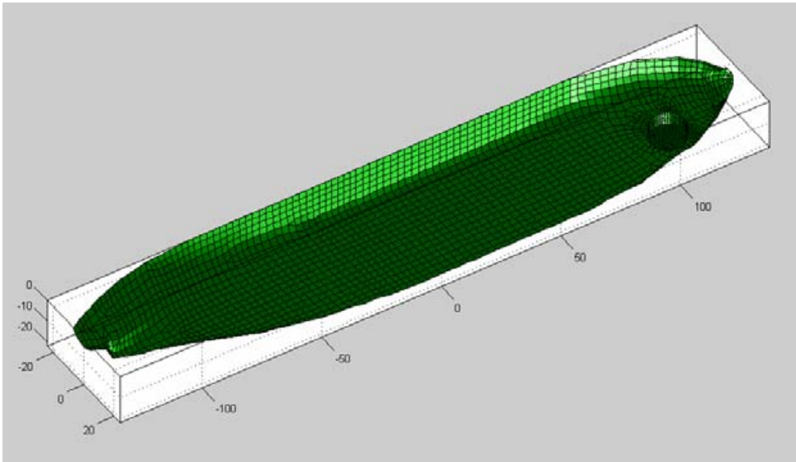


Figure 6. Mesh used for hydrodynamic calculations.

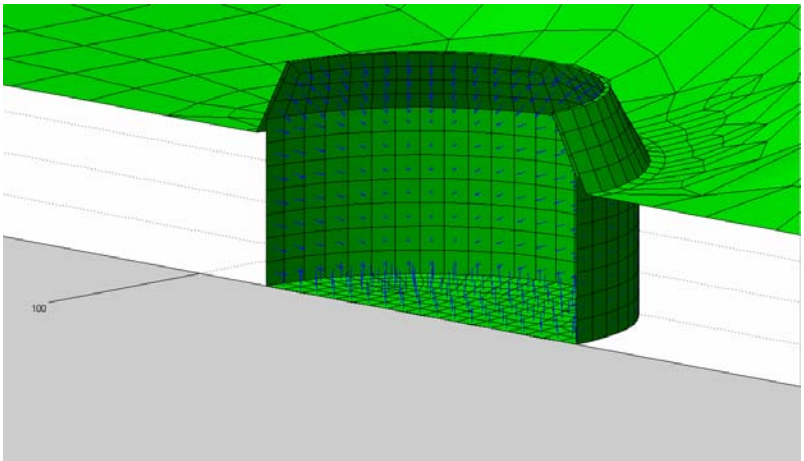


Figure 7. Presentation of normal vectors of each panel with pressure strength.

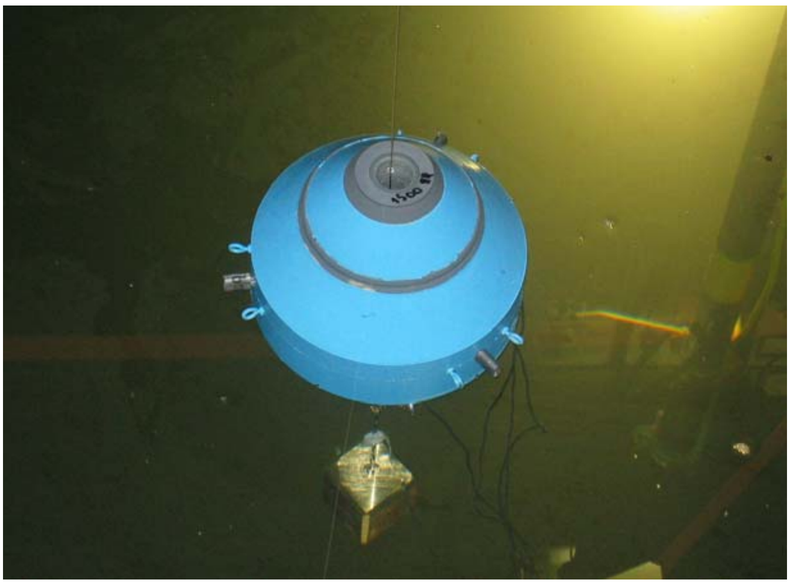


Figure 8. Spider buoy with clump weight for the drop tests.

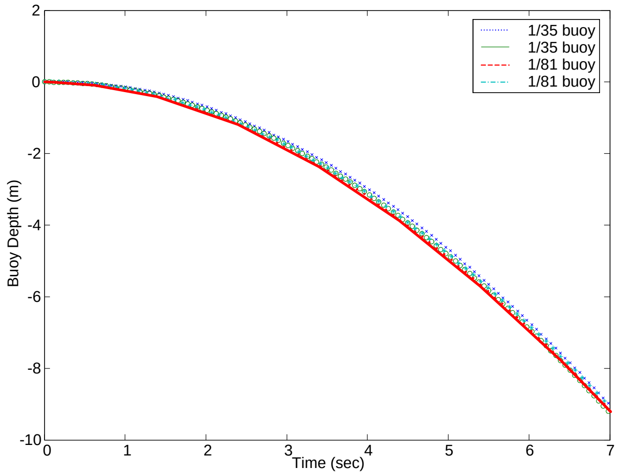


Figure 9. Buoy drop depth comparison between model test (markers) and prediction (solid line).

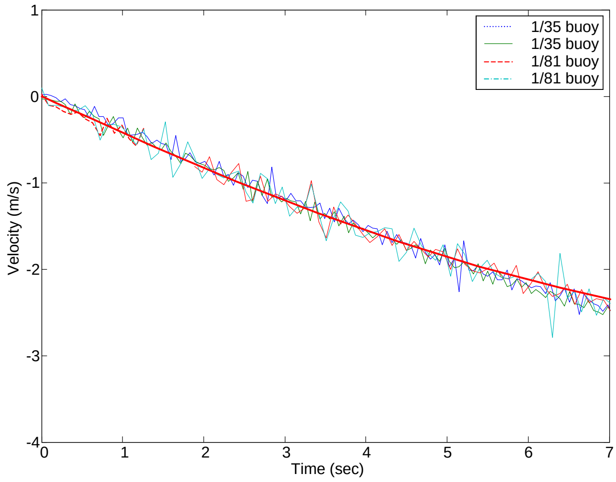


Figure 10. Buoy drop velocity comparison between model test (fluctuating lines) and prediction (smooth line).

The buoy drop depth and velocity comparison between model test and calculation results are shown in Figures 9 and 10. The agreement is seen to be excellent. Estimated inertia and drag coefficients are Cd_n = 1.0 (normal direction), Cd_a = 0.9 (axial), and Cm = 0.60 (inertia).

To take into account the drag and added mass due to the shape of the spider buoy, the spider buoy was made of a stack of multiple discs as shown in Figure 11, allowing different Cd and Cm coefficients for each disc. Figure 12 presents an elevation view of the numerical model used to study the spider buoy, mooring and riser system for the various disconnect and reconnect analyses.

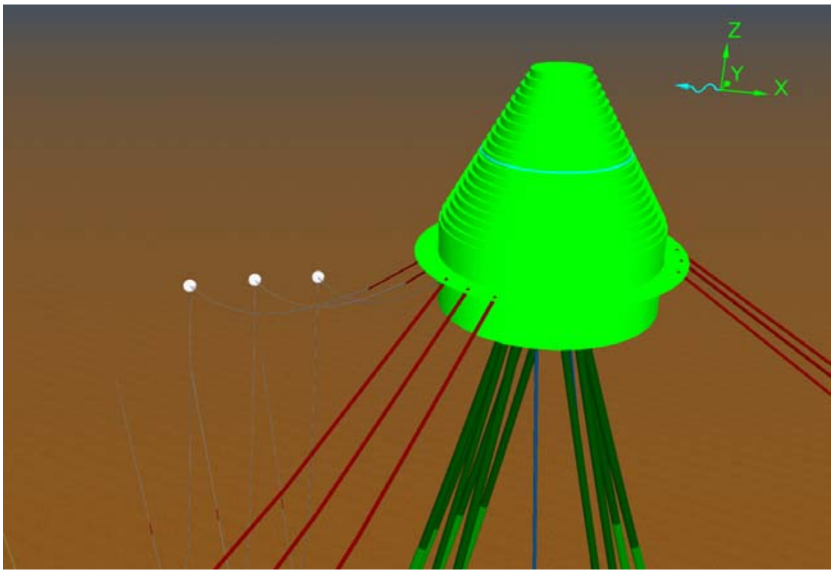


Figure 11. Representation of the spider buoy in the numerical model.

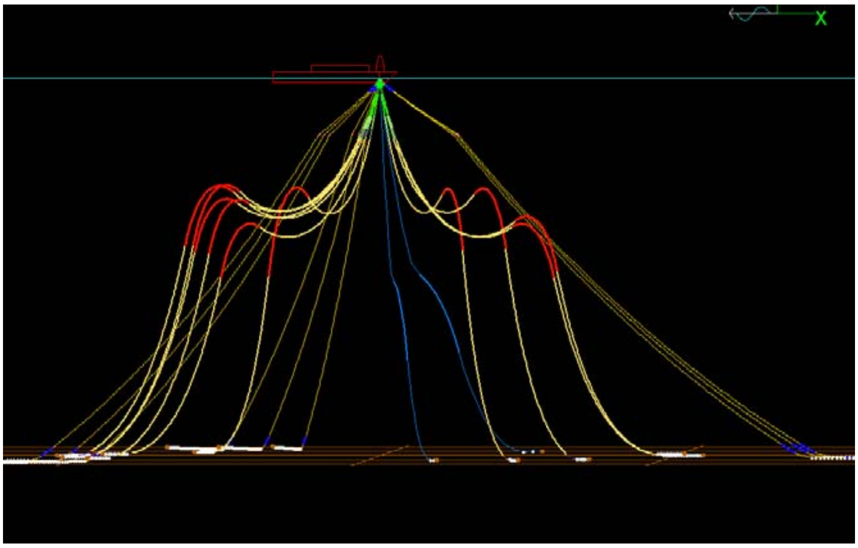


Figure 12. FE model of the entire spider buoy system.

Transient spider buoy disconnection

Time-domain simulations were conducted with the spider buoy system model connected to the vessel in regular waves with height of 10.2 m and period 15.4 seconds. The buoy was released at a pre-determined time and allowed to freefall. Figure 13 compares the predicted response to the results of the two model test runs conducted with the same parameters, and the comparison is seen to be excellent. This simulation and test demonstrate the capability of the DTM to disconnect in severe seastates without any interference with the vessel.

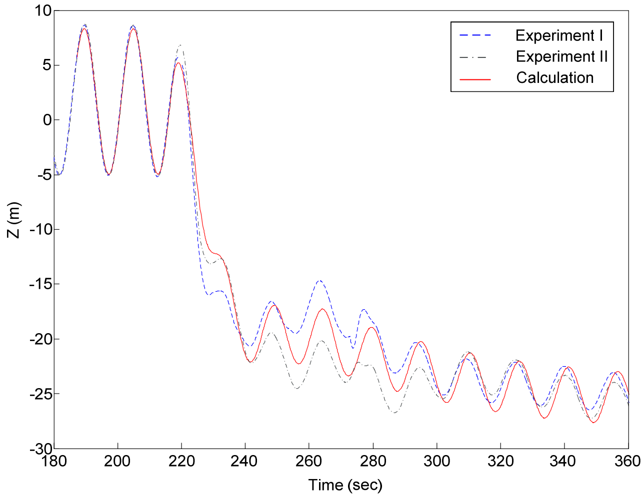


Figure 13. Validation of the buoy drop motion compared to model test results.

Disconnected spider buoy response

The disconnected spider buoy motion using the model presented in Figure 12 was studied for a number of 100-year cyclone conditions (Hs of 12.6 meters, peak period of 12.6 seconds) to ensure buoy, mooring and riser system performance. Figure 14 compares the results obtained for the spider buoy motion (X-Z) envelope predicted by the numerical model and the model test of the disconnected system for a regular wave of height 20.9 meters and period 12.9 seconds. As seen in the figure the comparison is excellent allowing us to use the numerical model to study situations and cases not represented by the available model test data.

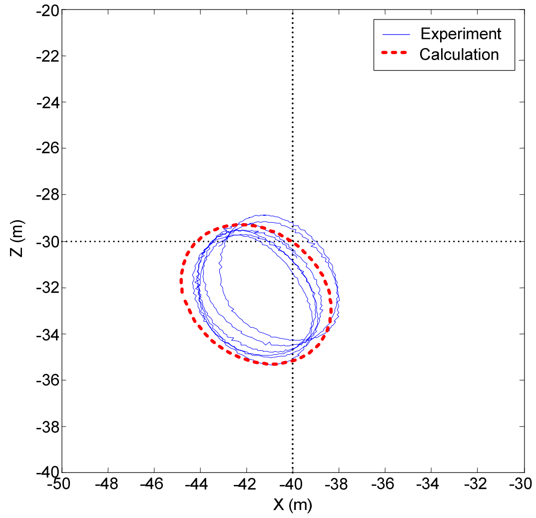


Figure 14. Disconnected buoy motion envelope comparison.

Analysis of spider buoy reconnect

The analysis of the spider buoy reconnection is a very important aspect of the DTM design and operational efficiency of the FPSO. The Stybarrow system is designed to allow reconnection in significant wave height of 3 meters without any assistance from other vessels. This requires accurate estimation of the relative FPSO – spider buoy responses during the entire retrieval scenario to ensure correct definition of lower turret and upper spider buoy geometry, winch sizing and retrieval lines loads, and sizing of the various fenders. The numerical model was developed in OrcaFlex and includes a detailed model of the FPSO with the retrieval winch and line modeled in addition to the spider buoy model presented in Figure 12. Figure 15 presents the details of the numerical model around the lower turret-spider buoy interface. The simulation (and model test) is then run using a fully-coupled model of the system, free to respond to the environmental conditions associated with a maximum reconnection seastate of Hs 3.0 meters.

Figures 16 and 17 present the retrieval load history from simulation and model tests respectively in irregular seas. Due to differences in modeling the shock absorber in the numerical model and model tests (simplified), speed of spider buoy retrieval, and the differences in wave realizations, the time histories of response cannot be compared directly but in a more qualitative manner. The figures show the estimation of the load history and system responses from the numerical model are very similar to that from the model tests, again confirming the accuracy of the numerical model.

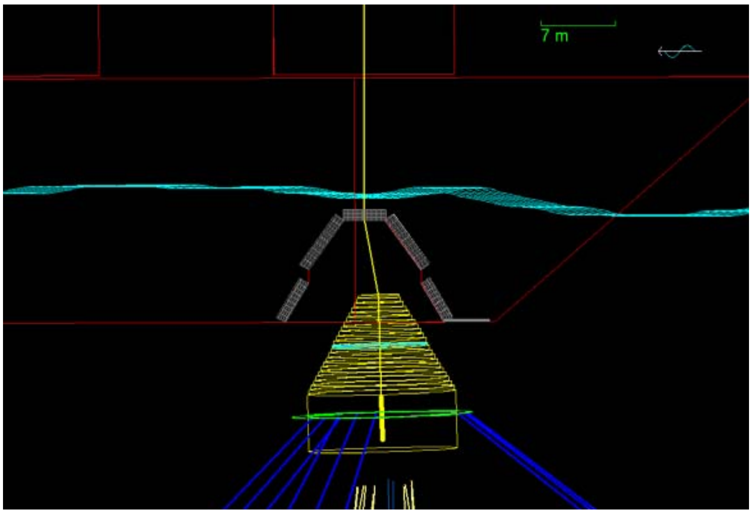


Figure 15. Numerical modeling of the buoy reconnection by considering turret/buoy contact with elastic blocks for the turret.

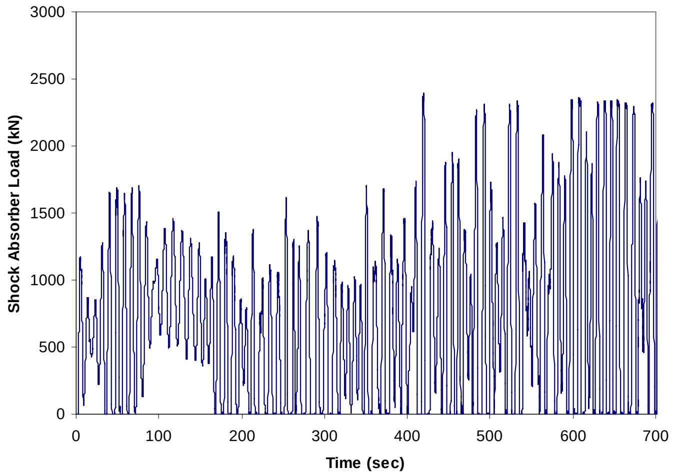


Figure 16. Estimation of the retrieval line load during reconnection.

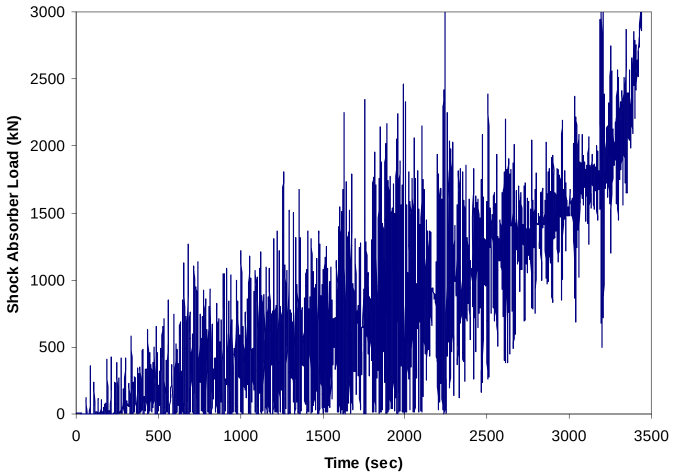


Figure 17. Experimental results of the retrieval line load during reconnection.

ROLL MOTION ESTIMATION IN DEEP WATER

As an example of the integration of model testing and analysis we look at the estimation of the roll response of a deepwater spread moored FPSO. The spread-moored FPSO is located in 2,200 meters of water offshore Brazil and is moored by 24 polyester ropes. The FPSO is also designed to support 50 risers on a riser balcony located on the port side of the vessel with the vessel bow headed towards the South West.

A key design requirement for the FPSO is to maintain the maximum roll motions below a specified value for a specified beam-sea condition and the design environment. Due to the roll natural period being close to the peak period of the waves incident beam-on to the vessel, standard tanker bilge keels would not be sufficient to limit the roll as required, thus requiring large bilge keels. Another challenge is to estimate the role of the mooring and riser system in the roll response in terms of stiffness, inertia and damping.

As discussed earlier a traditional model test program would result in an extremely small scale which would not be suitable for estimation of the roll response. After considering various options the decision was made to perform a model test program at a large scale 1:60 with the vessel in a horizontal mooring so that the roll response of the vessel with bilge keels (width and length varied) alone could be accurately estimated for various seastates and heading.

Once the model tests were completed a coupled analysis was performed with the FPSO in a horizontal mooring system using first order wave forces and hydrodynamic coefficients obtained from 3-D diffraction analysis, and a proprietary roll damping model which was tuned to provide similar response to that observed in the model tests for the various seastates and headings. Then simulations were performed with the mooring system only and then the mooring and risers to get estimates of the roll response inclusive of the mooring and riser effects. RAOs were then extracted from the numerical simulations data to provide a description of the roll response with mooring and risers included.

The following figures provide a description of the process for beam seas from the 90 and 270 degree directions (port and starboard). Figure 18 presents the roll response of the FPSO with the bilge keel roll damping model but no mooring or risers for both beam-sea directions. As expected the roll response from both directions is very similar with a three-hour maximum of just below 14 degrees.

Figure 19 presents the same information for the coupled model with all the mooring and risers included. Note the risers are suspended from a riser balcony on the port side. The interesting result is that the roll response with the waves from the port side is much reduced (less than 5 degrees maximum) compared to the same waves on the starboard side (13 degrees maximum). This behavior is also observed in the RAOs extracted from the time domain analysis presented in Figure 20.

In general the risers contribute to an increase in roll viscous damping and inertial effects; however this contribution is asymmetric due to the relative phasing of vessel motions and riser inertia and damping loads. The damping and inertial contribution is more significant for waves arriving on the vessel’s port side where the risers are installed.

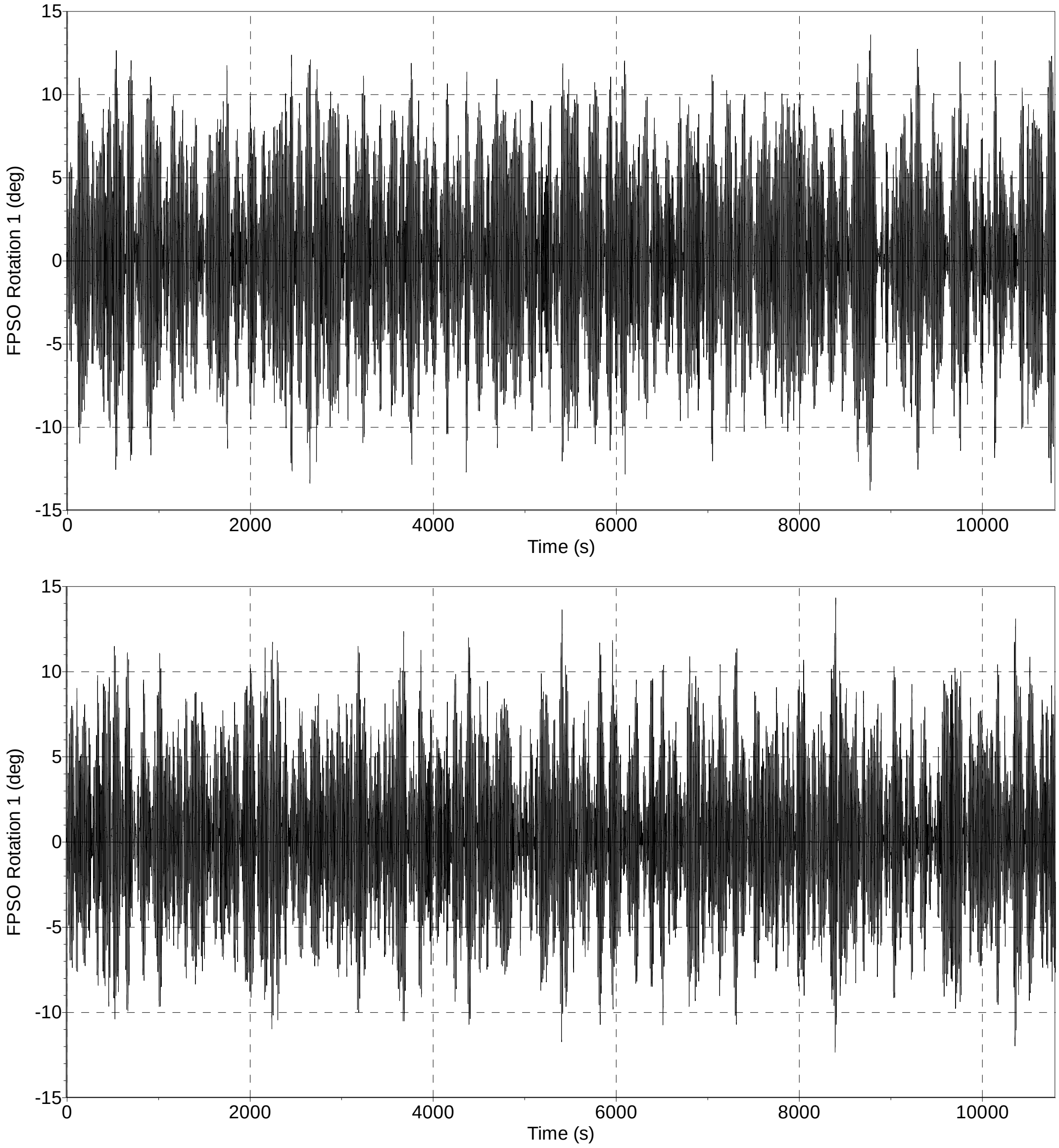


Figure 18. Roll response in beam seas with no mooring or risers for waves incident on (a) port side (b) starboard side.

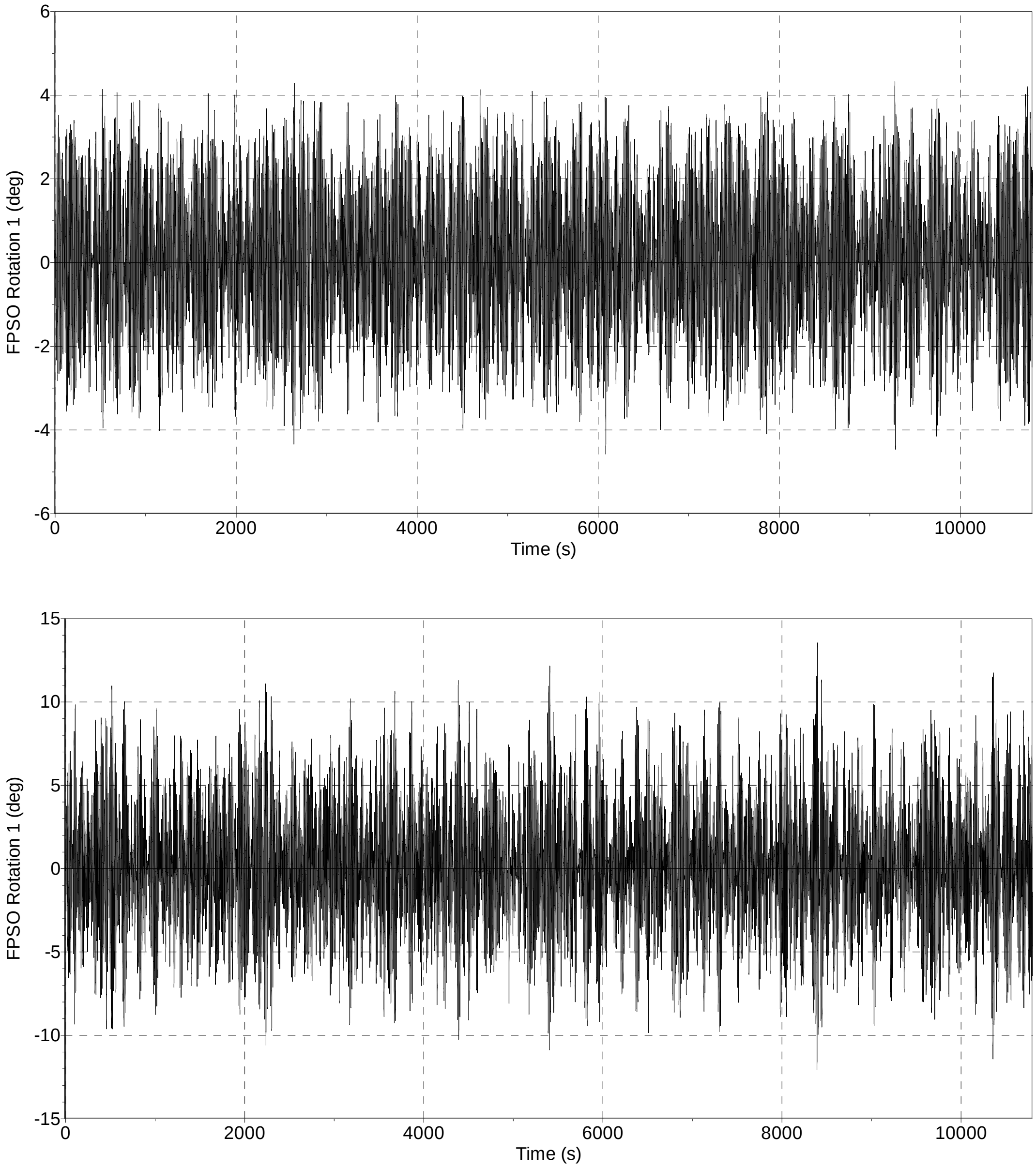
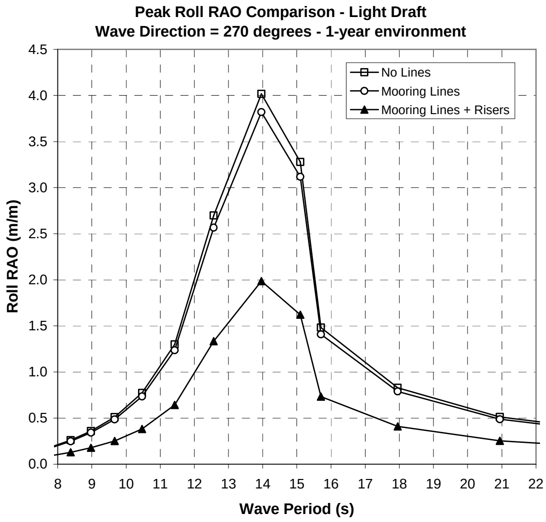


Figure 19. Roll response in beam seas with mooring and risers for waves incident on (a) port side (b) starboard side.



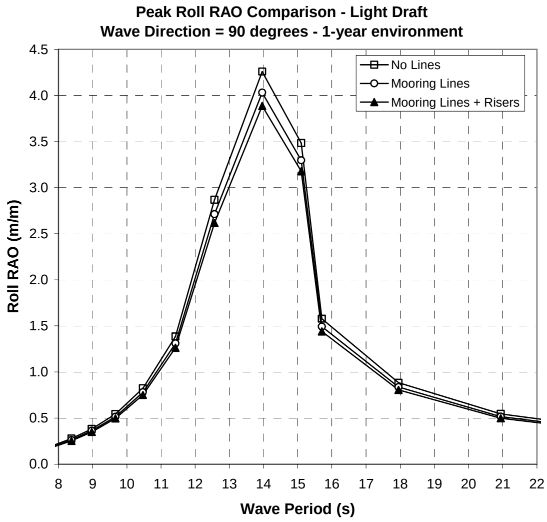


Figure 20. Roll Response RAOs for beam seas incident on (a) port side (b) starboard side

USE OF CFD COMPUTATIONS IN ROLL DAMPING PARAMETRIC STUDY

Another interesting application of numerical modeling, model tests and design was a parametric study for estimating roll damping using computational fluid dynamics (CFD). Advances in CFD make it possible to run focused simulations on specific physical phenomena to study the relative influence of the various appendages. In general, current CFD analysis requires some benchmark data for calibration of some parameters, but once the model is calibrated it can be used quite effectively to study variations in certain parameters.

For the current example we were interested in obtaining the relative contributions of the hull, various bilge keel dimensions, and appendages like a riser balcony on the roll damping of the system. With a base result obtained from model tests it was determined that CFD may provide an opportunity to study the change in roll damping for the various appendages and their arrangement. For this study 5 cases were studied: (a) the bare hull, (b) the hull with 1.0 meter bilge keels, (c) the hull with 2.0 meter bilge keels, (d) case (c) with lower riser balcony structure (e) the hull with a riser balcony on the port side and a 2.0 meter bilge keel on the starboard. Figure 21 shows the various cases looked at.

The analysis was performed in two dimensions by solving the Navier-Stokes equations with a turbulence model at full scale. This also included a VOF free surface model. The vessel was force oscillated through 5 and 10 degree amplitudes at its roll natural period and based on the dynamic moment measured the roll damping was extracted. Figure 22 shows a snapshot of the flow vortex development by the various appendages while Figure 20 also shows the relative roll RAOs for the hull extracted from the CFD results.

This allowed for an evaluation of the impact on the various appendages on roll motions without resorting to time consuming and expensive model tests.

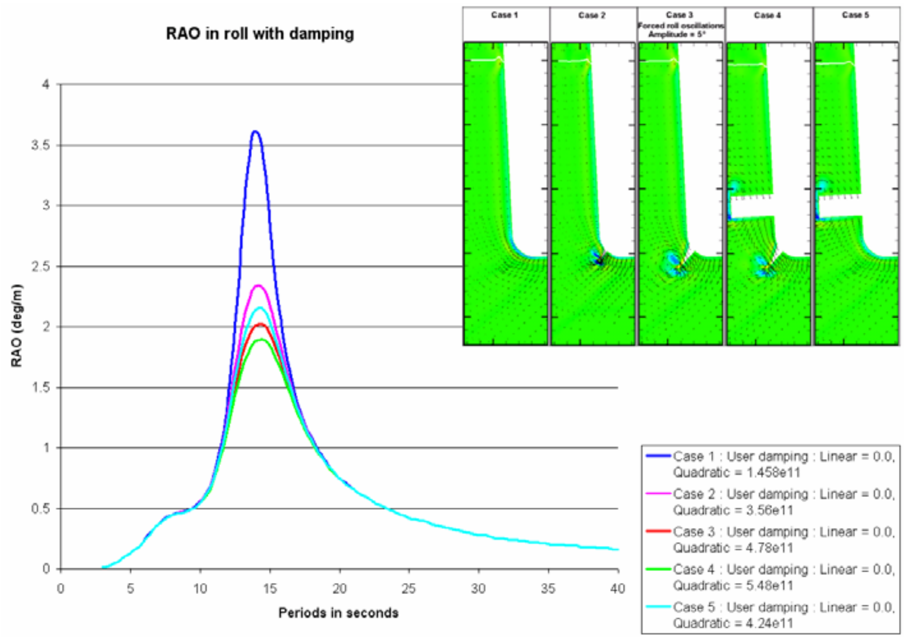


Figure 21. Cases studied and estimated roll RAOs.

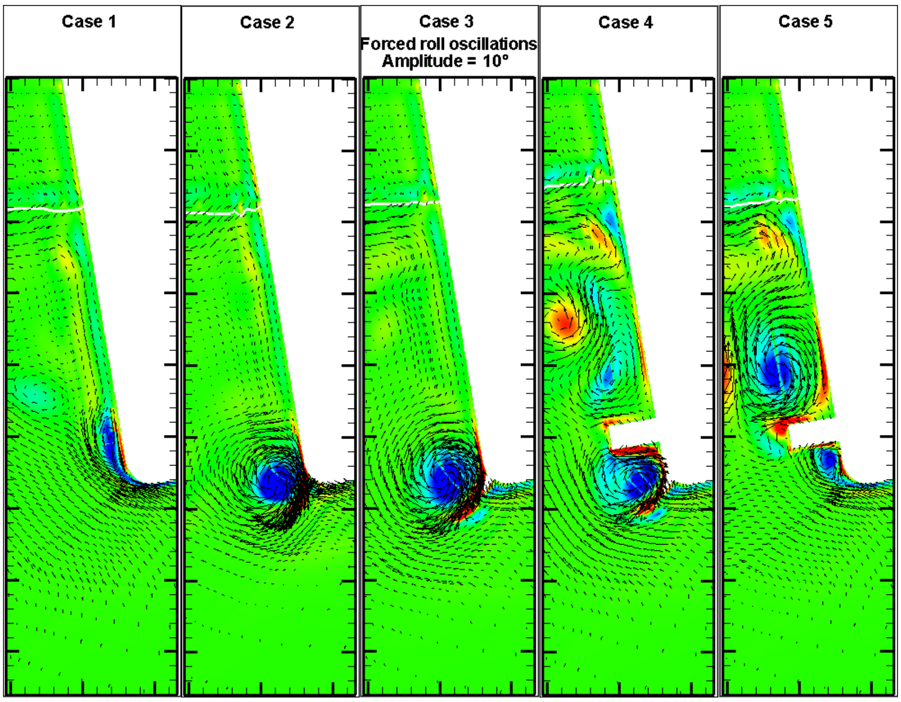


Figure 22. Vortex development induced by appendages.

CONCLUSIONS

The paper presents the authors philosophy for model testing and provides general discussion and guidance for the design and execution of model tests, specifically for deepwater floating production systems. The paper demonstrates that model test programs still play a major role in offshore concept development and design but in many cases may be integrated with the overall analytical and numerical development work to create an efficient process.

Examples of model testing for design data, validation and integration with numerical analysis are presented to demonstrate the methodology used by the authors to approaching model testing, especially when the system tested falls out of the range of an effective scaled model test program.

In summary even with advances in analytical and numerical models, and increased processing power, laboratory and model testing will still play a role in offshore engineering for the foreseeable future. The challenge will always be in understanding its role and effectiveness for deepwater systems and finding efficient ways to integrate the model tests with the numerical analysis and design.

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