The Ocean Engineering Committee

Final Report and Recommendations to the 24th ITTC

1. INTRODUCTION

1.1 Membership and Meetings

The Members of the Ocean Engineering Committee of the 24th International Towing Tank Conference were as follows:

- Dr. Carl Trygve Stansberg (Chairman from May 2003).
  Norwegian Marine Technology Research Institute, Norway.
- Dr. Martin Downie (Secretary).
  University of Newcastle upon Tyne, United Kingdom.
- Ir. Radboud van Dijk.
  Maritime Research Institute Netherlands, The Netherlands.
- Prof. Antonio C. Fernandes.
  LabOceano, Universidade Federal do Rio de Janeiro, Brasil.
- Dr. Pierre Ferrant.
  Laboratoire de Mécanique des Fluides, École Centrale de Nantes, France.
- Dr. Nuno Fonseca (from December 2003)
  Instituto Superior Técnico, Portugal.
- Dr. Yasushi Higo.
  Hiroshima University, Japan.
- Dr. Sa Young Hong.
  Korea Ocean Research and Development Institute, Korea.
- Mr. Fraser Winsor (from November 2003)
  Institute for Ocean Technology, National Research Council, Canada.
- Dr. Bruce Colbourne (Chairman until April 2003).
  Institute for Ocean Technology, National Research Council, Canada.
- Dr. Claudio Lugni (until November 2003).
  Instituto Nazionale per Studi ed Esperienze di Architettura Navale, Italy.

Four Committee meetings were held respectively at:

- École Centrale de Nantes, France, June 2003.
- Norwegian Marine Technology Research Institute, Norway, March 2004.
- LabOceano, Brazil, November 2004.
- Hiroshima University, Japan, March 2005.

1.2 Tasks based on Recommendations of the 23rd ITTC

The original list of tasks recommended by the 23rd ITTC was found to be too large, and a reduced list was agreed with the Advisory Council of the 24th ITTC as follows:

State of the Art Reviews.

- Review the state-of-the-art, comment on the potential impact of new developments on the ITTC and identify the need for research and development for predicting the behaviour of bottom founded or stationary floating structures including moored and dynamically positioned ships. The review should include the modelling and simulation of waves, wind and current environments in deep and finite depth water. The review of wave modelling and simulation should include topics such as wave generation on a current and in finite depth waters; active wave absorption and reduction of parasitic laboratory waves; and further integration of model test waves with numerical modelling. Review the state-of-the-art of the prediction of the roll of floaters with risers and mooring systems.

- Monitor and follow the development of new experimental techniques and extrapolation methods.
- Identify the requirements for new documentation or procedures, updates, benchmark data, validation and uncertainty analysis and stimulate the research necessary for their preparation.

Develop New Documentation /Procedures.

1. Monitor research on Vortex Induced Vibrations (VIV).
2. Study and recommend guidelines for issues of importance to shallow water testing such as wave spectra, response non-linearity and mooring modelling.
3. Recommend a procedure for the definition of directional irregular wave spectra, including measurement, accuracy, analysis and validation.
4. Make an assessment of uncertainties in the modelling of nonlinear effects in a 100-year steep sea state, by a comparative benchmarking analysis including laboratory experiments, numerical models, theoretical prediction models as well as field data.

Review Existing Documentation.

1. Review the techniques for hybrid model testing and amend procedure 7.5-02-07-03.4 for Hybrid Mooring Simulation Model Test Experiments as required.
2. Review the first attempt of the Loads and Responses Committee of the 23rd ITTC to develop Procedures for the Validation of Codes in the Frequency Domain.
3. Review the ITTC Procedure 7.5-02-07-03.3 for Model Testing on Tanker-Turret Systems, and update as required.

1.3 Structure of the Report

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

State of the Art Reviews.

- Section 2: Modelling/Simulation of Wave and Current Environments,
- Section 3: Modelling/Simulations of Wind Environments,
- Section 4: Predicting the Behaviour of Bottom Founded Structures,
- Section 5: Predicting the behaviour of Stationary Floating Systems,
- Section 6: Predicting the Behaviour of Dynamically Positioned Ships,
- Section 7: Vortex Induced Vibrations and Vortex Induced Motions,
- Section 8: Prediction of the Roll of Floaters with Risers and Mooring Systems.

Review of Existing Documentation.

- Section 9 reviews existing documentation relating to: Procedures for hybrid model testing (7.5-02-07-03.4), turret tanker systems (7.5-02-07-03.3) and floating platform experiments (7.5-02-07-03.1). It also discusses the validation of codes in the frequency domain.

New Documentation.

- Section 10: Truncation of Test Models and Integrations with Numerical Models,
- Section 11: Guideline on the Modelling of Directional Wave Spectra.
- Section 12: Wave Generation in Shallow Water,
- Section 13: Nonlinear Effects in Steep 100 Year and Random Waves.

Appendices.

- Appendix A: Questionnaire on Modelling/ Simulation of Wind Environments.
- Appendix B: Nonlinear Effects in Steep 100-Year Random Waves (Specification)

2. MODELLING / SIMULATION OF WAVE AND CURRENT ENVIRONMENTS

2.1 Wave Spectra

Commonly used models for specification of ocean wave spectra, including single-peaked as well as two-peaked spectra, have been previously described in the 22nd and 23rd ITTC. Among newer results, three particular topics are addressed here: Multi-peaked spectra (two and more peaks); spectral evolution; and the decay of the spectral tail (f^{-4} or f^{-5}).

Multi-peaked spectra are being observed in various full scale measurements in several parts of the world. The effect may be quite important in resulting responses. Normally, such spectra are modelled by a sea plus swell two-component representation, but more than two peaks have also been observed in West Africa waters (ISSC, 2003).

The evolution of a narrow-band spectrum over a relatively short travel distance (typically 20 – 40 wave lengths) has been documented numerically by the nonlinear model by Dysthe et al. (2003). This is relevant for spectral homogeneity in large wave basins and tanks, and qualitatively confirms earlier measurements by Stansberg (1995).

The shape of the spectral tail is commonly modelled as f^{-5}. However, recent data indicate that f^{-4} may in many cases be a better representation, although it may depend on the case (ISSC, 2003). New results by Torsethaugen and Haver (2004) show exponent values between 4 and 5, and they recommend 4 as a conservative choice. The numerical evolution model by Dysthe et al. (2003) fits very well with an exponent of 4.

2.2 Nonlinear and Extreme Waves

Nonlinear and Non-Gaussian effects in steep deep-water random waves have been documented through a number of studies during the recent 10 - 20 years. Second-order modelling has become a quite well established tool, for which recent results have been presented by Prevosto and Forristall (2002), Myrhaug et al. (2003) and Stansberg (2003). Comparisons to available full scale data on crest heights show reasonable agreement with second-order predictions. Comparisons to model test data (with unidirectional waves) show slightly higher measured crests.

Some unexpected high waves and crests observed in field data (Haver, 2001) as well as in laboratory measurements (Stansberg, 2002), so-called “Freak” or “Rogue” waves, are difficult to explain or describe by second-order theory. These are normally considered a result of higher-order effects, but the topic is still not finally resolved for use in statistical prediction models. One possible physical mechanism, discussed in the latter reference, is self-focusing due to nonlinear modulation in energetic wave groups. Theoretical modelling of extremes, taking into account higher-order or fully nonlinear effects, are presented in Onorato et al. (2001 and 2004), Xue et al. (2001), Baddour and Parsons (2003), Krogstad et al. (2004).

A number of papers on the topic of extreme waves were presented at the Rogue Waves 2004 Symposium (Olagnon, 2004). During the MaxWave project (Nieto Borge et al., 2003), several papers were published on the analysis of large waves and wave groups from space-borne radars and in-situ buoys. The modelling of extreme waves in random records is addressed in more detail in Section 13 of this report.

The deterministic reproduction of selected extreme wave events, or “transient waves”, is an approach used to focus on those actual events only, without having to run full irregular wave records. Clauss et al. (2002) presented experimental results from application of a specially designed wave packet on a ship. A related technique was used by Pastoor et al. (2003) in a fully nonlinear numerical study. One challenge in this approach is how to select the "proper" wave event. Stansberg et al. (2004) picked out random extreme events from long irregular records in a wave basin, thus obtaining a statistical ensemble for robust estimates of deck impact loads in a storm sea state.

2.3 Active Wave Absorption

In open sea, the wave energy reflected by a ship or a marine structure is naturally dispersed in the environment. In a confined domain such as a wave flume or basin, this energy is re-reflected by the wave maker and basin walls, inevitably corrupting the incident sea state, and reducing the useable duration of the test. Implementing active absorption techniques in the wave maker control system can reduce this effect. Such techniques were first used in coastal engineering facilities, because of the large reflection coefficients of massive structures such as dikes or breakwaters. In ocean engineering applications, models are usually less reflective, but there is also a need for the elimination of spurious reflected waves, to maintain a good control of incoming waves in long duration tests. Another interest of active absorption systems is to reduce the waiting time between tests in large basins, by damping residual waves after the end of the wave generation sequence. On the other hand, it may have an influence on repeatability of incident wave conditions for different model configurations, as the actual wavemaker motion will depend on reflected waves, and thus on the model characteristics.

Models for active absorption need feedback from the actual free surface flow in the basin. This is accomplished by exploiting wave height measurements right on the wave maker surface (Van Dongeren et al., 2001 and Schäffer, 2001), or a three wave probe array upstream of the wave board (Frank et al. 2003). The use of the latter arrangement is restricted to the absorption of waves with normal incidence on the wave maker. Other techniques are based on the measurement of the instantaneous fluid loading on the waveboard (Chatry et al. 1998)).

The performance of 2D wave absorption techniques can be assessed by determining the reflection coefficient of the device. Van Dongeren et al. (2001) announce a wave amplitude reflection coefficient close to 5% for short waves. Frank et al. (2003) focus on the deviation of measured incident wave spectra from given targets to illustrate the performance of their system. In 3D, more elaborate methods rely on communication between neighbouring waveboards.

Although offshore or ocean engineering basins have been equipped in recent years with segmented wave makers with active absorption capabilities, the performances and operability of such systems in short crested seas remain to be documented, as only qualitative results on this matter have been published so far. Stability problems in the motion control of segmented wavemakers fitted with active absorption have also been reported. This indicates that active absorption in ocean engineering basins equipped with segmented wavemakers is not a fully mature technique.

2.4 Reduction of Parasitic Effects in Laboratory Basins

These effects fall into the following categories:

- Effects of side walls in the generation of oblique waves
- Generation of unwanted free waves due to wavemaker nonlinearities
- Beach "nonlinearities" - free long waves from the beach.
- Excitation of seiching modes by wavemaker transients
- Generation of a return current

Sidewall Effects. One of the first published first order theories for the generation of oblique waves is due to Biésel (1954), who derived the basic snake's principle, in which the basin is considered to be of infinite extent in the transverse direction, i.e. without sidewalls. In such a situation, the effect of sidewalls is not accounted for, and the useable area of the basin is reduced, with a shape close to an isosceles triangle based on the wavemaker, and an area inversely proportional to the angle of propagation of the generated wave. In Dalrymple (1989), the influence of sidewalls is taken into account in the specification of wavemaker segments amplitude and phases, in an optimisation process, the objective function being associated with the homogeneity of the generated wave on a transverse line at a given distance from the wavemaker. In this approach, the useable zone has a rhombus shape of the same width as the basin. In Boudet and Pérois (2001), the wave quality is optimised on a circle of arbitrary radius and position in the basin. Both methods lead to wider useable zones, the position of which may be parameterised. Such wavemaker motion control methods may be combined with second order prediction and minimization of free wave generation, see below.

Generation of Unwanted Free Waves Due to Wavemaker Non Linearities. When operating a wavemaker with a control law issued from a linearised theory, spurious wave components are observed, due non linearities. These non linearities are present both in the wavemaker boundary condition and in free surface conditions. In the latter case, non linear effects called bound waves locally correct the first order propagating solution in order that fully non linear conditions are satisfied. They are part of the complete propagating wave, and must not be considered as a corruption of the generated wave. On the other hand, higher order waves emitted from the physical wavemaker are an artefact of the generation process in which the wavemaker surface is moving, instead of being a stationary flux surface as in linearised theories. The result is that 'free' waves (i.e. propagating at their own phase speed, and not bound to the first order solution), are emitted. These waves represent a pollution of the wave system. Their amplitudes depend on water depth, wavemaker type and motion amplitude. They can be of the same order of magnitude as bound waves. In certain cases, both bound and free waves can be predicted explicitly by second order theories. Such theories are especially useful for the prediction of free waves, as they allow the determination of corrections to first order wavemaker motions, in order to minimise free wave generation. These matters are discussed further in Section 12.2 dealing with Wave Generation in Shallow water.

A complete two dimensional second order solution for arbitrary planar wavemakers including irregular wave generation was presented by Schäffer (1996).

Suh and Dalrymple (1987) extended the theory for three dimensional regular oblique waves, for which the free wave amplitudes can be as large as Stokes second order bound waves, to the generation of directional spectra. Schäffer and Steenberg (2003) produced a second order theory for irregular short-crested wave generation. These studies, just as in Biésel (1954), were based on the assumptions of a basin of infinite extent in the direction parallel to the wavemaker, and semi-infinite in the direction perpendicular to the wavemaker. These assumptions reduce the possible usefulness of these models to generation at low angles, since wall reflection will completely modify the linear wave system generated by the snake principle.

A complete second order solution for the generation of oblique waves by a snake wavemaker motion in a basin was developed by Li and Williams (2000). In Bonnefoy et al. (2003), another complete second order theory for oblique wave generation in a basin was presented, demonstrating particularly that the new expressions for second order free waves allow any first order generation to be accounted for. Especially, the amplitude of second order free waves generated using the snake's principle or Dalrymple's method were compared, showing that the use of Dalrymple's first order theory leads to free wave of larger amplitudes than in the case of snake motion. Bonnefoy et al. (2003) then demonstrated how those free waves could be eliminated for any of the first order wavemaker motion, by deducing a correction to that motion, cancelling the predicted free waves. These demonstrative calculations were run using a second order time domain model based on spectral theory developed by Le Touzé et al. (2002).

Further developments should be devoted to extend this type of method to the second order control of irregular directional waves using advanced Dalrymple-type wavemaker control.

Excitation of Seiching Modes by Wavemaker Transients. Another source of spurious waves lies in the transient stage of the wave generation process, which will excite all natural modes of the basin. Low frequency modes damp out very slowly and last throughout the test and beyond. Molin (2001a) presented a 2D theory for determining the amplitude of the first excited mode from the wavemaker motion history. A correction aiming at generating an 'antimode' was proposed. The concept was validated both in numerical models and in a physical wave tank. Although elegant and efficient, this approach does not seem to be have been applied in other facilities.

Generation of a Return Current. Following Stokes' works, it is well known that in water waves propagating in an inviscid fluid, a steady drift velocity of fluid particles is obtained, in the direction of wave propagation. This drift velocity appears at second order in wave steepness, in a Stokes expansion of the solution. In a finite length flume, the associated mass transport is balanced by a return current which for long tanks and inviscid fluids appears as a uniform flow towards the wavemaker.

In a viscous fluid, boundary layers are generated at the free surface and at the bottom. Longuet-Higgins (1953) derived a second order analysis of these boundary layers, demonstrating that steady effects were obtained at the outer limits of the boundary layers. At the bottom, it is a steady drift, and at the free surface, a steady shear equal to the vertical gradient of the Stokes drift. Longuet-Higgins (1960) gave experimental confirmation of the analysis. Following this, Baklouti et al. (2003) conclude that a free surface residual current of growing thickness and decreasing intensity should be observed in the wave direction after wave generation has been stopped. They provide experimental and numerical evidence that this phenomenon is effectively observed for low amplitude waves, while at larger amplitude, a residual current a few millimetres thick is observed, flowing from the flume beach to the wavemaker. Experimental results were obtained by detailed analysis of PIV velocity measurements. For the numerical part of the study, a free surface Navier Stokes solver was implemented, extreme care being taken in the grid generation and in the selection of computing parameters, in order to correctly capture the subtle free surface boundary layer effects at the origin of the observed phenomenon.

2.5 Current Generation

Current is generated by re-circulating the water, either in the basin or outside the basin. Typical aspects for the generation of currents depend on the system used for circulating the water. In general current generation in shallow water will be easier than in deep water because of the smaller volume of water that needs to be displaced. The following aspects play a role in generation of current:

- Horizontal profile: the generated current needs to be constant over the width of the test section
- Vertical profile: the generated current needs to follow the specified vertical profile as close

as possible.

- Turbulence: current turbulence is generally defined by:

τ= Stdev(Vc)/mean(Vc).

This turbulence should ideally match the prototype situation, but in practice the prototype turbulence level is not known. Furthermore, as viscosity does not scale properly the model scale turbulence can be expected to be higher than the prototype situation. In general turbulence levels of around 5% are considered acceptable. However, evaluation of the standard deviation only is not sufficient. A spectral analysis of measured current velocity should be performed to evaluate the current turbulence near the natural frequencies of the mooring system, to avoid large (unnatural) effects on the low frequency mooring behaviour (Buchner et al. 2001).

In some cases a highly sheared vertical current profile is specified, for a Hurricane inertial current for example. It is important to realise that generating such a sheared current in a model basin can lead to extreme turbulence levels due to the viscosity of water at model scale, unless special precautions are taken to minimise the turbulence.

3. MODELLING AND SIMULATION OF WIND ENVIRONMENTS

3.1 Modelling in Wave Basins

Wind loading is one of the important environmental loads to be considered for the design and analysis of offshore structures, especially in the design of station keeping systems.

Wind velocity itself consists of mean and fluctuating parts in space and time, and the induced wind load has mean and fluctuating parts accordingly. Most work on physical modelling of the wind environment in wave basins has been confined to simulating wind forces rather than the wind field itself. Since the Froude scaled velocity does not reproduce the target wind force correctly when simulating mean wind forces, a calibration curve is needed to obtain the corresponding wind speed. Froude scaling is used to generate the wind speed at model scale, under the assumption that the above water shape of ships and offshore structures are insensitive to Reynolds number. However, it seems that there is no clear similitude law for the physical modelling of wind even though there are many unknown factors that have an affect at model scale, such as wind driven currents, the splash of waves due to strong winds and shielding effects, etc.

Up until now, the following three methods have been used for generating wind forces in model basins; arrays of wind fans, wind fans directly attached to the model, and spring-weight systems.

The use of arrays of fans seems to be the most popular method and it is widely accepted in most of the commercial wave basins. The array system generates wind over a wide area where the model is located, and computerised control systems are employed to obtain target wind velocities (mean and fluctuating).

The method of using fans mounted on the model deck above the water was devised to generate wind loads by Huang et al. (1993). Bobillier et al. (2000) used the same concept. The fans onboard approach simulates wind loads by controlling the pitch angle of the blades of a variable pitch fan run at constant speed.

It has been reported that spring systems can be effectively used for simulating equivalent wind forces instead of using wind fans (Brown et al., 1998).

Since the wind induces damping effects on floating bodies as well as wind loads, modelling wind environments should aim to reproduce both wind loading and damping effects simultaneously as closely as is physically possible. In this context, using fans mounted on the model deck, or using spring systems, may fail to simulate the damping effects due to wind. Furthermore, mechanical systems cannot simulate cases in which the direction of wind force changes, such as when a floating structure rotates, as realistically as a wind field can. The squall effect, where the wind load suddenly changes its magnitude and direction, is one of current issues in simulating wind forces in model basins. This was discussed in detail by Buchner et al. (2001).

In harsh environments, the nature of the wind field above sea water level may significantly affect the wind loads. Mizutani et al. (2003), using the PIV technique, measured the air-flow field in strong wind conditions, close to water surface, over actual wind waves. It was found that airflow separation and a large-scale vortex are generated in front of the breaking wind driven waves.

The shielding effect due to neighbouring structures is a matter of concern for simulating wind forces in model basins if the model test is focused on multiple moored structures. Buchner and Bunnik (2002) measured wind forces on models of a FPSO and offloading tanker in tandem offloading conditions using a segmented model consisting of three parts. It was found that the shielding effect is significant, and that it is large on the bow part and small on the stern segment. The shielding effect is mainly influenced by the size of the wake, the magnitude of the wind velocities, and the relative distance between the FPSO and the offloading tanker. Suzuki et al. (2003) measured wind loads on the columns of a semi-submersible-type VLFS. They found that the wind load might cause a problem in the mooring design for the structure.

Some other papers have reported model tests on floating structures under combined wave-current-wind environments but their description in the context of wind modelling was not sufficiently complete to be included in this review.

3.2 Simulation of Wind Forces

Some CFD studies have been applied to the estimation of wind forces (Witbread et al., 1997 and Aage et al., 1997). Although good agreements with wind tunnel tests were reported, CFD is not yet competitive with experiments due to time, memory and processing resources required for setting up the computational meshes and solving the equations over the problem domain. Bjørset et al. (2003) compared the drag coefficients predicted for two-dimensional circular and triangular cross sections using CFD with wind tunnel test results. They obtained satisfactory agreements for the drag coefficients but overestimated the shedding frequency.

Most of numerical simulations of wind forces use empirical formulae proportional to the square of the wind velocity, and the harmonic superposition method for generating time series for the wind velocity. In a different approach, a time series generation method for non-stationary wind, wave and current has been presented by Mo and Reinholdtsen (2003). The time series were generated by filtering white noise using an auto regressive moving average (ARMA) model.

The effects of wind on the stability of a moored FPSO were investigated by Lee and Choi (2000) but they considered only the mean wind force in the analysis.

3.3 Questionnaire on Modelling/Simulation of Wind Environments

A questionnaire has been distributed to collect state of the art information on techniques and procedures for the modelling and simulation of wind environments in model basins. Thirteen institutes answered the questionnaire. Details of the questionnaire are presented in Appendix A. The results of the questionnaire are summarised below.

Most institutes use arrays of fans to simulate wind forces caused by the wind field. Spring-weight-wire systems seem to be used as a complementary method. Most of all the institutes adopt RPM control for adjusting wind forces. About half of the institutes simulate wind spectra in their basins.

The force matching method and the Froude scaling method are used equally for generating wind forces. Wind drag coefficients are obtained from wind tunnel tests and other empirical data but CFD results are not yet accepted as being sufficiently accurate.

All the institutes involved in numerical simulations use empirical formula proportional to square of wind velocity. In the event they simulate wind spectra, they use the harmonic superposition method to generate time series for the wind. Only a few participants consider non-stationary properties such as squall, which causes significant changes of wind in time and space.

3.4 Concluding Remarks

Wind in itself is a very complicated physical phenomenon, fluctuating both in time and space, and wind induced forces are inherently nonlinear viscous forces that are very sensitive to scale effects. Most of the model basins, however, have concentrated so far on generating mean wind forces. Arrays of fans, deck mounted fans and spring wire-weight systems have been used for this purpose.

As installation sites for floating structures move into regions of deeper and deeper water, the importance of wind forces is becoming recognised as a serious issue more than ever before. It is becoming accepted that model scale winds should represent damping effects, shielding effects and gust effects such as squall, as well as mean wind forces, to ensure the satisfactory safety assessment of moored bodies using model tests. In this context, there is a requirement for more studies aimed at developing methods to achieve a realistic physical portrayal of the sophisticated nature of wind mentioned above at model scale.

It can be argued that the array of fans is the most promising amongst the three methods currently used, for the following reasons:

- Simulating the wind field can model not only the forces but also damping and shielding effects,
- Simulating the wind field is the method most capable of accounting for the response of large weather-vaning models,
- Only the method of simulating the wind field provides external forces without unphysical interference under gust or squall conditions.

It is a challenge to develop a standard procedure for modelling the wind environment as closely as possible to reality. In order to achieve this, more basic and systematic experimental data on wind forces, damping and shielding effects should be collected through further ITTC comparative studies since there is not yet sufficient data or understanding of wind physical mechanisms at model scale.

4. PREDICTING THE BEHAVIOUR OF BOTTOM-FOUNDED STRUCTURES

4.1 Introduction

Many types of bottom founded structures have been designed and installed over the years but they fall broadly into two main categories with respect to the dominant flow phenomena involved and how they are modelled and analysed. The first category is comprised of structural elements that are slender with respect to the characteristic wave of the sea environment, and their behaviour is heavily influenced by viscous effects. These are chiefly dealt with by empirical approaches, notably the Morison equation (Morison et al., 1950) and its variants, although more sophisticated approaches have been proposed, e.g. Rainey (1989) and Sarpkaya (2001). Members of the second category are large enough to modify the ambient wave field, are largely insensitive to viscous effects, and are approached using potential flow theory. The techniques are similar to those used to predict the loads on conventional ship forms described in previous reports of the ITTC Loads and Responses Committees. A third category includes all those structures that are a hybrid of the first two.

The basic Morison equation describing the inline force, *f*, on a fixed structure in an ambient periodic flow of undisturbed velocity, *U*, takes the form

$$f = \tfrac{1}{2}\rho A C_D U|U| + \rho V_R \dot{U} + \rho V_R C_A \dot{U} \qquad (4.1)$$

where,
A is the projected area V_R is a reference volume enclosing the object and C_D and C_A are empirical coefficients referred to as the drag and added mass coefficients. The first term on the right hand side of the equation, the drag term, is associated with viscous effects such as flow separation and vortex shedding. The second term, the Froude Krylov term, is associated with accelerating the displaced fluid with the ambient flow and disappears if the body is oscillating and the flow is quiescent. The second and third terms combine to form the inertia term with an inertia coefficient $C_M = 1 + C_A$. If the body moves with a velocity, u, in response to the flow the Morison equation becomes

$$\begin{aligned} f &= \tfrac{1}{2}\rho A C_D (U-u)|(U-u)| \\ &\quad -\rho V_R C_A \dot{u} + \rho V_R C_M \dot{U} \end{aligned} \qquad (4.2)$$

The coefficients are functions of the Reynolds number, the Keulegan Carpenter number ($U_m T/D$) and the surface roughness of the body, and a great deal of work has been carried out to determine the force coefficients suitable for bottom founded structures, e.g. Sarpkaya (1991) and Chaplin et al. (1994).

For use in linear frequency domain calculations the nonlinear drag term is linearised with the linearised drag coefficient being selected to minimise the error over the time series for *f*, as discussed by Wolfram (1999).

4.2 Studies on Bottom Founded and Other Fixed Structures

Studies on bottom founded structures can be further classified generically in the context of their type, compliant or rigid for example, or the analysis applied to them, such as linear or non-linear. In addition, they can be referred to with respect to phenomenological or environmental conditions such as separated flows, diffracted flows, shallow water, green water, and impact forces from steep and breaking waves. A review of the literature shows the applications of bottom founded structures and the approaches taken to modelling and analysing them are myriad and too wide ranging to be comprehensively covered in the present work. Instead a representative sample of state of the art examples that have been recently published will be reviewed. This also includes works on fixed bodies in deep water.

4.3 Small Volume (Morison Type) Structures

Vertical Cylinders. A large number of authors describe experimental and numerical work done using vertical cylinders. Zaman and Baddour (2004) studied the loading of an oblique wave-current field on a slender cylinder in a 3D flow frame. The kinematics of the flow field were formulated using the wave-free uniform current and the current-free waves. These were used to calculate the loads imparted on a bottom mounted slender cylinder. Results were compared to three available models, including the superposition principle from API, and Morison.

Jacket/Jackup Structures. The dynamic behaviour of offshore platforms subjected to wave loading, has been studied by Kuntiyawichai et al. (2004) using Wavelet and Finite Element analysis. They present results for the effects of wave velocity, height, and period on platform behaviour. Wave velocity was shown to have little effect on the response of braced caissons, while wave height and period have more effect.

Results for the dynamic response of a jacket structure subject to simultaneous wave and earthquake loads have been presented by Etemad et al. (2004). They modelled the soil/pile interaction by the Konagai-Nogami, and the structure using a finite element method. They found that with the longitudinal components of the earthquake and wave in the same direction, the wave may reduce the platform response. When they are in different directions, an increase in response may be seen.

Detailed laboratory measurements have been made by Cox and Scott (2001) of the instantaneous free surface elevation in front of a fixed deck and the free surface elevation, velocity, and overtopping rate at the leading edge of the deck. The study showed that the exceedance probabilities for the normalised maximum instantaneous overtopping rate and the normalised overtopping volume were predicted by a simple exponential curve.

Numerical investigation of the wave impact loads on the deck of the Ekofisk platforms have been described by Iwanowski et al. (2002). They used three theoretical wave models: the Airy, modified Airy with Wheeler stretching, and 5th order non-linear Stokes models. These approaches were applied to various wave loading models including Navier-Stokes (VOF method) and a Morison/momentum displacement method.

Cox and Ortega (2002) describe a small-scale laboratory experiment conducted to quantify a transient wave overtopping a horizontal deck fixed above the free surface. Detailed free surfaces and velocity measurements were made for two cases with and without the deck structure to quantify the effect of the deck on the wave kinematics.

A statistical model of wave overtopping volume and extreme wave rates on a fixed deck has been developed by Mori and Cox (2003). The probability density function for the volume and rate of overtopping water are formulated based on the truncated Weibull distribution. The model prediction of exceedance probability of deck overtopping gave qualitatively good agreement with laboratory data for large overtopping values.

Daghigh (2002) has used a modified Morison type formulation from DNV regulations to estimate hydrodynamic forces on an equivalent pile representing the slender bodies of Jacket / Jack-up structures.

A time domain Finite Element analysis of the dynamic response of offshore towers due to wave forces has been carried out by Mostafa and El Naggar (2002). The tower response was calculated with emphasis placed on the effects of dynamic pile-soil interaction for a range of wave conditions.

A large-scale experimental study of wave loading on offshore platform decks with a focus on different deck elements has been presented by Sterndorff (2002). A range of wave types, air gaps, and inundations have been tested. Results provide hydrodynamic load coefficients to wave-in-deck programmes based on change of fluid momentum and a CFD analysis using the VOF method.

Cassidy et al. (2001) investigated issues relating to the dynamic assessment of jack-ups. Consideration has been given to the non-linearities in the structure, foundation, and wave loading. The spectral content of wave loading has been considered using New Wave theory, and the importance of random wave histories shown by constraining the deterministic New Waves into a completely random background. A method for determining short-term extreme response statistics for a sea-state using Constrained New Waves is detailed.

4.4 Large Volume (Diffraction Type) Structures

Vertical Cylinders. Rahman and Mousavizadegan (2004) have presented results for the wave-induced second-order time independent drift force and moment on fixed vertical cylinders of varying depth to radius ratios. The analytical technique determined the first-order velocity potential considering the interior and exterior regions. The numerical solution used a higher order panel method in which the kernel of the integral equation was modified to make it non-singular and amenable to solutions by the Gaussian quadrature formula.

Kim et al. (2003) have presented a time domain numerical method to study the diffraction of nonlinear Stokes waves by a vertical circular cylinder. They developed a new scheme to match the 2D far field to the 3D diffracted wave in the near field. Results for diffraction of Stokes waves of various steepnesses have been investigated. The wave elevation and run-up compare favourably with theoretical results.

An experimental investigation of wave run-up on a fixed, vertical, circular cylinder, has been presented by Morris-Thomas et al. (2002) who focus on wave steepness and body slenderness. The zero-, first-, and second-harmonic components of the wave run-up are compared with WAMIT. Linear diffraction prediction of the first-harmonic component is reasonable, however, the zero- and second-harmonics are not well captured. The importance of higher-order wave steepness effects on the wave run-up is demonstrated.

Experiments in which wave run-up has been simulated using a surface-piercing cylinder driven with a horizontal motion have been undertaken by Retzler et al. (2004). In the experiments 112 wave gauges recorded the surface elevation at high frequency. Non-linear components at temporal and spatial frequencies up to the third harmonic were identified. The results compared well with those made using conventional linear potential theory.

Laboratory measurements of the run-up on vertical cylinders from sets of random waves have been made by Indrebo and Niedzwecki (2004). They used a two parameter Weibull distribution function utilised empirical coefficients to model surface wave run-up. The analysis focussed on interpreting the tails of the probability distributions by carefully fitting the analytical model to the measured model data.

Nielsen (2003) presented results from a comparative study on numerical predictions of the nonlinear wave amplification near a single fixed column, also including experimental data. A significant scatter was observed, and it was concluded that predictions were not robust. Based on parts of the same experiments, the wave disturbance close to a fixed vertical column has been investigated by Stansberg and Braaten (2002). Deviations from linear prediction were investigated by experimental and second order numerical methods using WAMIT. Model tests were done in regular, bi-chromatic, and random waves. Significant non-linear effects were observed, especially in steep waves. The experimental results showed an underestimation of wave disturbance by the linear approach. The second order diffraction model represents significant improvements, while there are still some discrepancies in steep waves. Follow-up investigations by Kristiansen et al. (2004) show that amplitudes of basic harmonics are often under-predicted and second-harmonics generally over-predicted by second-order theory, but they do not generally cancel out each other.

Akyildiz (2002) describes an experimental investigation of pressure distribution around a large, fixed vertical cylinder subjected to regular waves. The experimental and computational pressure results were compared and showed good agreement, but tended to diverge approaching the free surface.

The interaction of steep incident waves with a vertical, surface-piercing column has been studied by Sheikh and Swan (2003). Their work was prompted by observed wave impact damage on the undersides of gravity-based structures. It has been demonstrated that multiple-column structures, where the individual diameters lie outside the typical diffraction regime display an unexpected mechanism that leads to the scattering of unexpected high-frequency waves. It is shown that the scattering of these high frequency waves and their subsequent nonlinear interaction with incident waves has significant implications for the specification of air-gap and deck elevations.

4.5 Compliant Structures

The non-linear dynamic behaviour of a Double Hinged Articulated Tower (DHAT) under long crested random sea and directional random seas has been investigated by Islam and Ahmad (2003). They took a number of parameters into account for modelling the forcing functions of the equation of motion, which is derived by Lagrangian approach. A long crested random sea was modelled by Monte-Carlo Simulation using a P-M spectrum. The dynamic behaviour was investigated in detail in terms of various parametric combinations.

A three-leg articulated tower has been studied by Nagamani and Ganapathy (2000) using analytical and experimental techniques. The effects of mass distribution on the variations of the bending moment and the deck accelerations have also been presented. The model was tested in a 2m flume for various wave frequencies and wave heights of regular waves.

4.6 Second Order and Fully Non-Linear Analysis

In Ferrant et al. (1998), a fully non linear time domain boundary element model and a third order frequency domain semi-analytical formulation were applied to the study of higher order load components on a bottom-mounted cylinder in regular waves. In the low steepness regime, fully nonlinear simulation results recover the behaviour of the third order analysis, while for larger amplitudes, sensible deviations from perturbation analysis are exhibited by fully non linear simulation results, a result in full agreement with the experimental work of Grue and Huseby (2002).

Büchmann et al. (2000) used a fully non-linear time domain boundary element model and a second order time domain boundary element model to study wave and current induced run-up on a large fixed body. The results from the two models agree well in the low Froude number and low wave steepness regimes. For higher Froude numbers and wave steepnesses, the fully nonlinear approach provides the most reliable results.

4.7 Non-Linear Wave Amplification, Green Water and Impact Forces of Steep and Breaking Waves

A number of authors have examined issues related to Gravity Based Structures (GBS), particularly non-linear wave amplification and its effect on green water deck impact loads

Van Iperen et al. (2004) used a 3D radiation/diffraction program and compared their results with experimental surface elevation data. The objective was to determine deck elevation required to avoid green-water impact under extreme storm conditions. They attempted to predict extreme crest heights from diffracted spectrum using a Weibull distribution. Wave breaking was seen to be a factor limiting crest heights. The feasibility of using numerical simulations of wave enhancement, supplemented with non-linear corrections for extreme crest heights was investigated.

Model tests on a GBS platform in extreme waves have been performed by Stansberg et al. (2004). A wave realisation comprising 50 extreme wave crests was used, and deck impact loads were measured. The effects of nonlinear wave amplification were studied. The scatter in force measurements demonstrated the need to take into account the natural variation of random waves. Significant nonlinear wave amplification was observed in front of the deck. The effect of this on deck impact loads was investigated further in Baarholm and Stansberg (2004), where a simplified load model based on the conservation of momentum was presented and compared to the model test results. A good agreement was observed..

Molin et al. (2005) investigated highly nonlinear wave run-up on a vertical bottom-mounted plate. The phenomenon is explained by third order interactions between incident and reflected wave-fields. Resulting focussed wave elevations on the plate are significantly higher than those predicted by linear theory, and may have significant implications on run-up and green water effects on GBS and ships in beam seas.

Most work in this area uses potential theory or experiments. However, a numerical study, using a Volume of Fluid method to investigate wave run-up and green water impact on the deck of a GBS used as an LNG terminal has been presented by Loots and Buchner (2004).

4.8 Hybrid Potential/CFD Modelling

Original CFD-potential flow hybrid approaches recently appeared, showing interesting perspectives for the efficient simulation of wave-body interactions, incorporating viscous effects.

In Ferrant et al. (2003), a potential splitting approach in which a fully non linear potential formulation for incoming waves is accounted for in the formulation of the general problem of wave-body interaction in real fluid. In this formulation named SWENSE (Spectral Wave Explicit Navier-Stokes Equations), the resulting solution satisfies the initial fully non linear boundary value problem without approximation, with significant advantages in terms of performance and accuracy over direct RANSE equation solvers. In (Luquet et al 2004), the initial 2D formulation for stationary bodies is extended to 3D ship-wave interactions with forward speed.

Graham and co-researchers (see Kendon et al., 2004, for example) have developed an approach in which they treat the irrotational and vortical components of flow as separate nonlinearly coupled equations. The approach uses a Helmholtz decomposition of the velocity vector and solves the potential and rotational components using a classical boundary element technique and a high order spectral/hp code applied on a Eularian mesh, respectively (see Section 8.4 for further details). The technique has been applied to a number of problems including circular cylinders in uniform and wave flows, and also to floating bodies (Kendon et al., 2003). Good agreement was obtained between the computed results and other theoretical and experimental studies.

Such formulations may be especially effective for simulating wave body interaction problems in which the flow characteristics are intermediate between purely diffracting (large volume) regime, and small volume, detached flow regime.

4.9 Miscellaneous

The determination of wave forces on multiple structures in close proximity has been investigated by Chakrabarti (2000), who uses an analytical/numerical approach modelling multiple vessel interaction and wave scattering. The technique is based on an extension of the semi-analytical multiple vertical cylinder analysis, achieved by combining the direct method of linear diffraction with a semi-closed analytical method of multiple scattering developed from an array composed of vertical cylinders.

Forristall (2004) discusses the present inadequacy of knowledge on the effects of shallow water wave height limits in relation to study of environmental forces on LNG terminals. He indicates that additional laboratory and field measurements are necessary before depth limited waves can be confidently specified.

Another area that is receiving increasing attention is the prediction of wave loading on the towers of offshore wind turbines. Trumars et al. (2003) studied wave forces and moments on a mono-pile support for an offshore wind energy converter, using the Morison equation. A second order time domain wave model was used to determine wave motion. The calculated force and base moments were found to be highest at the crest. Okan et al. (2005) investigated a number of different wave theories for use with the Morison equation to investigate the loading on wind turbine structures in shallow water and steep waves.

Byrne and Houlsby (2002) explore various structural options that may be used for offshore wind turbine application. Experiments investigating the different loading conditions are explored. A theoretical approach that describes the experimental results in a way that can be implemented in typical structural analyses programs is outlined. Details of a major research program into developing the necessary design guidelines for foundations for offshore wind turbines are described.

5. PREDICTING THE BEHAVIOUR OF STATIONARY FLOATING SYSTEMS

Floating structures play an increasingly important role within ocean engineering. A major part of this takes place within oil and gas production and related activities, which goes into deeper and deeper waters but also represents new challenges in shallow waters. Other areas include floating islands (VLFS) and renewable energy production from wind and waves. New frontiers require systems exposed to various types of design conditions depending on the actual location, ranging from harsh weather with extreme waves, to more benign conditions but with strong deep-water currents or sudden wind loads. Cost-effective solutions are sought, and new or modified concepts are being developed. Challenges are also related to the accurate prediction of floater motions in mild operational conditions, especially during installation or when two or more structures are interacting. All these new factors imply that tools for analysis and prediction of system behaviour need to be constantly updated and verified for the new applications, and model testing is crucial for the software validation and for the final design verification

In this section, recent challenges and developments within the following topics are reviewed:

- New concepts and challenges.
- Coupled analysis.
- Green water, air-gap, slamming.
- Hydrodynamic multi-body interactions.
- Very large floating structures (VLFS).
- Energy systems.

5.1 New Concepts and Challenges

Monocolumn floater designs, which have much shallower drafts than traditional spars, have been described and analysed in Chou et al. (2004), Torres et al. (2004), and Syvertsen et al. (2004). Such floaters have some favourable features compared to conventional systems. At the same time, stability and vertical motion characteristics (heave, roll and pitch) need to be thoroughly investigated. The above references include some numerical and experimental results showing that details determining damping and stability parameters can be improved by use of model testing.

Moon-pools can also be included, for which numerical hydrodynamic prediction can be a challenge. Analytical formulations for moon-pools with vertical sides have been proposed by Molin (2001b). A method to handle this problem by means of a numerical "lid" was presented by Lee et al. (2002).

Smaller floaters such as mono-buoys require particular attention in numerical modelling, due to the relatively large weight contributions from moorings and risers. A coupled analysis study was carried out in Cozijn et al. (2004), while Fernandes et al. (2004) presented a frequency domain study.

Spar buoy concepts have received increasing attention over the last few years (see for example, Stansberg et al., 2001) However, require improved vortex induced motion (VIM) control in currents as discussed, for example, by Smith et al. (2004) and Irani et al. (2004). This problem is described in more detail in Section 7 of this report.

For deepwater systems, Steel Catenary Risers (SCR's) are often a subject of investigation. They require small top-end motions for relatively short wave periods (10 – 12s) to avoid fatigue problems, which influences the actual floater design (e.g. deeper draft), which, in turn, should be verified by model tests. Similarly, higher payload demand may require deeper drafts. Submerged (hybrid) riser solutions have also been considered, for example, by Fernandes et al. (2003).

In the design verification of ultra-deep water systems, model testing must be done by the use of truncated mooring and riser systems and integrated with advanced numerical simulations, due to model basin depth limitations. This topic is described separately in Section 9.

Recently, increased attention has also been focussed on floater hydrodynamics in shallow water due to the development of offshore LNG terminals, see for example, Naciri et al. (2004), and Grant (2004). Compared to deep water, there are special effects that need to be taken into account and investigated in detail. Slow-drift surge and sway forces may be dominated by off-diagonal QTF contributions not included in Newman's approximation. Multi-body hydrodynamic interaction effects may also differ significantly. In experimental studies, unwanted basin effects in the wave generation, such as "parasitic waves", may affect the results, and need to be taken into account or reduced. This is addressed in more detail in Sections 2.4 and 12.

Offloading, transport and installation operations are other areas where model testing play an increasingly important role in validation as well as in demonstration of effects. See e.g. Tahar et al. (2004). In operations, multi-body hydrodynamic interactions must often be taken into account, described in a later section.

5.2 Coupled Analysis

Over the last five to ten years, so-called coupled analysis tools have been developed and established for the study of global performance of floater systems. This advanced analysis approach takes into account the full dynamical coupling between floater motions and the forces from individual mooring lines and risers, normally carried out in the time domain. A review of the method is presented in Ormberg et al. (2005). A number of new case studies have been recently carried out, including verification against other tools and against experiments. Luo et al. (2004) and Steen et al. (2004) presented results for an FPSO system and a Spar system, respectively, both in 900m water depth. A similar analysis was carried out in Zou et al. (2004) for a TLP in 1800m depth. Details of the numerical modelling in the latter case were presented by Ormberg et al. (2003). Roveri et al. (2004) carried out a coupled analysis on a semi-submersible, while Cozijn and Bunnik (2004) analysed a CALM buoy. In the latter case, the coupled approach may be particularly relevant due to the relatively large forces from lines and risers on the floater. Coupled analysis is also an important part tool in hybrid verification (integration of truncated model test set-up with numerical simulations), described in more detail in Section 10.

5.3 Green Water, Air-Gap, Slamming

A comprehensive experimental investigation of green water loads on FPSOs has been presented by Buchner (2002). The investigation focused on the relative motions including nonlinear effects, the details of the water flow on the deck, and the loads due to green water on the deck and on the deck structures. The effects of the bow geometry and flare on the relative motions and flow on the deck have been investigated by using several bow geometries. The pressures on deck have also been measured and analysed from which it was concluded that the loading on deck is not static and that the dynamic contribution is important.

Soares and Pascoal (2002) have presented statistics for relative motions at the bow of FPSOs considering vertical elliptical bows. The analysis starts with determining the probability functions that best fit the incoming wave heights and the crest trough asymmetry, the vessel motions are characterised, making it possible to determine that the first source of non-linearity in the relative movement is actually due to the waves, and finally the most important one is then caused by the freeboard exceedance. The analysis leads to the probabilities of freeboard exceedance and the conditional probabilities of exceedance of the height of green water at the bow.

Nielsen and Mayer (2004) apply a Navier Stokes solver based on the VOF (Volume of Fluid) model to calculate the green water loads on a moored FPSO in head waves. Two cases are investigated, namely with a vessel restrained at its mean position and with a vessel moving in waves. In both cases the numerical results are compared with published experimental data and the agreement is good. For the second case, 2D and 3D models were used to model green water loads and the results show that 3D effects are small. Other fully nonlinear predictions were presented by Barcellona et al. (2003), Greco at al. (2004), Mori and Cox (2003), Yilmaz et al. (2003), Kleefsman et al. (2004), reflecting a significant activity in the area.

A simplified engineering tool for green water loads and bow flare slamming on an FPSO has been described and compared to model tests in Stansberg et al. (2004); Hermundstad et al. (2004). Among the primary parameters identified are the incident crest elevation and the water particle velocity predicted from a second-order random wave formulation. Promising comparisons to a Volume-of-Fluid approach for the water-on-deck propagation and loads were also made. Nonlinear diffraction and flare effects were investigated in Stansberg and Kristiansen (2004).

For nonlinear wave amplification and air-gap between large-volume platform legs, results from a comparative numerical study were presented and compared to experimental data in Nielsen (2003). A significant scatter was observed. Comparisons between second-order free-surface predictions and model tests were also presented in Stansberg et al. (2005). Improvements from linear theory were clearly seen, but also higher-order effects were seen in steep waves. For wave-in-deck loads on platforms, a fully nonlinear approach was described by Baarholm and Faltinsen (2004). Further works on similar problems are reviewed within the previous section of fixed structures behaviour.

5.4 Hydrodynamic Multi-Body Interactions

The main effort in this area has been focused on the improvement of numerical accuracy in predicting motions (global and local) and wave drift forces when the distance between two (multi) bodies is small. Boundary element methods still play the major role in the numerical analysis of multi-body hydrodynamic interactions.

Numerical overestimation was reported when using conventional CPM (Constant Panel Method) by Huijsmans et al. (2001), who proposed the so called LID method in which some part of free surface flow between two adjacent bodies is artificially suppressed in order to obtain a realistic drift force estimation. Buchner et al. (2001) addressed the implementation of a fully coupled retardation function, which is a prerequisite for considering hydrodynamic interactions in time domain simulations. Inoued et al. (2001) demonstrated that there is an abnormal sensitivity of drift force to roll resonance motion for vessels moored side-by-side. Choi and Hong (2002) applied HOBEM (Higher-Order Boundary Element Method) to the analysis of multi-body hydrodynamic interactions and Hong et al.(2002) showed by model tests that HOBEM gives a very accurate estimation up to second order except in a very narrow frequency range where strong interactions occur due to a Helmholtz resonance. Hong et al. (2003) also discusses the capability of HOBEM to analyse multi-body hydrodynamic interaction problems. Time-domain simulation of multi-body effects in offshore operations were presented in Reinholdsen et al. (2004).

In Malenica et al. (2005), amplification effects occurring in the small free surface area between side by side vessels are controlled using an approximate method accounting for non-potential dissipation effects. A new mid-field formulation for second order drift forces on multi-body configurations is also proposed and validated.

5.5 Very Large Floating Structures.

Although a substantial investigation of VLFS by the Japanese Government has been completed, research required for its realisation, such as the re-expansion plan of Haneda Airport (Kato et al., 2005), is ongoing. The hydro-elasticity of VLFS is a longstanding area of research that has been addressed by many researchers. Park et al. (2004) showed a design example of a pontoon type VLFS using hydro-elastic analysis based direct analysis method. Hong et al. (2004) also carried out extensive hydro-elastic analysis on a pontoon type VLFS to investigate wave loads and induced structural stresses for various environmental and structural stiffness conditions. Seto et al. (2001) introduced practical numerical calculation methods for estimating their hydro-elastic responses, and numerical analytic solutions for verification purposes of general numerical codes for hydro-elasticity were presented by Peter et al. (2003) and Watanabe et al. (2003).

Many investigators have studied the breakwater performance of pontoon type VLFS in order to reduce the effects of waves on them (Hong et al., 2002, 2003, Ikoma et al., 2002a). Hong et al. (2003) introduced an eigen-function method that can account for breakwater, shoreline effects and the draft of the mat structure simultaneously. The concept of wave breaking by using submerged-plate was also introduced, and its effects were investigated by Takaki et al. (2001) and Higo et al. (2002).

The characteristics of slowly varying wave drift forces and moments acting on VLFS, which are important in the design of the mooring system, were studied by Shimada and Maruyama (2002). Utsunomiya et al. (2001) derived near field wave drift force formulae for pontoon type structures, and Hong et al. (2002) derived near field expressions for wave drift forces considering the elastic deflection of general bodies in an analytically consistent manner.

Various methods have been proposed for reducing the hydro-elastic responses. Maeda et al. (2001) and Ikoma (2002b) proposed to set up air chambers on the bottom of VLFS to control hydro-elastic behaviour. Masanhobu et al. (2001) and Mural et al. (2002) investigated VLFS supported by columns, and made clear the effect of winds and the effect of viscosity acting on the columns.

The bottom topography effect on hydro-elastic responses was considered by Iijima and Shiraishi (2002), and Murai et al. (2003). Bellibassakis and Athanasoulis (2004) developed a coupled mode technique to apply to the analysis of hydro-elastic responses of VLFS lying over variable bathymetry regions.

The variational principle applied to hydro-elastic responses was attempted by Isshiki and Nagata (2001) and Meylan and Hazard (2002) applied Spectral theory. A wet-mode superposition technique was used by Hamamoto and Fujita (2002). Lee and Choi (2003) applied FEM-BEM hybrid method to solving for the transient hydro-elastic response of a pontoon structure.

5.6 Energy Systems

The utilisation of renewable energy is becoming increasingly important from the viewpoint of the conservation of the global environmental. The ocean waves have a huge potential for clean energy production and the estimated useful resources around the world are between 1 and 10 TW. The offshore wind farms also promise to become an important source of energy in the near future.

The experimental investigation with scaled models of wave energy devices offers new opportunities for ocean basins. With the increasing pressure to produce energy from renewable sources, the development of wave energy devices is gaining momentum. The European thematic network WaveNet presents some of the concepts (WaveNet, 2003) and identifies the needs in term of R&D. The IEA-OES (2003a) also identifies with detail the status and R&D priorities. In general one may say that model testing will contribute to develop wave energy systems optimised with respect to the energy production and safer with respect to extreme wave loading. The IEA-OES (2003b) recommends a set of practices and guidelines for testing and evaluation of wave energy systems. Many references to the scientific work developed recently within several areas related to wave energy system can also be found in the three references presented before.

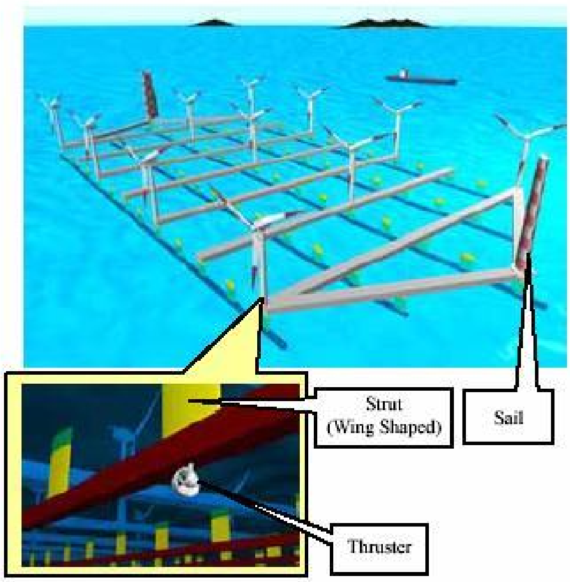


Figure 5.1- Floating wind farm with mooring-less system.

Although some seabed-mounted offshore wind farms were constructed in the shallow seas off European countries (Henderson et al., 2002a, Zaaijer et al., 2004), most of sea bottoms around Japan get quite deep as apart from coast lines, and hence other concepts will need to be utilised (Henderson et al., 2002b, Kogai et al., 2003). It is a progressive idea to deploy many floating wind farms in deep seas. The key technologies for designing them are to secure structural strength and station-keeping performance. Conventional catenary mooring system is no longer practical for station-keeping a kilometre sized floating structure in over hundreds of meters of water depth. The unique shaped floating structure shown in Fig. 5.1, which consists of many wing shaped struts and slender shaped lower hulls, is considered by Inoue et al. (2005) to be the most promising new concept for floating wind farms. This floating structure has self-mobile capability and is effectively manoeuvred to the designated offshore region using lifting forces generated at the struts.

6. PREDICTING THE BEHAVIOUR OF DYNAMICALLY POSITIONED SHIPS

Dynamic Positioning (DP) was developed in the late 60's and has been used since then mainly for drilling operations. With the trend towards offshore operations in increasingly deeper water the application of DP has become a commodity. Due to growing experience the reliability has also increased while the costs of DP-systems have decreased and nowadays DP is found on a wide variation of offshore vessels and even on dredgers, small yachts and cruise vessels. A description of DP systems was given previously in the 23rd ITTC Stationary Floating Systems Report. In this section, the focus will be mainly on the numerical and physical modelling aspects.

6.1 Definition and Components

DP is "a means of holding a vessel in relatively fixed position with respect to the ocean floor, another vessel or a floating structure, without using anchors, accomplished by two or more propulsive devices controlled by inputs from sonic instruments on the sea bottom and on the vessel, by gyrocompass, by satellite navigation or by other means." Based on this definition, DP can be considered to be a special type of mooring. A special case of DP is when it is used to control the motions of a vessel along a predetermined track, so-called dynamic tracking.

A DP-system consists of several components. The main DP-components are:

- Sensors (motions, wind, thruster feedback)
- Control system, consisting of mathematical model (including Kalman filter), feedback controller, wind feed forward and thruster allocation
- Thrusters

6.2 Components of a DP-System

A DP-system consists of several components. The main DP-components are:

- Sensors (motions, wind, thruster feedback)
- Control system, consisting of mathematical model (including Kalman filter), feedback controller, wind feed forward and thruster allocation
- Thrusters

6.3 Specific Aspects

DP system reliability and performance depends on a number of aspects:

- Control system stability, robustness and optimisation.
- Position reference and sensor stability and performance.
- Thruster operational performance.

Hydrodynamically the thruster performance research is the most relevant aspect of DP technology development. It focuses on thruster interaction effects (see below). A second aspect is the development of adequate hydrodynamic (manoeuvring) models for the Kalman filter, i.e. for vessel speeds from 0 to 8 knots.

6.4 Evaluation of DP-Systems

To evaluate the performance of DP-systems the following methods are available:

<u>DP Capability Calculations.</u> In this approach the equilibrium between mean environmental forces and maximum thruster forces are calculated as functions of the vessel heading. Several commercial programs are available; see also the report of the Specialist

Committee on Stationary Floating Systems (23rd ITTC). Characteristics of this approach are:

- Quasi static approach (mean forces only, constant heading)
- No vessel dynamics (only a fixed margin for dynamics)
- Fixed relation between waves and wind
- Fixed current speed (and direction)
- Software available from several sources

The main advantage of the method is the speed of calculation and the ease of comparison of one design compared to another.

The main disadvantage is that the results depend heavily on the chosen approach of force calculation and only designs using the same capability calculation method can be compared. Another disadvantage is that no real vessel dynamics are taken into account. DP capability calculations therefore tend to over-estimate the DP performance in severe sea states.

DP Time Domain Simulations. In time domain calculations a numerical model is built that describes the DP-vessel. Most often only low frequency motions are considered, which reduces the numerical model to three equations of motion (surge, sway and yaw). Characteristics of this approach are:

- Low frequency dynamics included (surge, sway and yaw)
- Option to include wave frequency dynamics
- More detailed results on DP performance:
- Statistics
- Range of headings for given sea state
- Optimisation of DP control settings possible for different sea states

The main disadvantage of time domain simulations is that the results are only as good as the numerical model. Thruster interaction effects are at best taken into account in a generic way. Furthermore, most simulations consider a no-noise situation, so the effect of position filtering is not taken into account. The wave drift forces in a real sea environment may differ from the numerical values due to effects of large first order motions, actual wave shape, wave directionality and current interaction effects which are not yet fully described in theory.

DP Model Tests. In DP Model tests a physical model of the DP-vessel is built. All components of the DP-system are present in the model, although it may not be necessary to model all details. For instance, in some cases it may be possible to “lump” some of the thrusters into a single thruster delivering the total thrust. Key features of DP model tests are:

- Controlled real environment (waves, wind and current)
- A complete physical model, i.e. combined wave, wind and current loads and all thruster interaction effects and response times are present
- Closed loop automatic DP control including:

1. Kalman filter
2. Controller (PID or other)
3. Minimum power thruster allocation

The main disadvantage of DP model tests are the costs and time it takes to perform the test program.

An advantage of (DP) model tests is that unexpected phenomena will show up in an early stage of the design process. Furthermore the DP model tests can be combined with 'traditional' sea keeping tests. See also van Dijk et al. (1999).

Full-scale Measurements. After the DP vessel is built, full-scale measurements can be performed to assess its DP performance. Key features are:

- Evaluation of DP performance on delivery
- Observation of possible interactions between DP system and power management system

The advantage of full-scale measurements is that these are the most accurate assessment of DP performance of the DP-vessel.

The main disadvantages of full-scale measurements are that it is more costly and that any errors found are more difficult to correct (as the vessel is already built). Furthermore, the conditions that can be tested depend on the environment the vessel is in at that moment and it may take a long time before a specific sea state is encountered. On top of that it will not be feasible (from a safety point of view) to test full scale in survival conditions.

6.5 Aspects of the Investigation of DP Model Tests and Simulations:

When evaluating a DP-system using either simulations or model tests the following aspects of DP-performance can be investigated:

- Position accuracy
- Thrust and power requirements
- Heading window assessment
- Sudden wind squall procedures
- Thruster - Hull interaction
- Thruster - Current interaction
- Thruster - Wave interaction
- Control coefficient optimisation
- Thruster failure scenarios
- Drift - off / Drive - off scenarios

6.6 Future Research and Development:

Current loads are an important parameter in total environmental loading of an offshore structure. These loads are normally derived using model tests or wind tunnel tests, but both have Reynolds numbers that are orders of magnitude lower than the prototype situation. In general the scale effects are considered to be negligible, but in some special cases model tests and wind tunnel tests may underestimate the prototype current loads.

Development of manoeuvring models for Kalman filters for a speed range between 0 and 8 knots is an area that should be studied further (to be used in DP, dynamic tracking and auto piloting).

Existing data on thruster - current interaction is valid for current speeds up to 0.7 m/s (bow thruster results are available up to 2 m/s). Thruster interaction modules in existing software often use this data to predict thrust losses due to current. In most of the DP operations considered today much higher current speeds are encountered, e.g. GoM loop current condition with current velocities up to 3-4 knots. It is therefore important to update the databases with new thruster current interaction data valid for these higher current velocities in order to accurately be able to predict DP performance in high current conditions.

While performing DP model tests it is important to model the complete system as will be used in the prototype situation. It is therefore important to use a DP control system in the model tests similar or identical to the one used in reality. This may involve more cooperation with suppliers of prototype DP systems. Points that need to be addressed are:

- Thruster allocation. There are many ways of allocating the demand thrust to the thrusters, how significant is the effect of this on overall performance. If an algorithm that differs from the manufacturers is used, how important an effect is this?
- Controller tuning. How significant is the effect of controller tuning on the results of a model test and how do these tuning parameters translate to full-scale performance?
- Thruster response time modelling, i.e. time to reverse propeller, time to azimuth thruster. How does this affect DP performance?

To improve the DP performance wave feed forward can also be applied. A recent joint industry project (DP-JIP) has studied this method (see also Waals, 2002). Both model tests as well as full-scale measurements are part of this effort.

As DP is becoming more widely accepted, multi-vessel DP and interaction between DP vessels is an area of interest. Since the DP system is a "virtual mooring" two vessels positioning relative to each other (such as in an offloading scenario involving workboat/drill ship or FPSO/tanker) become as single system both from a controls perspective as well as hydrodynamically. How does this interaction affect the overall safety and stability of both vessels?

DP reliability: DP is a mature control technology (at least 40 years) and many of the reliability issues have been dealt with. That having been said, the integration of DP with the power management and other functions has lead to more complexity and thus the potential for design or operator errors. It has been shown that the linkage between power management and reliability is becoming increasingly important (Weingarth, 2002 and Millan, 2002).

To improve numerical predictions the effects of large first order motions, actual wave shape, wave directionality and current interaction effects on the wave drift forces must be better understood.

7. VORTEX INDUCED VIBRATIONS AND VORTEX INDUCED MOTIONS

VIV is the resonant motion behaviour of a structure due to the shedding of vortices and its structural mechanical properties. If the vortices are shed coherently over the full length of the structure large oscillating forces act on the structure. If the frequency of vortex shedding more or less coincides with (one of) the natural frequencies resonance occurs, with resulting large motions. A review of the relevant theory is given in the report of the Specialist Committee on Stationary Floating Systems (23rd ITTC), Section 2.7, 'Vortex Induced Vibrations'.

To reduce VIV of a structure mitigation devices can be applied to reduce the coherence of the vortex shedding. The most common mitigation devices are strakes.

In offshore technology two different aspects of VIV can be distinguished:

- Riser VIV
- Spar VIV or VIM (vortex induced motions)

7.1 Riser VIV

Although there are some good analytical prediction tools for riser VIV, such as Shear7, VIVANA or VIVARRAY, these tools are mostly semi-empirical and do have shortcomings e.g. with respect to in-line effects. However, this is the most commonly used approach in the VIV analysis of real offshore risers. It is based on the assumption that the forces exerted by the flow on the structure can be locally described by a non-linear oscillator equation. The approach is adjustable to experimental results and is thus capable of predicting most characteristic phenomena associated with riser VIV.

Deepwater catenary risers are significantly curved in the static equilibrium. This complicates the problem, and implies that even in the linear approximation (with respect to the structural vibrations) the vibrations in the directions tangential and normal to the static equilibrium position of the riser are coupled. Consequently, the structural modes interact not only through the flow but also within the structure itself. Furthermore, the lift and the drag forces become necessarily coupled through the structural component of the model. Accordingly, considering the cross-flow vibrations independently of the in-line oscillations makes much less sense than it does in the case of straight risers. Secondly, the touchdown point of a catenary riser is not fixed to the seabed and necessarily travels along the seabed in the course of the VIV, thereby changing the length of the riser. This effect makes the structural vibrations significantly nonlinear. Thirdly, some parts of the catenary risers are significantly inclined with respect to the vertical. The flow in the vicinity of these parts is far from normal to the riser. These three peculiarities of the catenary risers may play a crucial role in the VIV and therefore must be accounted for in the prediction model.

Model testing provides another approach to obtain dedicated coefficients for the semi-empirical predictions tools. The effectiveness of VIV mitigation devices or complex riser geometries can be studied. A small section (e.g. 4 m) of the actual risers is towed through the tank and the hydrodynamic coefficients are measured. Tests can be free vibrating or with forced oscillation. To minimise scale effects the Reynolds numbers in the model tests are often close to or equal to the full scale Reynolds numbers. Typical Reynolds numbers in these riser VIV tests can be up to 1E+06 and the tests are referred to as 'High Reynolds'. To accommodate for the large tow forces a special test set up is required. The current state of the art riser VIV model test set-up has a carriage with the riser suspended horizontally. The riser is allowed to move in one direction only, transverse to the tow direction (denoted as 'cross flow'). This set-up gives repeatable results independent of tow direction or facility (Ding, 2004, de Wilde, 2004). However, in the critical Reynolds range (between approximately 100 000 – 400 000) the results for smooth cylinders can be less repeatable.

A similar test set-up where the riser is allowed to make a slight arc motion, i.e. combined "in-line" and "cross flow" has shown significant differences in results as function of tow direction for high Reynolds numbers (de Wilde, 2004, 2003). For low Reynolds numbers however the arc type motion results coincide with the pure vertical motion results. This indicates the sensitivity of riser VIV to small variations. This phenomenon is not yet understood and, as risers will not display pure cross flow motions this needs to be investigated in the future.

A recent development is research into 3D multi mode riser VIV. State-of-the-art fibre optical measuring techniques are deployed to obtain detailed insight into the complex (3D) VIV response of the risers (de Wilde, 2004).

Three different approaches for the prediction of VIV have been compared by Chaplin et al. (2005) with experimental results: (i) modal approach, (ii) fluid oscillator approach, (iii) local 2D CFD calculations (strip approach). No 3D calculations were reported.

A state of the art study of interaction modelling for multiple risers has been presented by Fontaine et al. (2005). Scale effects associated with Reynolds number are studied and the amplification effect for a tandem arrangement of two risers is illustrated by experiments.

Bending moment data from an earlier fjord test on high mode VIV experiments with a 90m long riser model are analysed in Baarholm et al. (2005a), with a focus on fatigue damage. Tests on a densely instrumented 10m model in a rotating rig facility are reported in Tognarelli et al. (2004). Trim et al. (2004) present results from VIV model tests on a 38m long flexible riser subjected to uniform and sheared flow. Though ignored in semi-analytical codes, all three test programmes show that in-line fatigue damage is as severe as cross-flow fatigue damage. High-mode VIV data from field experiments are also presented in Vandiver et al. (2005).

Baarholm et al. (2005b) performed a free/span VIV test on a 20 m full-scale prototype section of an umbilical. The umbilical was heavily instrumented with fibre-optic strain gauges and accelerometers to acquire records of bending and axial strain and lateral accelerations in both the cross flow and the in line direction. Reynolds numbers range from 30 000 to 260 000. Bare, straked, and partly straked configurations were tested.

Baarholm et al. (2005c) report experiments on the riser interaction and clashing of two

10m long, densely instrumented flexible riser models. The scope included: i) the spatial distribution of riser clashing, ii) the relative velocity at clashing, and iii) the riser VIV and wake-induced oscillations (WIO). Both bare and straked risers as well as those with bumper elements included on the risers were tested.

7.2 Spar VIM

Due to the much longer periods of Spar motions the vortex induced vibrations of spar structures are more commonly referred to as Vortex Induced Motions (VIM). As Spars are still a relatively new concept, Spar VIM is not as widely studied as riser VIV, although over the last three years there has been a lot of attention and numerous model test programs have been performed to study this subject (Finn et al., 2003; van Dijk et al., 2003; Magee et al., 2003; Huang et al., 2003). Furthermore some full scale data have been published on measured Spar VIV (Eward et al., 2003; Leverette et al., 2003; Kokkinis et al., 2004; Smith et al., 2004).

In Spar VIM model testing three different methods are currently used:

- Low Reynolds number 6 d.o.f. Spar tow tests (van Dijk and Magee, 2003)
- Low Reynolds number 6 d.o.f. Spar flume tests (Finn, 2003)
- High Reynolds number 1 d.o.f. Spar tow tests (Yung, 2003 and 2004)

The first two methods are very similar, although the tow tests allow zero turbulence but have limited test length, whereas the flume tests will always have some turbulence but allow tests of infinite length. The third is much the same as the method applied for riser VIV testing. However, as Spar full scale Reynolds numbers are in the range of 10^7, the high Re Spar tow tests require much higher tow speeds and results consequently in much higher tow loads. The Reynolds numbers in these high speed model tests are typically of the order 10^6, still one order of magnitude lower than the prototype situation. These tests require very long tow lengths and a very robust tow carriage. The main reason to perform high Re tow tests is to reduce or eliminate possible scale effects. However, the scale used in high Re Spar VIM is smaller than used in the tow tests. As scaling of boundary layers on Spar like structures is not well understood it is not clear if these high Reynolds tests actually result in smaller scale effects. The table below summarises the different aspects of the three mentioned methods of Spar VIM testing.

	low Re tow	low Re flume	High Re tow
Tow length	limited	unlimited	limited
Motions	6 d.o.f.	6 d.o.f.	1 d.o.f.
Scales	40 - 70	40 – 70	≈ 100
Scale effects	unknown	unknown	unknown

7.3 MMS Spar VIM Workshop

In October 2003 a special workshop was held on Spar VIM for the offshore industry, sponsored by MMS.

Some conclusions from this workshop are:

- At present model tests are considered to be the only means to verify the Spar design for VIM performance. The choice of model testing method is more or less personal or practical as there is no hard data to compare the three methods against each other or against full scale data.
- Numerical methods are at present not capable of predicting Spar VIM behaviour. It is expected that it may take at least a few more years before numerical methods are sufficiently developed to describe the complex 3D flow around a Spar.
- More data is needed on full scale turbulence and the effect on Spar VIM. It is possible to generate calibrated turbulence in the model basin but at present no reference full scale data is available to calibrate against.
- More data is needed on the effect of sheared current on Spar VIM. It is possible to generate sheared currents in the model basin,

but only limited tests have been performed so far. It is very likely that the effect of sheared current will be significantly different depending on the type of Spar.

7.4 Recent Developments

Recently a number of model test programs have been conducted focussing on the effect of shear current on Spar VIM response as well as the effect of waves on Spar VIM response. As generation of a highly sheared current in the model basin results in unrealistic high levels of turbulence, different methods of generating a sheared current are being considered:

- use of a shroud in a tow basin
- use of difference in density in a tow basin
- use of a false floor in a flume

A comprehensive paper on low Reynolds Spar VIM model testing was presented in Irani and Finn (2004). Yung (2004) described the high Reynolds model test approach. Furthermore, more full-scale Spar VIM data is becoming available which allows some comparison between model test results and full-scale VIM-response.

7.5 Future Research and Development:

During the 2003 VIM workshop the following points of attention with respect to further research were defined:

- 1 d.o.f. versus 6 d.o.f. Spar VIM model testing
- High Re versus low Re Spar VIM model testing
- Reynolds scaling effects:
- Modelling full scale damping at model scale (truss)
- Modelling sheared currents
- Statistical approach of A/D-values from VIM test
- Effect of waves on VIM behaviour

8. PREDICTION OF THE ROLL OF FLOATERS WITH RISERS AND MOORING SYSTEMS

8.1 Introduction

The prediction of roll due to wave excitation is a classical subject in Ship Naval Architecture. A good overall review of the subject has been given by Himeno (1981). The prediction of roll generally implies the determination of a roll damping coefficient for inclusion in a seakeeping package used to compute the roll transfer function or extreme values of roll. The roll damping coefficients have traditionally been generally determined through experiments. It is known that at least for traditional ship forms the response is non-linear and that quadratic, and possibly cubic, models provide a reasonable fit of experimental data. This approach leads to good results particularly for a ship in a seaway where the bilge keels that are usually present bring non-negligible lifting restoring moments. The well known equivalent cycle linearisation approach (Faltinsen, 1990), with the coefficients being obtained via decay tests, also yields good results.

With the use of platforms with non-ship forms such as Semi-submersibles, TLPs, and Spars, the procedure cited above has become standard. However, with the recent trend of stationary ship hulls in open seas, that is, with reduced lifting characteristics, the roll behaviour has become an issue again, to such a point that a JIP has been recently proposed (Marin, 2002).

8.2 Viscous Roll Damping

The roll damping mechanism modelled in conventional, unmodified, potential flow based seakeeping methods is one of wave radiation damping. However, for certain hull forms, if the wave energy in the sea is concentrated at a frequency similar to the vessel’s natural frequency, the wave damping can become relatively small, and the system can become dominated by viscous effects. The principal mechanism involved is one of flow separation from the hull leading to vortex shedding (Downie et al., 1988). This phenomenon is more pronounced for hull forms such as wall sided, flat bottomed barges because stronger vortices are shed from sharp edges than low curvature continuous surfaces. The mechanism is nonlinear because the strength of the vortices also varies with roll amplitude.

When conducting decay tests of an FPSO hull with larger than usual bilge keels, Sousa et al (1998) observed that a uniform matching through roll decay time series may not be adequate, and they proposed a matching that is different for large roll angles than for smaller angles. Later Fernandes et al. (2000) suggested a bilinear approach. This has led to an investigation by Oliveira (2003) that summarised several model test results and identified Keulegan-Carpenter (KC) effects that are different for the large and small roll angles. For large angles, there is a stronger damping due to a strong bilge-keel vortex attracted to the hull bottom. They concluded that at small angles, the vortices are shed because at the smaller amplitude of oscillation (smaller KC number) they may not be attracted to the hull Oliveira (2003).

Yuck et al. (2003) determined the roll damping coefficients of a series of unconventional midship sections. They divided the roll damping into a wave making and a viscous component by determining the former experimentally from a far-field momentum method and subtracting it from the total damping to give the latter. They found that the roll of a barge with a 'top hat' shaped section, referred to as a step section, was less than that of comparable conventional sections because of increased vortex shedding.

The relationship between viscous roll damping and the drift forces of multi-body floating systems was studied by Inoue and Islam (2001). They developed a numerical method in which slowly varying second order drift forces were determined by far field and near field approaches (direct pressure integration) and empirically determined viscous damping was added. They concluded that accurate estimates of the viscous roll damping is required for the accurate prediction of second order drift forces in regular and irregular long crested waves.

8.3 The Roll of FPSOs

Floating Production Storage and Offloading (FPSO) systems usually comprise a monohull kept on station by a spread mooring system attached to a turret that allows the vessel to weathervane to the prevalent wave system. However directional spreading due to wind driven seas can induce a roll motion that can have a critical effect on the fatigue life of the hull, risers and mooring lines. The roll motion also has implications for operability and safety in such applications as the offloading of LNG FPSOs. The presence of the moorings and risers introduces sources of damping that are not present in the classical roll damping problem. For these reasons FPSO design requires the accurate prediction of roll.

As deep water fields are developed, increasing quantities of risers are connected to the FPSO hulls, as is the case with platform P43 with 42 risers (Portella et al., 2003) and the platform P50 with 77 risers (Palazzo et al., 2003). For both cases the presence of the risers can be assumed to influence the overall damping. However further research is required to accurately determine the relative importance of this component of the damping.

The roll response of a barge-type LNG FPSO was investigated by Choi et al. (2004) for three different loading conditions, namely the ballast, design and towing conditions. They determined damping coefficients through free decay tests and RAOs using Fourier analysis of irregular wave trains generated from wide banded spectra.

Van Dijk et al. (2003) carried out full-scale measurements of the motions of the Girassol FPSO off the West of Africa over a period of a year. They obtained estimates of the viscous damping by tuning their numerical models to the full scale results, taking into account the effects of wave spreading. They considered a number of loading conditions with varying wave height, period and direction. In one of the cases presented the values of the potential roll damping (representing wave radiation damping) and the viscous roll damping were quoted as 0.5% and 3% of the critical damping respectively.

A joint industry project (JIP) named 'Roulis 2' was set up within the frame of CLAROM (a French club of engineering companies and research centres in the field of ocean engineering), with the objective of improving the roll damping prediction methodology with particular reference to deep water developments off the West Coast of Africa. The main findings of the project, which included both numerical and experimental studies, have been reported by Ledoux et al. (2004). An outcome of the numerical study was that risers and moorings of deep water FPSOs make a significant contribution to roll damping. It was found that this component was more important than viscous roll damping in mild sea states, but the reverse is true in more extreme conditions.

Finally it is worth mentioning here the work by Liu (2003), showing both numerically and experimentally that the slowly varying roll (typical periods of the order of 23 – 26 s) may play an important role. This behaviour is usually neglected for motion analysis.

8.4 Modelling Roll

Roll motions have generally been calculated by including empirically determined damping coefficients into potential flow seakeeping packages, which otherwise ignore viscous effects. An early attempt at a purely theoretical approach to calculating the roll response was made by Downie et al. (1988) who matched an inviscid discrete vortex model of the local flow around hull shedding edges to the global flow determined from a seakeeping package. More recently Graham et al. (2005) have embedded an inner viscous flow field within an outer potential flow following a Helmholtz split of the velocity field. The inner rotational flow-field, U_r, which is driven by the outer flow computed from a seakeeping programme, is modelled by the modified Navier Stokes equations

$$\frac{\partial \underline{U}_r}{\partial t} + \underline{U} \cdot \nabla \underline{U} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \underline{U}_r \tag{8.1}$$

which are solved using a spectral element code. Good agreement was obtained with experimental results.

Ferrant et al. (2003) also use a (different) potential splitting approach in which a fully non linear potential formulation for incoming waves is accounted for in the formulation of such problems as a floater rolling in waves (as discussed in Section 4.8).

A commercial solver has been used by Salui et al. (2004) to study the roll damping of a high speed hard chine vessel. They used a RANS based solver with a standard k-ε turbulence model and a HRIC differencing scheme for accurate resolution of the free surface described by a multiphase-type model. They obtained good agreement between computed and forced roll experimental results, but their work highlighted the (possibly prohibitive) requirements for computing resources capable of capturing the details of more complicated hull forms.

In the CLAROM project, 'Roulis 2', the roll motion of a barge was modelled using a general purpose CFD code (EOLE) based on the Pseudo-unsteady System, and also by the

VOF method (Ledoux et al., 2004). Good agreement with experiment was reported with respect to global loads and the velocity field.

8.5 Roll Damping Devices

The problem of reducing the roll of FPSOs and other types of floater has been has been investigated in a number of studies. A systematic study of FPSO bilge keels was undertaken by Na et al. (2002) who investigated a variety optimised section shapes and corresponding keel configurations, including one fitted with an end plate. The model tests were performed using a forced roll oscillator for a number of different roll centres. They concluded that by using a bilge keel with an end plate they could reduce the depth of the bilge keel significantly without sacrificing its damping capability.

Downie et al. (1999) suggested that since the total force exerted on a hull by a bilge keel is made up of a drag component, which contributes to the viscous damping, and an inertia component, it could be made more effective by maximising the drag component. They proposed that this could be achieved by using perforated plates, which maximise the length of shedding edge per unit area. Their experiments and analysis showed that in fact the flow mechanisms involved are complex, and although the damping can be significantly improved, care must be taken in selecting the correct set of design parameters.

Park et al. (2004) reviewed several anti-rolling devices with a view to their application to FPSOs, including the shape of the bilge, different types of bilge keel and variations of the U-tube anti rolling tank (ART). They concluded that the ARTs are the most effective and suggested improvements to the classical design using split plate and spring mass systems to widen their range of effectiveness beyond their natural frequency.

9. REVIEW OF EXISTING ITTC PROCEDURES

9.1 Validation of Sea Keeping Computer Codes in the Frequency Domain

The committee reviewed the existing procedure 7.5-02-07-02.4 for the Validation of Sea Keeping Computer Codes in the Frequency Domain and proposed that the part of the procedure dedicated to ocean engineering should be extended. The original procedure focuses only on forward speed problems. The proposed new version, as is appropriate for ocean engineering problems, will focus also on stationary structures. The new document should thus be structured according to the two main problems; firstly, the wave-body interactions (a) with, or (b) without, forward speed, and secondly, the Wave plus Current problem. In addition, it is proposed to include new sections on the following topics: the computation of Second Order Wave Forces; computation with Irregular Waves; the computation of Hydrodynamic Pressures. The last topic addresses the problem of pressure estimation for fluid/structure coupling.

The committee also thought that objective information should be included that is important for the validation of the codes, namely:

- Benchmark analytical, numerical or experimental values should be stated, and
- Key asymptotical values should also be stated.

In addition, it was thought that the importance of higher order BEM for accurate estimation of drift forces should be referred to, and that the list of references with benchmark experimental data should be updated to include recent work in this area.

An alternative to merging the above new content into the existing procedure would be to develop a new procedure for stationary problems instead.

9.2 Hybrid Mooring Simulation Model Test Experiments

Procedure 7.5-02-07-03.4 on Hybrid Model Testing was recently introduced by the 23rd ITTC (2002). The purpose was to document a tool or method for carrying out deep-water model tests in a test basin of limited depth, by means of a truncated set-up combined with computer simulations.

The present (24th) ITTC Ocean Engineering Committee suggests renaming the existing Procedure into "Active Hybrid Model Testing". This reflects the actual content of the described approach utilising online integration of experiments and computer simulations, while no other changes are, at this stage, proposed in the actual document. However, a new Procedure 7.5-02-07-03.5, on truncated model systems with passive (off-line) integration is also proposed, since it is considered that at the present stage, this approach reflects the state-of-the-art laboratory practice, while the active one is still in its development stage. Some results on the active method have been presented by Fryer et al. (2001). The new Procedure is described in more detail in Section 10 below, together with some background for the proposal. It is recommended that the existing Procedure be reviewed again at a later stage when more experience is gained within active hybrid testing.

9.3 Model Testing on Tanker-Turret Systems

During its review of the existing ITTC procedure 7.5-02-07-03.3 on Model Tests on Tanker-Turret Systems, the committee referred back to the ITTC procedure on Floating Offshore Platform Experiments (Procedure 7.5-02-07-03.1). It was found that there were significant areas of overlap between the two and that only a few modifications were required to the original procedure to extend its scope to cover Tanker-Turret Systems. The committee therefore concluded that the procedure on Tanker-Turret Systems should be removed and that the procedure on Floating Offshore Platform Experiments should be appropriately extended. An update has therefore been made to the latter procedure.

10. TRUNCATION OF TEST MODELS AND INTEGRATION WITH NUMERICAL SIMULATIONS

A new Procedure, 7.5-02-07-03.5, is proposed on so-called "passive" hybrid model testing; to be distinguished from the "active" approach described in Procedure 7.5-02-07-03.4, see Section 9.2 above. Both procedures describe tools and methods in model testing of deep-water floater systems, including floater, moorings and risers, when limitations in the model basin require truncation in the set-up. The background for proposing two different procedures is that although some principles are similar for the two procedures, there are also clear differences. It is also considered that the passive (off-line) approach is the one that is currently in practical use in various model basins. The following gives some background and remarks to the new procedure.

10.1Background

Previous work on the model testing of deepwater floater systems and truncation of models has been carried out within the 22nd and 23rd ITTC. The present work is based partly on this, and partly on other published literature and experience in the field. The challenge encountered is to minimise the uncertainties within model testing due to truncation. It is important to keep in mind that in many cases, there is no better alternative, and such uncertainties are inevitable.

Significant efforts were carried out within two Norwegian JIPs on deep-water model testing in the late 90's, Verideep (Stansberg et al., 2000a) and NDP (Stansberg et al., 2000b). It was found that when used as a tool for verification of global analysis of a floater design, model testing with a truncated set-up generally requires a combination with computer simulations. In particular, the dynamics of the mooring line forces are hard to reproduce by tests only, but also floater motion damping may be inaccurate.

The combination can in principle be done either by an on-line (active) coupling to computer-controlled actuators simulating mooring and riser forces, or by an off-line (passive) two-step procedure where the model tests are used as input to final simulations at full depth. In the work referred to above, the passive approach was chosen while the active type was considered quite complex with a need for substantial development before it can be used in practical applications. An overview of the chosen procedure was given by Stansberg et al. (2002). A DeepStar project on the same problem has also been carried out (Stansberg et al., 2004).

10.2 Principles of the Method

In the design of a truncated set-up, model test reproduction of the floater motions is emphasised. This includes low-frequency as well as wave frequency motions. Thus the force vectors from the moorings and risers on the floater should be the same as for the full-depth system. This is obtained in the truncated design by reproduction of the following set of parameters, with priority as given:

1. Total mass of floating system (hull, topside, full-moorings and risers),
2. Total horizontal stiffness,
3. Quasi-static coupling between important vessel responses (e.g., between surge and pitch for a Semi-submersible or Spar),
4. Total horizontal and vertical mooring and risers restoring forces,
5. “Representative” level of mooring and riser system damping in waves and currents, and current force (e.g. by adjusting the effective mooring line and riser diameters),
6. “Representative” single line tension characteristics for each mooring line and riser (at least quasi-static).

In most cases, this means that individual lines are modelled, with their quasi-static properties reasonably close to the full-depth specification, while risers are sometimes lumped together in a few equivalent riser models. Dynamic mooring line forces are, however, generally hard to reproduce by truncated models, and must be verified by subsequent computer simulations.

Tests are run in actual environmental conditions specified for the design, typically at scales of 1:50 – 1:80. The results are then used to calibrate an accurate numerical model of the truncated set-up, preferably by a coupled analysis model. Normally, among the most uncertain parameters are the low-frequency wave drift excitation and damping parameters, which have to be checked or modified from the experiments. This also includes, in some cases, full quadratic transfer functions including off-diagonal elements.

Finally, a full-depth simulation model is established on basis of the above calibrations. A coupled analysis model is normally recommended.

10.3 Verification of Method

It is essential that the method be verified through double experiments where results from a truncated set-up combined with simulations are compared to corresponding full-depth experiments. Such comparisons were presented in Stansberg et al. (2000a, 2000b), showing good agreement. More verification studies on different cases are, however, encouraged

11. GUIDELINE ON MODELLING OF DIRECTIONAL WAVE SPECTRA

A new Guideline has been worked out and is recommended by this Committee, on the

Laboratory Modelling of Multidirectional Irregular Wave Spectra (Guideline Document No. 7.5-02-07-01.1). The Guideline gives an overview of the most commonly used principles, methods and definitions adopted within the generation and analysis of directional (short-crested) waves in a model basin, mainly for ocean engineering and naval architecture purposes. It is not the intention to provide particular recipes for all steps in the process, for which more details can be found in e.g. IAHR (1997).

Definitions of basic parameters such as the mean direction, the spreading and circular moments are given. Commonly used models for target directional distributions (spectra) are described. Basic principles of generation (synthesis) and measurement techniques are briefly addressed. Finally, various methods for analysis (estimation) and documentation of the measured directional spectra are outlined, all based on cross-spectral analysis between different measuring channels. Particular characteristics of some of the methods are addressed.

An important issue in the estimation of directional spectra from a given set of measurements is the inherent statistical nature of the directionality in an irregular sea. Thus a "unique" sample distribution estimate is difficult to define; estimated results are inherently subject to statistical errors, and certain characteristics of the estimates will be coloured by the estimation method actually used.

12. WAVE GENERATION IN SHALLOW WATER

12.1 Wave Generation

As with current generation there are different methods of generating waves, all of them on oscillating flaps or oscillating air pressure chambers. The most common type of wave maker is the single flap rotating type. For shallow water wave generation also translating flaps can be used or combined translating and rotating flaps. For extreme shallow water these will produce better quality waves. Second order control is normally used to reduce the generation of second order free waves from the wave makers. Care should be considered since these 2nd order control laws are still based on linear first order waves, which in very shallow water will not be the case. The following aspects require attention in wave generation:

<u>Reflection on Beaches and Wave Makers.</u> All model basins have beaches opposite the wave makers to absorb the waves and prevent reflections. It is well known that no beach is perfect and especially significant reflections of low frequency waves can occur. As the emphasis of model tests is more and more to calibrate numerical tools, the reflection coefficient is getting more important in order to accurately calculate what happened in the basin.

Most beaches are only effective below a certain wavelength, which means that long waves are reflected between beaches and wave makers. Some basins have some kind of active reflection compensation (ARC). This type of compensation is mostly effective in the high frequency regime and less effective on the low frequency waves.

<u>Wave Generation on Current.</u> Depending on the method of current generation the wave makers need a correction to produce the desired wave spectrum on the location of the model.

<u>Free Incident and Reflected Low Frequency Waves.</u> In general, a wave field consists of high frequency waves and low frequency waves induced by these high frequency (short) waves. These low frequency (or "long") waves consist of a number of components. One component is phase-locked to the wave groups propagating away from the wave board and is called the "incident bound" long wave (or "set-down"). This set-down wave increases with decreasing water depth. This wave has the

celerity of the wave groups, i.e. the group velocity. Another component is the “incident free” long wave, which propagates in the same direction but with the free long wave celerity. This component originates from imperfections from the wave maker control as well as possible shoaling effects on a ramp in the basin. The third component is the reflected bound wave which is phase locked to the high-frequency components which reflect from the beach opposite to the wave maker. This component is expected to be very small as the reflected high frequency waves are typically less than 10% of the incident waves. Finally, a “reflected free” wave is present which is due to the reflection of the incident long waves on the beach as well as reflection of the incident bound wave. As the long waves are expected to hardly dissipate the reflection of the long waves may be significant and even full reflection may occur. The reflected waves (bound and free) will propagate towards the wave maker.

Model basins have finite lengths. This length determines the maximum low frequency wavelength that can be sustained in the basin.

The low frequency incident bound wave is taken into account in most numerical tools. The low frequency free waves are often ignored because they are small. However, if a moored offshore structure has a natural period that coincides with the frequency of the low frequency waves the vessel motions may be much larger than expected by the set-down waves only, especially if the moored vessel has very little damping (Naciri 2004).

The following aspects require special attention in shallow water wave generation:

Refraction of Generated Waves Oblique to a Ramp in the Basin Floor. If oblique waves are generated in shallow water and the basin has a ramp between the wave makers and the test section, the long waves will experience more refraction than short waves. As a result the sea will not be long crested at the test section.

Set-Down or Bound Low Frequency Waves. It is well know that irregular waves on shallow water contain significant low frequency bound waves associated with the fundamental wave groups. This bound wave is also known as the "set-down" wave as it effectively reduces the under keel clearance of a vessel in shallow water (Pinkster, 1908 and Huijsmans, 1983). This set-down wave can have a significant effect on the drift forces of a vessel moored in shallow water (Pinkster, 1992). It is often assumed that the set-down wave develops instantly in shallow water (Liu, 1989), but more research is required to determine if this is indeed true in a model basin.

The current state-of-the art is that maximum effort is made to minimise the reflection of waves on the beaches as well as minimise the generation of free low frequency waves on the wave maker. See also Section 2.4 of this report. To assess the remaining wave energy (reflections, free low frequency waves and sloshing modes of the basin) a wave probe array is installed during wave calibration to separate and identify the individual wave components, preferably in X and Y-direction.

12.2 Future Research and Development

Research is required to assess the contribution of the individual wave components (wave frequency and low frequency, bound and free, incident and reflected) to the overall vessel response in order to better predict the vessel motions using numerical tools.

Free low frequency waves are not restricted to model basins but may occur in the prototype situation too, due to bathymetry effects like shoaling in coastal areas. Normal full scale wave measurements often ignore the low frequency content, for reasons such as the use of buoy measurements. If a vessel is sensitive to the response of low frequency waves in shallow water, the wave measurements and design analysis should also include these wave components.

13. NONLINEAR EFFECTS IN STEEP 100-YEAR RANDOM WAVES

13.1 Introduction

A benchmark study was carried out by the Committee, with the purpose of comparing non-linearities (or non-Gaussian effects) in extreme waves observed in the modelling of steep storm wave conditions. All data submitted were obtained from laboratory modelling of random unidirectional wave trains in wave basins. 3-hours extreme crest heights and peak-to-peak wave heights were considered. The reference sea state was a 100-year Northern North Sea storm:

H_{m0} =15.0m; T_p =16.0s

where,
H_{m0} is the significant wave height and $T_p$is the spectral peak period. A range of sea states around this was also included. For further details on the specification and description of the study, on the participating institutes and the data, we refer to Appendix B of the Ocean Engineering Committee Report. In the following, the main results are presented.

13.2 Results

Results are based on contributions from four participating institutes. The contributors are here denoted as Lab A-B-C-D, for which the order is randomly chosen and has no connection to the order of the list of actual institutes given in Appendix B.

Figure 13.1a shows 3-hours extreme crests $A_{C,max}$ from sample records, normalised by the significant wave height H_{m0} :

$$RC \equiv A_{C,max} / H_{m0} \qquad (13.1)$$

and plotted against a steepness parameter for the actual sea state:

$$s = H_{m0} / L_p \qquad (13.2)$$

where,
L_p is the wavelength corresponding to T_p. Comparisons are made to the Rayleigh prediction commonly used for linear models,

$$RC_{Rayl} = ¼ \,[\surd\,(2ln(N))+0.577/\surd\,(2ln(N))] \qquad (13.3)$$

as well as to a simplified second-order prediction model for deep water, based on Kriebel and Dawson (1993):

$$RC_{Sec} = RC_{Rayl}\,(1 + ½\, k_p\, RC_{Rayl}\, H_{m0}) \qquad (13.4)$$

Here N = the number of zero-crossing waves in the 3-hour records, while k_p is the angular wave number ≡ $2\pi/L_p$. (We have used N = 900 in these plots, which corresponds approximately to a peak period of 15s.) The model in Eq. 13.4 was found to compare reasonably well to more accurate formulations, and to numerical simulations, in Stansberg (1998). Notice that the estimates from the prediction models are statistically expected values, which do not take into account sampling scatter.

Therefore, a variability band showing the expected standard deviations of the sample extremes is also shown. For the linear case (i.e. zero steepness), the method by Gumbel (1959) is used, while otherwise the variability prediction is based on the numerical results in Stansberg (1998).

Some of the sample records were different 3-hours realisations based on the same spectrum (thus giving a longer effective duration of the actual sea state). For a better observation of systematic trends, the average 3-hours values for each such sea state are shown in Fig. 13.1b. The corresponding effective sea state duration is also shown for each laboratory. Similarly, results for the normalised extreme wave heights $H_{,max}$ are presented in Figs. 13.1c and 13.1d, with:

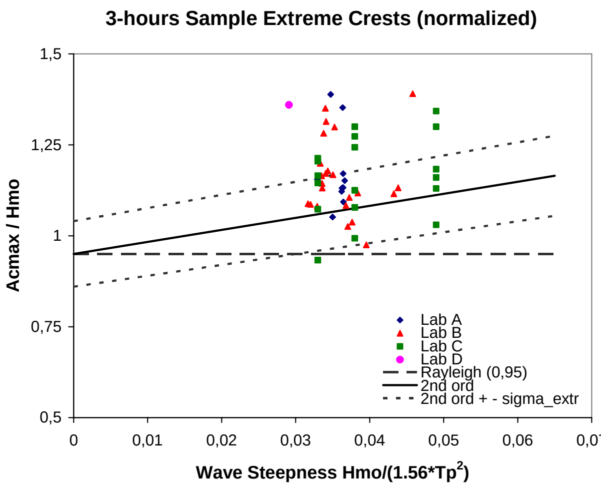
$$RH \equiv H_{,max} / H_{m0} \qquad (13.5)$$

and compared to the Rayleigh prediction:

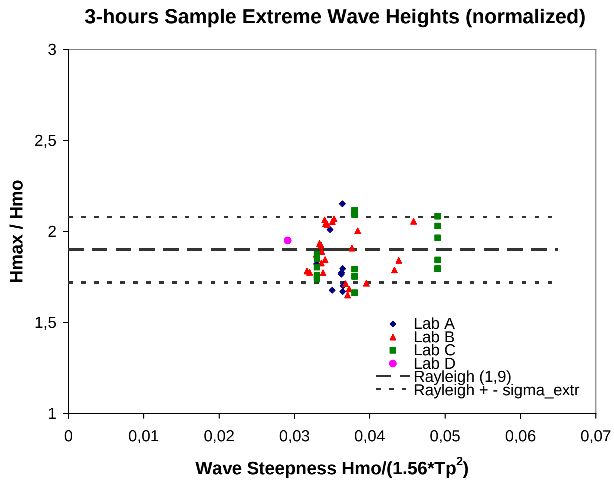
$$RH_{Rayl} = 2\ RC_{Rayl} \qquad (13.6)$$

(Since second-order effects are not expected to affect wave heights, the second order model is omitted here). The sampling variability according to Gumbel (1959) is indicated.

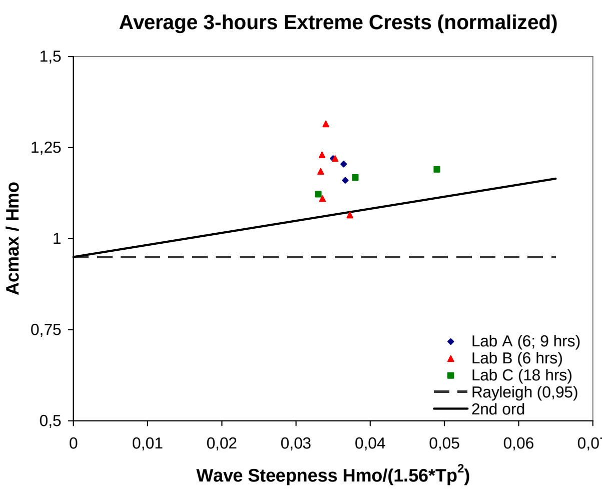
A



C



B



D

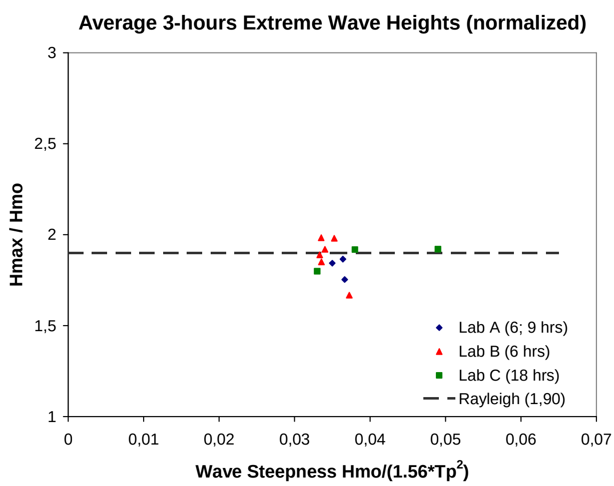


Figure 13.1- Extreme crests and wave heights vs. steepness of sea state.

13.3 Discussion

The results show quite different behaviours for the crests and the wave heights. For the *crest heights*, we notice the following:

- The measurements are clearly higher than the linear (Rayleigh) estimates.
- The second-order model reflects some of the trend, but not in full.
- The statistical scatter in sample extremes is significant, but not dramatically higher than

predicted.

- The results from four different laboratories are reasonably consistent.

For the *wave heights*, however, a good agreement with the Rayleigh model is observed. This is as expected, at least as predicted from a second-order model. The statistical scatter is less than for the crests, and clearly within the Gumbel model.

While field data appear to compare fairly well with second-order formulations (Prevosto and Forristall, 2002), the above laboratory results show some crest under-prediction by the model. Similar deviations have also been shown from other laboratory experiments (Kumar and Kim, 2002; Stansberg, 2003). Here the following remarks can be made: All the tests are run with unidirectional waves, which may lead to stronger higher-order effects. Also, the field data sets available from storms are limited, and there are still uncertainties in this field.

Further analysis and interpretation of these data and results could also be made, taking into account the supplementary information available behind the main results. This could be considered for future work.

14. CONCLUSIONS

The conclusions drawn from the above work and the Recommendations of the Ocean Engineering Committee to the 24th ITTC are made in relation to the topics as presented, and following the same order.

14.1 State-of-the-Art Review

New developments in the prediction of nonlinear and non-Gaussian effects in steep and extreme random waves have been identified, also including “unexpected” (freak) waves. Advanced nonlinear tools are being established. Still, for robust prediction of extreme crests and heights, methods beyond second order are hardly available yet, and more work is also needed to document when such methods are insufficient. Laboratory reproductions are typically slightly higher.

Advanced techniques for reduction of wave reflections and re-reflections in laboratories, being developed during the last 5-10 years, have been reviewed. At present, it seems that the theoretical models for this are well developed, although not widely in use yet. Special challenges are encountered in laboratory wave generation for floaters in shallow water (“parasitic waves”).

Wind generation is physically modelled by external fans in most wave basins. Often, mean wind forces only are considered. Scaling cannot be treated as in a wind tunnel, and therefore represents a challenge. CFD techniques are improving, but are not yet competitive.

Basic theory of wave loads on fixed structures is generally well known, but has not been extensively treated previously within the ITTC. Therefore a brief background has been included in this report. There is a growing interest in nonlinear wave run-up, air-gap and local / global impact problems on fixed structures, e.g. for shallow-water LNG terminals, and for the re-assessment of older structures. Experimental techniques and analyses are essential. Wave forces on wind turbines in shallow water is an area of topical interest the needs further research.

Also for floating structures, a significant development has been made in the prediction of air-gap, green water, sloshing and wave impact problems. Progress has been made on nonlinear theoretical tools, while model testing plays an important role in calibration and validation, especially for extreme slamming loads.

The use of CFD in the context of ocean engineering showed significant progress in recent years, especially for problems involving violent fluid motions: green water on deck, simulation of sloshing and impact in LNG tanks. In the latter case, the accurate estimation of impact loads and coupled fluid-structure interaction remains a challenge. Particle methods such as SPH are competing with more established VOF-type solvers for this kind of problem. The simulation of viscous vortical flows about risers is becoming a mature subject. The estimation of roll damping of floaters seems to remain most often based on experimental data, but CFD approaches will also inevitably become a valuable alternative. Original CFD-potential flow approaches recently appeared, showing interesting perspectives for the efficient simulation of wave-body interactions, incorporating viscous effects.

New results on the numerical modelling of hydrodynamic interaction in stationary multi-body problems have been published. This is important for analysis of marine operations. Tools are mainly linear. For non-linear multi-body solutions, including drift forces, more work is needed, especially in shallow water.

Significant work has been reported on improved modelling of hydro-elastic effects on VLFS, especially as a result of the Mega-Float project in Japan.

Within offshore oil and gas production, new and alternative floater solutions are being developed. These often represent special linear or nonlinear effects or challenges, and model testing is essential. This is also the case for new applications such as wave energy devices. One example is the development of floating wind farms.

In interpretation of time-domain simulations with DP, it must be noted that the systems are generally simplified, especially in high waves. Thus the effects from thrust loss, noise and higher-order drift forces are difficult to simulate. Parts of this can be included in model tests, which can be, on the other side, quite time-consuming.

A number of new studies on Vortex-Induced Vibrations and Motions (VIV / VIM) have been carried out. The physical mechanisms are complex, and large-scale model tests are essential. Semi-empirical models are in use, while CFD modelling is still in its development.

For the prediction of the roll of floaters, different contributing mechanisms have been identified. CFD models have made significant progress but more validation is needed, and viscous damping coefficients still require experimental input for robustness. A bi-linear viscous damping model has been addressed.

14.2 Review and Update of Existing ITTC Procedures

The ITTC Procedure 7.5-02-07-02.4 “Validation of Seakeeping Codes in the Frequency Domain” has been reviewed with focus on its use for stationary floating structures. A first attempt to update the existing version has been made in order to highlight the areas that need addressing, but it was found that more in-depth changes are needed before a final updated Procedure can be recommended. Alternatively, a new Procedure for stationary structures should be developed.

The ITTC Procedure 7.5-02-07-03.1 “Floating Offshore Platform Experiments” has been updated. It now also includes the topics of the Procedure 7.5-02-07-03.3 “Model Tests with Tanker-Turret Systems” since much of their contents overlapped.

14.3 New ITTC Documentation

There is a growing interest in offshore activities in shallow water areas. An overview of challenges within wave generation for the model testing of floaters in such areas has been given. It is found that particular attention must be paid to the generation of low-frequency wave components (“set-down”) in irregular waves, since unwanted contributions do easily arise. Effects similar to "unwanted" contributions may also occur in nature. Second-order methods for improved generation are available, but more studies are needed to optimise the test procedures.

Nonlinear effects in steep random waves have been investigated in a new ITTC experimental benchmark study. It is observed that on average, the largest and steepest crest heights are consistently higher than predicted by the traditional Rayleigh model. They are closer to predictions based on second-order corrections, although still on the high side. A significant statistical scatter is also observed, in accordance with theoretical predictions. Peak-to-peak wave heights compare well with the Rayleigh model.

A new ITTC Procedure "Truncation of Test Models and Integration with Numerical Simulations" has been worked out (7.5-02-07-03.5). This is supplementary to the existing Procedure 7.5-02-07-03.4 "Hybrid Mooring Simulation". Originally, the intention was to update the latter. However, the present Committee recommends an off-line (two-step) procedure that is currently in use in several laboratories, while the previous version describes an on-line (active) hybrid procedure that may still need some development before being used in practice. Due to the clear differences, it was decided that a completely new ITTC Procedure be written.

A first attempt to establish an ITTC Guideline for the laboratory modelling of directional wave spectra has been made. The work has to some extent been based upon experiences and recommendations from previous IAHR work. A set of main directional parameters has been defined, and commonly used methods and approaches have been briefly described and referred to.

15. RECOMMENDATIONS

Adopt the revised ITTC Procedure 7.5-02-07-03.1, "Floating Offshore Platform Experiments".

Remove the ITTC Procedure 7.5-02-07-03.3 "Model Tests with Tanker-Turret Systems" (included in ITTC Procedure 7.5-02-07-03.1).

Adopt the new ITTC Procedure 7.5-02-07-03.5 "Truncation of Test Models and Integration with Numerical Simulations".

Rename the existing ITTC Procedure 7.5-02-07-03.4 from "Hybrid Mooring Simulation" to "Active Hybrid Mooring Simulation".

Adopt as an ITTC Guideline, "Laboratory Modelling of Multidirectional Irregular Wave Spectra" (7.5-02-07-01.1).

16. REFERENCES AND NOMENCLATURE

16.1 References

Aage, C., Hvid, S.L, Hughes, P.H. and Leer-Anderson, M., 1997, "Wind loads on ships and offshore structures estimated by CFD", BOSS 97, Vol. 2, pp. 237-251.

Akyildiz, H., 2002, "Experimental investigation of pressure distribution on a cylinder due to the wave diffraction in a finite water depth", Ocean Engineering, Vol. 29, pp. 1119-1132.

Baarholm, R. and Faltinsen, O.M., 2004, "Wave impact underneath horizontal decks", Journal of Marine Science and Technology, Vol. 9, pp. 1-13.

Baarholm, R. and Stansberg, C.T., 2004, "Extreme Vertical Wave Impact on the Deck of a Gravity-Based Structure (GBS)

Platform”, Proc. Conference on Rogue Waves, Brest, 2004.

Baarholm, G.S., Larsen, C.M., and Lie, H., 2005a, “On Fatigue Damage Accumulation from In-Line and Cross-Flow Vortex Induced Vibrations on Risers”, accepted for publication in Journal of Fluid and Structures

Baarholm, R., Stansberg, C.T., Fylling, I., Braaten, H. and Lie, H., 2005b, “Model testing for deep water systems: Hybrid approach and component testing”, 2nd International Workshop on Applied Offshore Hydrodynamics, Rio de Janeiro.

Baarholm R., Kristiansen T. and Lie H., 2005c, “Experimental Investigation of Dual Riser Interaction”, Paper No. 6100, OMAE 2005, Halkidiki, Greece.

Baddour, R.E. and Parsons, W., 2003, “A Comparison of Dirichlet and Neumann Wavemakers for the Numerical Generation and Propagation of Nonlinear Long-Crested Surface Waves”, Paper No. 37281, OMAE 2003, Cancun, Mexico.

Baklouti, M., Kimmoun, O., Molin, B., Gentaz, L. and Alessandrini, B., 2003, “Numerical and Experimental Study of the Wave Induced Free Surface Boundary Layer in a Canal”, 18th IWWWFB, Le Croisic, France.

Barcellona, M., Landrini, M., Greco, M. and Faltinsen, O.M., 2003, “An Experimental Investigation on Bow Water Shipping”, Journal of Ship Research, Vol. 47, pp. 327-346.

Bellibassakis, K.A. and Athanasoulis, G.A., 2004, “Hydroelastic Responses of Very Large Floating Structures Lying over Variable Bathymetry Regions”, ISOPE 2004, Toulon, Vol. 1, pp. 584-591.

Biésel,F., 1954, “Wave Machines”, Proc. First Conference on Ships and Waves.

Bjørset, A., Leira, B.J. and Igland, R.T. , 2003, “Comparison of Simulated and Measured Wind Forces on Offshore Tower Structure”, OMAE 2003, Cancun, OMAE2003-37474

Bobillier, B., Chakrabarti, S. and Christiansen, P., 2000, “Generation and Analysis of Wind Load on a Floating Offshore Structure”, OMAE 2000, #OSUandOFT4144.

Bonnefoy, F., Le Touzé, D. and Ferrant, P., 2003, “Second Order Directional Wavemaker Theory: Prediction and Control of Free Waves”, 18th IWWWFB, Le Croisic, France.

Boudet, L. and Pérois, J.P., 2001, “Nouvelles Techniques de Pilotage d'un Batteur Segmenté pour la Génération de Houle Oblique”, Comptes Rendus des Huitièmes Journées de l'Hydrodynamique, Nantes (in French).

Brown, D.T. and Liu, F., 1998, “Use of springs to simulate the wind induced moments on turret moored vessels”, Applied Ocean Research, Vol. 20, pp. 213-224.

Büchmann, B., Ferrant, P. and Skourup, J., 2000, “Run-up on a body in waves and current. Fully nonlinear and finite-order calculations”, Applied Ocean Research, Vol. 22, pp. 349-360.

Buchner, B., Cozijn, H., van Dijk, R. and Wichers, J., 2001, “Important Environmental Aspects for Ultra Deep water Model Tests”, DOT 2001, Rio de Janeiro.

Buchner, B. and Bunik, T., 2002, “Wind Shielding Investigation for FPSO Tandem Offloading”, ISOPE-2002, not included in the Proc.

Buchner, B., 2002, “Green water on ship-type offshore structures”, Ph.D. thesis, Delft University of Technology, Delft.

Buchner, B., van Dijk, A. and de Wilde, J.J., 2001, “Numerical multiple body simulations of side by side mooring to and FPSO”, ISOPE-2001, Vol. 1, pp. 343-353.

Byrne, B. W. and Houlsby, G. T., 2002, “Investigating Novel Foundations for Offshore Windpower Generation”, OMAE 2002, Oslo, OMAE2002-28423.

Cassidy, M.J., Eatock Taylor, R. and Houlsby, G.T., 2001, “Analysis of jack-up units using a Constrained NewWave methodology”, Applied Ocean Research, Vol. 23, pp. 221-234.

Chakrabarti, S., 2000, “Hydrodynamic interaction forces on multi-moduled structures”, Ocean Engineering, Vol. 27, pp. 1037-1063.

Chaplin, J.R., Bearman, P.W., Graham, J., Subbiah, K., Otta, A., Mackwood, P. and Wouters, J., 1994, “Loading on a cylinder at large scale in irregular waves with currents”, International Symposium: Waves-physical and numerical modelling, UBC Vancouver, Vol. 1, pp. 1133-1142.

Chaplin, J., Bearman, P.W., Fontaine, E., Herfjord, K., Isherwood, M., Larsen, C.M., Meneghini, J.R., Moe, G. and Tryantafyllou, M.S., 2005, “Blind Predictions of Laboratory Measurements of Vortex Induced Vibrations of a Tension Riser”, To appear in Journal of Fluid and Structures.

Chatry, G., Clément, A.H. and Gouraud, T., 1998, “Self adaptive control of a piston wave-absorber”, ISOPE-98, Montreal. Vol. 1, pp. 127-133.

Choi, Y.R., Kim, J.H., Song, M.J. and Kim, Y.S., 2004, “An Experimental and Numerical Study of Roll Motions for a Barge-Type LNG FPSO”, ISOPE, Vol. 1, pp. 672-675.

Choi, Y.R. and Hong, S.Y., 2002, “An Analysis of Hydrodynamic Interaction of Floating Multi-Body Using Higher-Order Boundary Element Method”, ISOPE-2002, Kita-Kyushu, Vol. 1, pp. 303-308.

Chou, F., Chianis, J. and Zhang, X., 2004, “Self Installed Single Column Floater”, OMAE 2004, Vancouver, paper - 51466.

Clauss, G. and Hennig, J., 2002, “Computer Controlled Capsizing Tests Using Tailored Wave Sequences”, OMAE 2002, Oslo, paper no. 28297.

Cox, D.T., Ortega, J.A., 2002, “Laboratory observations of green water overtopping a fixed deck”, Ocean Engineering, Vol. 29, pp. 1827-1840.

Cox, D.T., Scott, C.P., 2001, “Exceedance probability for wave overtopping on a fixed deck”, Ocean Engineering, Vol. 28, pp. 707-721.

Cozijn, J.L. and Bunnik, T.H.J., 2004, “Coupled Mooring Analysis for a Deep Water CALM Buoy”, OMAE 2004, Vancouver, paper - 51370.

Daghigh, M., 2002, “A New Formulation for Equivalent Hydrodynamic Modelling of the Jack-Up Legs”, OMAE 2002, Oslo, OMAE2002-28342.

Dalrymple, R.A., 1989, “Directional Wavemaker Theory with Sidewall Reflection”, Journal of Hydraulic Research, Vol. 27, pp. 23-44.

de Wilde, J.J. and R.H.M. Huijsmans, 2004, “Laboratory Investigation of Long Riser VIV Response”, ISOPE-2004, Toulon, France

de Wilde, J.J., Huijsmans, R.H.M. and Triantafyllou, M.S., 2003, “Experimental Investigation of the Sensitivity to In-line Motions and Magnus-like Lift Production on the Vortex-Induced Vibrations”, ISOPE 2003, Hawaii, paper 2003-JSC-270.

de Wilde, J.J., Sworn, A., Cook, H., Willis, N, and Bridge, C., 2004, "Cross Section VIV Model Test for Novel riser Geometries", DOT, New Orleans.

Ding, Z.J., Balasubramanian, S., Lokken, R.T. and Yung, T-W., 2004, "Lift and Damping Characteristics of Bare and Straked Cylinders at Riser Scale Reynolds Numbers", OTC-16341, Houston.

Downie, M.J., Bearman, P.W. and Graham, J.M.R., 1988, "The Effect of Vortex Shedding on the Coupled Roll Response of Bodies in Waves", Journal of Fluid Mechanics, Vol. 189, pp. 243-264.

Downie, M.J., Graham, J.M.R. and Wang, J., 1999, "Effects of Porous and Solid Bilge Keels on the Response of FPSOs in Regular and Random Waves", OMAE 1999, Canada.

Dysthe, K.B., Trulsen, K., Krogstad, H. and Socquet-Juglard, H., 2003, "Evolution of a Narrow-Band Spectrum of Random Surface-Gravity Waves", Journal of Fluid Mechanics, Vol. 478, pp. 1-10.

Etemad, K., Gharabaghi, A.R.M., and Chenaghlou, M.R., 2004, "Nonlinear Dynamic Behaviour of Fixed Jacket-Type Offshore Platforms Subjected to Simultaneously Acting Wave and Earthquake Loads", OMAE 2004, Vancouver. OMAE2004-51498.

Eward, R., Shilling, R., Thethi, R. and Karakaya, M., 2003, "BP Horn Mountain Spar - Results of Comprehensive Monitoring of Platform and riser Responses", DOT, Marseille.

Faltinsen, O., 1990, Sea Loads on Ships and Offshore Structures, Cambridge University Press, UK.

Fernandes, A.C. and Kroft, S.A.B., 2000, "Bi-Linear Modeling Of Wider, Longer and Continuous Bilge-Keels for FPSOs Roll Motion Control", OMAE 2000, New Orleans.

Fernandes, A.C., Jacob, B.P., Vardaro, E., Franciss, R. and Almeida, J.C.L., 2003a "Sub-Surface Hybrid Riser System for Deepwater Application", OMAE 2003, Cancun, paper - 37422.

Fernandes, A.C., Lima, A.L.S. and Oliveira, C.A., 2003, "Frequency Domain Analysis of a Deepwater Monobuoy and Its Mooring", OMAE 2002, Cancun, paper - 37322.

Ferrant, P., Gentaz, L., Alesssandrini, B. and Le Touzé, D., 2003, "A Potential/RANSE Approach for Regular Water Waves Diffraction about 2D Structures", Ship Technology Research, Vol. 50, pp. 165-171.

Ferrant, P., Malenica, S. and Molin, B., 1999, "Nonlinear Wave Loads and Runup on a Vertical Cylinder", Chapter 3 in the Volume: 'Nonlinear Water Wave Interaction', Editors Mahrenholtz, O. and Markiewicz, M., Advances in Fluid Mechanics, Computational Mechanics Publications, pp. 101-135.

Finn L.D., Maher, J.V. and Gupta H., 2003, "The Cell Spar and Vortex Induced Vibrations", OTC, Houston.

Fontaine, E., Morel, Rippol, J.P. and Scolan, Y.M., 2005, "Riser Interference and VIV Amplification in Tandem Configuration", ISOPE-2005, Seoul.

Forrsitall, G.Z., 2004, "Environmental Forces on Offshore LNG Terminals: The Complications of Shallow Water", OMAE 2004, Vancouver, 51637.

Frank, G., Budvietas, A. and Mansard, E., 2003, "The Canadian Hydraulic Centre's Active Wave Absorption System", Proc. Canadian Coastal Conference.

Fryer, D., Watts, S. and Evans, M., 2001, "Experiment Methods for Non-Linear Hydrodynamic Response to Waves", Paper No. 1251, OMAE 2001, Rio de Janeiro, Brazil.

Graham, J.M.R., Sherwin, S.J., Kendon, T.E. and Downie, M.J., 2005, "The prediction of the Viscous Damping of Large Floating Bodies in Waves", 20th IWWWFB, Spitzbergen.

Grant, R. and Holboke, M., 2004, "Shallow Water Effects on Low-Frequency Wave Excitation of Moored Ships", OTC, Houston.

Greco, M., Landrini, M. and Faltinsen, O.M., 2004, "Impact flows and loads on ship-deck structures", Journal of Fluids and Structures, Vol. 19, pp. 251-275.

Grue, J. and Huseby, M., 2002, "Higher Harmonic Wave Forces and Runup of Vertical Cylinders", Applied Ocean Research, Vol. 24, pp. 203-214.

Gumbel, E.J., 1958, Statistics of Extremes, Columbia University Press, New York.

Hamamoto, T. and Fujita, K., 2002, "Wet-Mode Superposition for Evaluating the Hydroelastic Response of Floating Structures with Arbitrary Shape", ISOPE-2002, Vol. 1, pp. 290-297, Japan.

Haver, S., 2001, "Evidence of the Existence of Freak Waves", Proc., Rogue Waves 2000 (IFREMER), Brest.

Henderson, A.R., Morgan, C., Barthelmie, R., Smith, B., Sorensen, H.C. and Boesmans, B., 2002a, "Offshore Wind Energy -Review of the State-of the Art", ISOPE-2002, pp. 494-498, Japan.

Henderson, A.R., Leutz, R. and Fujii, T., 2002b, "Potential for Floating Offshore Wind Energy in Japanese Waters", ISOPE-2002, pp. 505-512, Japan.

Hermundstad, O.A., Stansberg, C.T. and Hellan, O., 2002, "Numerical and Experimental Analysis of Extreme Slamming Loads on FPSO Bows", OMAE 2002, Oslo. Paper No. 28565.

Higo, Y, Iwashita, H., Kanda, M., Nakagawa, H. and Kobayashi, M., "Hydrodynamic Forces Acting on Floating Breakwater using Submerged Plate and Its Motion", Journal of KSNAJ. Vol. 237, pp. 119-126.

Himeno, Y., 1981, "Prediction of Ship Roll Damping: State-of-the Art", Rep. No. 239, Dept Nav. Arch. and Mar. Eng., University of Michigan, Ann Arbor, Michigan, USA.

Hong, S.Y., Cho, S.K. and Kim, J.H., 2004, "Characteristics of Wave Loading and Structural Response of Mat-type VLFS due to Waves", ISOPE-2004, Toulon, Vol. 1, pp. 592-599.

Hong, S.Y., Choi, Y.R. and Hong, S.W., 2002, "Analysis of Hydro-elastic Response of Pontoon-type VLFS Coupled with Floating Breakwaters Using a Higher-Order Boundary Element Method", ISOPE-2002, Vol. 1, pp. 313-318, France.

Hong, S.Y., Kim, J.H., Cho, S.K. and Choi, Y.R. and Kim, Y.S., 2003, "Numerical and experimental study on hydrodynamic interaction of side-by-side moored multiple vessels", Proc. International Symposium: Deepwater Mooring Systems, Houston.

Hong, S.Y., Kim, J.H., Kim, H.J. and Choi, Y.R., 2002, "Experimental study on behaviour of tandem and side-by-side moored vessels", ISOPE-2002, , Vol. 3, pp.841-847, Japan.

Hong, S.Y., Kim, J.W., Ertekin, R.C. and Shin, Y.S., 2003, "An Eigenfunction-Expansion Method for Hydroelastic Analysis of a Floating Runway", ISOPE-2003, Vol. 1, pp. 121-128, USA.

Huang K., Chen, X. and Kwan, C., 2003, "The Impact of Vortex-Induced Motions on Mooring System Design for Spar-based Installations", OTC, Houston.

Huang, E.W., Beynet, P.A., Chen, J.H., Li, J.X. and Lu, Z.G., 1993, "FPSO model tests and analytical correlation", OTC, #7146, pp. 117-132.

Huijsmans, R.H.M. and Dallinga, R.P., 1983 "Non Linear Ship Motions in Shallow Water", Proc. Ship and Platform Motion Symposium, Berkeley, CA.

Huijsmans, R.H.M., Pinkster, J.A. and de Wilde, J.J., 2001, "Diffraction and radiation of waves around side-by-side moored vessels", ISOPE-2001, Stavanger, Vol. 1, pp. 406-412.

IAHR, 1997, Proc., IAHR Seminar on Multidirectional Waves and their Interaction with Structures, (Ed. E. Mansard), San Francisco, Cal., USA. (Published by NRCC, Ottawa, Canada).

IEA-OES, 2003a, "Status and Research and Development Priorities", IEA-OES Report, IEA-OES International Energy Agency - Ocean Energy Systems.

IEA-OES, 2003b, "Development of recommended practices for testing and evaluating ocean energy systems", IEA-OES Annex II Report, IEA-OES International Energy Agency - Ocean Energy Systems.

Iijima, K. and Shiraishi, S., 2002, "Response Analysis Method of VLFS in Coastal Area Considering Topographical Effects on Wave Deformations", ISOPE-2002, Vol. 1, pp. 342-349, Japan.

Ikoma T., 2002b, "A Fundamental Study on Hydroelastic Behaviours of Large Aircushion Supported Flexible Floating Structure in Regular Waves", Journal of SNAJ, Vol.192, pp. 227-235.

Ikoma, T., Maeda, H., Masuda, K., Rheem, C.K. and Arita, M., 2002a, "Effects of Submerged Vertical Plates and Air chamber Units in Hydroelastic Response Reductions", ISOPE-2002, Vol. 1, pp. 547-552 Japan.

Indrebo, A. K. and Niedzwecki, J. M., 2004, "Wave Runup on Cylinders Subject to Deep Water Random Waves", OMAE 2004 Vancouver, OMAE2004-51188.

Inoue, K, Tanaka, S., Kinoshita, T., Takagi, K., Terao, Y., Okamura, H., Takahashi, M., Esaki, H. and Uehiro, T., 2005, "Development of a Floating Wind Farm with Mooringless System", Proc.18th Ocean Engineering Symposium, CD-ROM.

Inoue, Y. and Islam, R., 2001, "Effect of Viscous Roll Damping on Drift Forces of Multi-Body Floating Systems in Waves", ISOPE-2001, Vol. 1, pp. 279-285, Norway.

Irani, M. and Finn, L. 2004, "Model Testing the Vortex Induced Motion of Spar Platforms", OMAE 2004, Vancouver, paper - 51315.

Islam, N. and Ahmad, S., 2003, "Random Wave Response of Double Pendulum Articulated Off-Shore Tower", OMAE 2003, Cancun, OMAE2003-37296

ISSC, 2003, Report, Environmental Modelling, Proc. 15th ISSC, San Diego.

Isshiki, H. and Nagata, S., 2001, "Variational Principles Related to Motions of an Elastic Plate Floating on a Water Surface", ISOPE-2001, Vol. 1, pp. 190-197, Norway.

Iwanowski, B., Grigorian, H. and Scherf, I., 2002, "Subsidence of the Ekofisk Platforms: Wave in Deck Impact Study - Various Wave Models and Computational Methods", OMAE 2002, Oslo, paper OMAE2002-28063.

Kato, M, Inoue, S., Sasajima, H. and Fukuoka, T., 2005, "The Present Situation of Megafloat for Re-expansion of Haneda Airport and the future view of Megafloat Project", Proc.18th Ocean Engineering Symposium, CD-ROM.

Kendon, T.E., Sherwin, S.J., Graham, J.M.R., 2003, "An irrotational/vortical split-flow approach to viscous free surface flow", In: 2nd MIT conference on computational fluid and solid mechanics, editor Bathe K.J., Oxford, Elsevier Science, Boston, MA, pp. 950-955.

Kim, J.W., Kyoung, J.H., Ertekin, R.C., Bai, K.J., 2003, "Wave Diffraction of Steep Stokes Waves by Bottom-Mounted Vertical Cylinders", OMAE 2003, Cancun, OMAE2003-37293.

Kleefsman, K.M.T., Fekken, G., Veldman, A. E.P. and Iwanowski, B., 2004, "An Improved Volume-of-Fluid Method for Wave Impact Problems", ISOPE-2004, Toulon.

Kogai, T., Matsumiya, H. and Nagai, M., 2003, "Technical and Economic Aspects of Offshore Wind Energy Development in Japan", ISOPE-2003, pp. 289-293, USA.

Kokkinis, T., Sandström, R.E. Jones, H.T., Thompson, H.M. and Greiner, W.L., 2004 "Development of a Stepped Line Tensioning Solution for Mitigating VIM Effects in Loop Eddy Currents for the Genesis Spar", OMAE 2004, Vancouver, OMAE2004-51546.

Kriebel, D.L. and Dawson, T.H., 1993, "Nonlinearity in Wave Crest Statistics", Proc. 2nd ASCE International Symposium on Wave Measurement and Analysis, New Orleans, LA, USA, pp. 61-75.

Kristiansen, T., Baarholm, R.J. and Stansberg, C.T., 2004, "Validation of Second-order Analysis in Predicting Diffracted Wave Elevation around a Vertical Cylinder", ISOPE-2004, Toulon.

Krogstad, H., Socquet-Juglard, H., Dysthe, K.B. and Trulsen, K., 2004, "Spatial Extreme Value Analysis of Nonlinear Simulations of Random Surface Waves", OMAE 2004, Vancouver, Paper No. 515336.

Kumar, A. and Kim, C.H., 2002, "Limitation of 2nd-order Theories for Laboratory High Sea Waves and Forces on Structures", International Journal of Offshore and Polar Engineering, Vol. 12, pp. 243-248.

Kuntiyawichai, K., Chucheepsakul, S., and Lee M.M.K., 2004, "Analysis of Offshore Structures Subjected to Various Types of Sea Wave", OMAE 2004, Vancouver, OMAE2004-51040.

Le Touzé, D., Bonnefoy, F. and Ferrant, P., 2002, "Second Order Spectral Simulation of Directional Wave Generation and Propagation in a 3D Tank", ISOPE-2002, Japan.

Ledoux, A., Molin, B., de Jouette, C. and Coudray, T., 2004, "FPSO Roll Damping Prediction from CFD and 2D and 3D Model Test Investigations", ISOPE-2004, Vol. 1, pp. 687-695, France.

Lee, C.-H., Letcher, J.S., Mack, R.G., Newman, J.N., Shook, D.M. and Stanley, E., 2002, "Integration of Geometry Definition and Wave Analysis Software", OMAE 2002, Oslo, Paper No. 28645.

Lee, D.H. and Choi, H.S., 2000, "A dynamic analysis of FPSO-shuttle tanker system", OMAE 2000, Vol 1, pp. 302-307, USA.

Lee, D.H. and Choi, H.S., 2003, "Transient Hydroelastic Response of Very Large Floating Structures by FE-BE Hybrid Method", ISOPE-2003, Vol.1, pp. 100-105, USA.

Leverette S., Rijken, O., Dooley W. and Thompson, H., 2003, "Analysis of TLP

VIV responses to Eddy Currents", OTC, Houston.

Li, W., Williams, A.N., 2000, "Second Order Waves in a Three-Dimensional Wave Basin with Perfectly Reflecting Sidewalls", Journal of Fluid and Structures, Vol. 14, pp. 575-592.

Liu, P.L.-F., 1989, "A note on long waves induced by short-wave groups over a shelf.'' Journal of Fluid Mechanics, Vol. 205, pp. 163-170.

Liu, Y., 2003, "On Second Order Roll Motions of Ships", Proc. 22nd OMAE, Cancun, OMAE2003-37022.

Longuet-Higgins, M.S., 1953, "Mass Transport in Water Waves", Philosophic Transactions of the Royal Society of London. A, Vol. 245, pp. 535-581.

Longuet-Higgins, M.S., 1960, "Mass Transport in the Boundary layer at a Free Oscillating Surface", Journal of Fluid Mechanics, Vol. 8, pp. 293-306.

Loots, E. and Buchner, B., 2004, "Wave Run Up as Important Hydrodynamic Issue for Gravity Based Structures", OMAE 2004, Vancouver, OMAE2004-51084.

Luo, Y., Baudic, S., Poranski, P., Wichers, J., Stansberg, C.T. and Ormberg, H., 2004, "Deepstar Study on Predicting FPSO Responses – Model Tests vs Numerical Analysis", OTC, Houston. Paper No. 16584

Luquet, R., Alessandrini, B., Ferrant, P. and Gentaz, L., 2004, "Simulation of the Viscous Flow Past a Ship in Waves using the SWENSE Approach", Proc.24th ONR Symposium on Naval Hydrodynamics, St John's, Newfoundland.

Maeda, H., Rheem, C.K., Ikoma, T., Masuda, K. and Fujita, N., 2001, "An Experimental Study on Hydroelastic Responses of Elastic Floating Bodies with Air Chambers in Irregular Waves", Journal of Society of Naval Architects of Japan, Vol. 190, pp. 387-393.

Magee, A., Sablok, A. and Gebara, J., 2003 "Mooring Design for Directional Spar Hull VIV", OTC, Houston.

Malenica, S., Orozco, J.M. and Chen, X.B., 2005, "Some Aspects of Multibody Interactions in Seakeeping", ISOPE-2005, Seoul.

MARIN, 2002, FPSO Roll JIP, www.marin.nl (current projects/ joint industry projects)

Masanhobu, S., Suzuki, H. and Oka, N., 2001, "Response Characteristic of Semisub-Megafloats in Winds and Waves", Journal of Society of Naval Architects of Japan, Vol. 190, pp. 373-379.

Meylan, M.H. and Hazard, C., 2002, "Spectral Theory for a Floating Massless Thin Plate on Water of Arbitrary Depth", ISOPE-2002, Vol. 1, pp. 365-370, Japan.

Millan, J., 2002, "Coordination of FPSO and Tanker Offloading Operations", MTS Dynamic Position Conference, Houston.

Mizutani, N. and Hashimoto, N., 2003, "Air Flow Characteristics over Wind Waves from Measurements by the PIV Technique", ISOPE-2003, Vol. 3, pp. 253-257, USA.

Mo, K., and Reinholdtsen, S.-A., 2003, "Methods for Generating Non-Stationary Current, Wind and Wave Time Series in the Time Domain", ISOPE-2003, Vol. 3, pp. 277-285, USA.

Molin, B., 2001a, "Numerical and Physical Wave Tanks: Making Them Fit", Ship Technology Research, Vol. 48, pp. 2-22.

Molin, B., 2001b, "On the piston and sloshing modes in moonpools", Journal of Fluid Mechanics, Vol. 430. pp. 27-50.

Molin, B., Rémy, F., Kimmoun, O. and Jamois, E., 2005, "The Role of Tertiary Wave Interactions in Wave-Body Problems", Journal of Fluid Mechanics, Vol. 528, pp. 233-254.

Mori, N., and Cox, D.T., 2003, "Dynamic properties of green water event in the overtopping of extreme wave on a fixed dock", Ocean Engineering, Vol. 30, pp. 2021-2052.

Morison, J.R., O'Brien, M.P., Johnson, J.W. and Schaf, S.A., 1950, "The Forces Exerted by Surface Waves on Piles", Petroleum Transactions, AIME, Vol. 189, pp. 149-157.

Morris-Thomas, M., Thiagarajan, K. and Krokstad, J., 2002, "An Experimental Investigation of Wave Steepness and Cylinder Slenderness Effects on Wave Run-Up", OMAE 2002, Oslo, OMAE2002-28050.

Mostafa, Y.E., El Naggar, M.H., 2002, "Effect of Dynamic Behaviour of Piles on Offshore Towers Response", OMAE 2002, Oslo, OMAE2002-28582.

Murai, M. and Kagemoto, H., 2002, "On the effect viscosity on the hydroelastic of a column-supported VLFS", Journal of the Society of Naval Architects of Japan, Vol. 191, pp. 69-76.

Murai, M., Inoue, Y. and Nakamura, T., 2003, "The Prediction Method of Hydroelastic Response of VLFS with Sea Bottom Topographical Effects", ISOPE-2003, Vol. 1, pp. 106-112, USA.

Myrhaug, D., Stansberg, C.T. and Wist, H., 2002, "Aspects of Nonlinear Random Wave Kinematics", OMAE 2002, Oslo. Paper No. 28205.

Na, J.H., Lee, W.C., Shin, H.S. and Park, I.K., 2002, "A Design of Bilge Keels for Harsh Environment FPSOs", ISOPE-2002, Kitakyushu, Japan, ISBN 1-880653-58-3 (Set); ISSN 1098-6189 (Set).

Naciri, M. and Poldervaart, L., 2004, "Design Aspects of SPM LNG Terminals in Shallow Water", OTC, Houston.

Nagamani, K. and Ganapathy, C, 2000, "The dynamic response of a three-leg articulated tower", Ocean Engineering, Vol. 27, pp. 1455-1471.

Nielsen, F.G., 2003, "Comparative Study on Airgap under Floating Platforms and Run-up along Platform Columns", Journal of Marine Structures, Vol. 16, pp. 97-134.

Nielsen, K.B., and Mayer, S., 2004, "Numerical prediction of green water incidences", Ocean Engineering, Vol. 31, pp. 363-399.

Nieto Borge, J.C., Niedermeier, A., Lehner, S. and Rosenthal, W., 2003, "Determination of Wave Field Properties in the Spatial Domain from Space Borne SAR Images", OMAE-2003, Cancun. Paper No. 37403.

Okan, B, Downie, M.J. and Incecik, A., 2005, "A Method for Predicting Breaking Wave Forces on an Offshore Wind Turbine Support Structure", International Conference on Marine Science and Technology for Environmental Sustainability, Newcastle, UK.

Olagnon, M. (Editor), 2004, Proc., Rogue Waves, IFREMER, Brest. (To be published).

Oliveira, A.C., 2003, "Investigações Sobre a Teoria Bilinear na Análise do Balanço Transversal de FPSOs" (Investigation about the Bilinear Theory for the Analysis of FPSOs Rolling), Ocean Engineering, Federal University of Rio de Janeiro (in Portuguese).

Onorato, M., Osborne, A.R., Serio, M. and Bertone, S., 2001, "Freak Waves in Random Oceanic Sea States", Physics Review Letters, Vol. 86, pp. 5831.

Onorato, M., Osborne, A.R., Serio, M., Cavaleri, L., Brandini, C. and Stansberg, C.T., 2004, "Observation of Strongly Non-Gaussian Statistics for Random Sea Surface Gravity Waves in Wave Flume Experiment", Physical Review E, Vol. 70, 067302:1-4.

Ormberg, H., Baarholm, R. and Stansberg, C.T., 2003, "Time-Domain Coupled Analysis of Deepwater TLP, and Verification against Model Tests", ISOPE-2003, Hawaii.

Ormberg, H., Lie, H. and Stansberg, C.T, 2005, "Coupled Analysis of Offshore Floating Systems", in Numerical Modelling in Fluid-Structure Interactions, Ed. S. Chakrabarti, WIT Press, London, UK. (Chapter 10).

Palazzo, F.G., Simos, A.N., Tannuri, E.A., Sparano, J. and Masetti, I.Q., 2003, "Evaluation of the Dynamic Behaviour of the P50 FPSO System Using DYNASYM: Comparison with Experimental Result", OMAE 2003, Cancun, OMAE2003-37178.

Park, I.-K., Yang, J.-H. and Shin, H.-S., 2004, "Roll Motion Reduction Devices for Harsh Environmental FPSOs", ISOPE-2204, Vol. 1, pp. 682-686, France.

Park, S.W., Hong, S.Y. and Lee, T.K., 2004, "A study of preliminary structural design of pontoon type VLFS", ISOPE-2004, Toulon, Vol. 1, pp. 630-635, France.

Pastoor, W., Helmers, J.B. and Bitner-Gregersen, E., 2003, "Time Simulation of Ocean-Going Structures in Extreme Waves", OMAE 2003, Cancun, Paper No. 37490.

Peter, M.A., Meylan, M.H. and Chung, H., 2003, "Wave scattering by a circular plate in water of finite depth: a closed form solution", Proc. of 13th International Offshore and Polar Engineering Conference, Vol.1, pp.180-185.

Pinkster, J.A. and Huijsmans, R.H.M., 1992, "The Wave Drift Forces in Shallow Water", BOSS, London.

Pinkster, J.A., 1980, "Low Frequency Second Order Wave Exciting Forces on Floating Structures", PhD Thesis, Delft University of Technology, Delft.

Portella, R.B., Kameyama, V., Wibner, C. and Maloney, J., 2003, "P43/P48 Global Motion and Stability Analysis: A Compromise Combination to Define the FPSO Operational Behavior", OTC, 15138.

Prevosto, M. and Forristall, G.Z., 2002, "Statistics of Wave Crests from Models vs. Measurements", OMAE 2002, Oslo, Paper No. 28443.

Rahman, M. and Mousavizadegan, S.H., 2004, "On the Drift Forces of a Vertical Cylinder in Water of Finite Depth", OMAE 2004, Vancouver, OMAE2004-51086.

Rainey, R.C.T., 1989, "A New Equation for Calculating Wave Loads on Offshore Structures", Journal of Fluid Mechanics, Vol. 204, pp. 295-324.

Reinholdtsen, S.-A., Mo, K. and Sandvik, P.C., 2003, "Useful Force Models for Simulation of Multibody Offshore Marine Operations", ISOPE-2003, Vol. 1, pp. 33-39, USA.

Retzler, C.H., Rainey, R.C.T., and Chaplin, J.R., 2004, "Non-Linear Run-Up on a Vertical Surface-Piercing Cylinder", OMAE 2004, Vancouver, OMAE2004-51549.

Roveri, F.E., Rodrigues, M.V. and Jacob, B.P., 2004, "Coupled Motion Analysis of a Semisubmersible Platforms", OMAE 2004, Vancouver, paper - 51120.

Salui, K.B., Shigunov, V. and Vassalos, D., 2004, "A RANS Based Method for the Estimation of Ship Roll Damping with Forward Speed", OMAE 2004, Vancouver.

Sarpkaya, T., 1991, "Hydrodynamic Lift and Drag on Rough Circular Cylinders", OTC, 6518.

Sarpkaya, T., 2001, "On the Force Decompositions of Lighthill and Morison", Journal of Fluids and Structures, Vol. 15, pp. 227-233.

Schäffer, H.A., 1996, "Second Order Wavemaker Theory for Irregular Waves", Ocean Engineering, Vol. 23, pp. 47-88.

Schäffer, H.A., 2001, "Active Wave Absorption in Flumes and 3D Basins", Proc. 4th International Symposium on Ocean Wave Measurement and Analysis, Vol. 2, pp. 1200-1208.

Schäffer, H.A., Steenberg, C., 2003, "Second Order Wavemaker Theory for Multidirectional Waves", Ocean Engineering, Vol. 30, pp. 1203-1231.

Seto, H., Ochi, M., Ohta, M. and Kawakado, S., 2001, "A Theoretical Approach to Hydroelastic Behaviour of a Very Large Floating Structure in Regular Waves", Journal of Society of Naval Architects of Japan, Vol. 189, pp. 47-54.

Sheikh, R. and Swan, C., 2003, "The Interaction Between Steep Waves and a Vertical, Surface-Piercing Column", OMAE 2003, Cancun, OMAE2003-37154.

Shimada, K. and Maruyama, F., 2002, "Characteristics of Slowly-varying Wave Drifting Moments Acting on VLFS", Journal of Society of Naval Architects of Japan, Vol. 192, pp. 319-323.

Smith, D.W., Thompson, H.M., Kokkinis, T. and Greiner, W.L., 2004, "Hindcasting VIM-Induced Mooring Fatigue for the Genesis Spar Platforms", OMAE 2004, Vancouver, paper - 51547.

Soares, C.G. and Pascoal, R., 2002, "Experimental study of the probability distributions of green water on the bow of floating production platforms", OMAE 2002, Oslo, paper - 28626.

Souza, J.R., Fernandes, A.C., Masetti, I.Q., da Silva, S. and Kroft, S.A.B., 1998, "Nonlinear Rolling of an FPSO with Larger-than-usual Bilge Keels", OMAE 98, Lisbon.

Stansberg, C.T., Nygaard, I., Ormberg, H., Downie, M., Incecik, A. and Graham, J.M.R., 2001, "Deep Water Truss Spar in Waves and Current - Experiments vs. Time Domain Coupled Analysis", DOT Rio de Janeiro.

Stansberg, C.T., Baarholm, R., Fokk, T., Gudmestad, O.T., and Haver, S., 2004, "Wave Amplification and Possible Deck Impact on Gravity Based Structure in 10^{-4} Probability Extreme Crest Heights", OMAE 2004, Vancouver, OMAE2004-51506.

Stansberg, C.T. and Braaten, H., 2002, "Nonlinear Wave Disturbance Around a Vertical Circular Column", OMAE 2002 Oslo, OMAE2002-28620.

Stansberg, C.T., 2002, "Nonlinear Amplitude Dispersion Effects in Extreme Deep-Water Random Waves", Proc. ASCE Waves '01 Symposium, San Francisco, Vol. 1, pp. 454-463.

Stansberg, C.T. and Kristiansen, T., 2004, "Linear and Nonlinear Wave Amplification Effects Observed at FPSO Bow", PRADS 2004, Editors Keil H. and Lehmann E., Lübeck-Travemünde, Vol. 2, pp. 736-742.

Stansberg, C.T., 1995, "Effects from Directionality and Spectral Bandwidth on Nonlinear Spatial Modulations of Deep-Water Surface Gravity Wave Trains", Proc. 24th ASCE International Conference on Coastal Engineering, Vol. 2, Kobe.

Stansberg, C.T., 1998, "Non-Gaussian Extremes in Numerically Generated Second-

Order Random Waves on Deep Water", ISOPE-98, Montreal, Vol. 3, pp. 103-110.

Stansberg, C.T., 2003, "Second- and Higher Order Effects in Steep Random Waves", ISOPE-2003, Hawaii.

Stansberg, C.T., Baarholm, R., Kristiansen, T., Hansen, E.W.M. and Rørtveit, G., 2005, "Extreme Wave Amplification and Impact Loads on Offshore Structures", OTC, Houston, paper 17487.

Stansberg, C.T., Berget, K., Hellan, O., Hermundstad, O.A., Hoff, J.R., Kristiansen, T. and Hansen, E.W.M., 2004, "Prediction of Green Sea Loads on FPSO in Random Waves", ISOPE-2004, Toulon.

Stansberg, C.T., Karlsen, S.I., Ward, E.G., Wichers, J.E.W. and Irani, M.B., 2004, "Model Testing for Ultradeep Waters", Paper No. 16587, OTC, Houston.

Stansberg, C.T., Øritsland, O. and Kleiven, G., 2000a, "VERIDEEP: Reliable Methods for Laboratory Verification of Mooring and Stationkeeping in Deep Water", Paper 12087, OTC, Houston.

Stansberg, C.T., Ormberg, H. and Oritsland, O., 2002, "Challenges in Deepwater Experiments – Hybrid Approach", ASME Journal of Offshore Mechanics and Arctic Engineering, Vol. 124, pp. 90-96.

Stansberg, C.T., Yttervik, R., Øritsland, O. and Kleiven, G., 2000b, "Hydrodynamic Model Test Verification of a Floating Platform System in 3000m Water Depth", OMAE 2000, New Orleans, paper no. 00-4145.

Steen, A., Kim, M.H. and Irani, M.B., 2004, "Prediction of Spar Responses: Model Tests vs. Analysis", OTC, Houston, paper no. 16583.

Sterndorff, M.J., 2002, "Large-Scale Model Tests With Wave Loading on Offshore Platform Deck Elements", OMAE 2002, Oslo, OMAE2002-28624.

Suh, K. and Dalrymple, R.A., 1987, "Directional Wavemaker Theory: a Spectral Approach", Proc. IAHR Seminar, Lausanne, pp. 389-395.

Suzuki, H., Sawai, T., Oka, N., Masanobu, S. and Kobayashi, K., 2002, "Wind Loads on Columns of Semi-Submersible-Type-MegaFloat", Proc.11th International Offshore and Polar Engineering, Vol. 1, pp. 267-274.

Syvertsen, K. and Lopes, C., 2004, "The SSP: A New Class of Hull for the Oil Industry", OMAE 2004, Vancouver, paper - 51539.

Tahar, A., Halkyard, J., Stenn A. and Finn, L., 2004, "Float Over Installation Method: Numerical and Model Test Data", OMAE 2004, Vancouver, paper - 51069.

Takaki, M., Imai, Y., Lee, S.M., Shibata, S. and Chiba, S., 2001, "Effect of Submerged-Plate on Hydrodynamic Forces Acting on a Very Large Floating Structure", Transactions of The West-Japan SNA. Vol. 103, pp. 195-204.

Tognarelli, M.A., Slocum, S.T., Frank, W.R., and Campbell, R.B., 2004, "VIV Response of a long Flexible Cylinder in Uniform and Linearly Sheared Currents", OTC, Houston, paper no. 16338.

Torres, F.G.S., Cueva, M., Malta, E.B., Nishimoto, K. and Ferreira, M., 2004, "Study of Numerical Models of Moonpol as Minimization Device of Monocolumn Hull", OMAE 2004, Vancouver, paper - 51540.

Torsethaugen, K. and Haver, S., 2004, "Simplified Double Peak Spectral Model for Ocean Waves", ISOPE-2004, Toulon, France.

Trim, A., Braaten, H., Lie, H. and Tognarelli, M. A., 2005, "Experimental Investigation of Vortex-Induced Vibration of Long Marine Risers", In press, Journal of Fluid and Structures.

Trumars, J.M.V., Jonsson, J.O. and Bergdahl, L., 2003, "Extreme Non-Linear Wave Forces on a Monopile in Shallow Water", OMAE 2003, Cancun, OMAE2003-37049.

Utsunomiya, T., Watanabe, E. and Nakamura, N., 2001, "Analysis of Drift Force on VLFS byExperiments", the Near-Field Approach", ISOPE-2001, Vol. 1, pp. 217-221.

Vandiver, J.K., Marcollo, H., Swithenbank, S. and Jhingran, V., 2005, "High Mode Number Vortex-Induced-Vibration Field Paper No. 17383, OTC 2005, Houston, TX, USA.

van Dongeren, A., Klopman, G., Reniers, A. and Petit, H., 2001, "High Quality Laboratory Wave Generation for Flumes and Basins", Proc. 4th International Symposium on Ocean Wave Measurement and Analysis, Waves'2001, Vol. 2, pp. 1190-1199.

van Dijk, R., 1999, "DP Model Testing: Purpose, Experience and Limitations", Proc. IMCA station keeping seminar, Paris.

van Dijk, R.R.T., Magee, A., Perryman, S. and Gebara, J., (2003), "Model Test Experience on Vortex Induced Vibrations of Truss Spars", OTC, Houston.

van Dijk, R.R.T., Quiniou-Ramus, V. and Le-Marechal, G., 2003, "Comparison of Full Scale Measurements with Calculated Motion Characteristics of a West of Africa FPSO", OMAE 3003, Mexico.

van Dijk, R.R.T., Voogt, A., Fourchy, P. and Mirza, S., 2003, "The Effect of Mooring System and Sheared Currents on Vortex Induced Motions of Truss Spars", OMAE, Cancun.

van Iperen, E.J., Forristall, G.Z., Battjes, J.A., and Pinkster, J.A., 2004, "Amplification of Waves by a Concrete Gravity Sub-Structure: Linear Diffraction Analysis and Estimating the Extreme Crest Height", OMAE 2004, Vancouver, OMAE2004-51022

Waals, O.J., Aalbers, A.B. and Pinkster, J.A., 2002, "Maximum Likelihood Method as a Means to Estimate the Directional Wave Spectrum and the Mean Wave Drift Force on a Dynamically Positioned Vessel", OMAE 2002, Oslo.

Watanabe, E., Utsunomiya, T., Wang, C.M. and Xiang, Y., 2003, "Hydroelastic Analysis of Pontoon-Type Circular VLFS", ISOPE-2003, Vol. 1, pp. 93-99, USA.

WaveNet, 2003, "Final Report of the European Thematic Network on Wave Energy", WaveNet Report, pp. 1-259.

Weingarth, L., 2002, "Avoiding Catastrophes in Dynamic Positioning Systems; Integrating Key Parameters Using a Systems Approach", IADC/SPE Drilling Conference

Whitbread, R.E., Davies, M.E. and Burton, D.G., 1997, "Implications for the use of CFD methods in the modelling of wind effects on offshore installations" Applications of Fluid Dynamics in the Safe Design of Topsides and Superstructures Conference, pp. 49-54.

Wolfram, J. 1999 "On alternative approaches to linearisation and Morison's equation for wave forces", Proc. Roy. Soc. Lond. Series A, Vol. 455, No. 1988, pp. 2957-2974.

Xue, M., Xu, H., Liu, Y. and Yue, D.K.P., 2001, "Computations of Fully Nonlinear Three-Dimensional Wave-Wave and Wave-Body Interactions. Part 1. Dynamics of Steep Three-Dimensional Waves", Journal of Fluid Mechanics, Vol. 438, pp. 11-39.

Yilmaz, O., Incecik, A. and Han, J.C., 2003, "Simulation of green water flow on deck using non-linear dam breaking theory", Ocean Engineering, Vol. 30, pp. 601-610.

Yuck, R.H., Lee, D.H. and Choi, H.S., 2003, "Estimation of Roll Damping Coefficients for Non-conventional Mid-ship Sections", ISOPE-2003, USA, ISBN 1–880653-60–5 (Set); ISSN 1098–6189 (Set).

Yung, T.-W., Sandström, R.E., Slocum, S.T., Ding, Z.J. and Lokken, R.T, 2004, "Advancement of Spar VIM Prediction", OTC, Houston, OTC2004-16343.

Zaaijer, M.B. and Henderson, A.R., 2004, "Review of Current Activities in Offshore Wind Energy", ISOPE-2004, Toulon, pp.101-108.

Zaman, M.H. and Baddour, R.E., 2004, "Loading on a Fixed Vertical Slender Cylinder in an Oblique Wave-Current Field", OMAE 2004, Vancouver, OMAE2004-51062.

Zou, J., Ormberg, H. and Stansberg, C.T, 2004, "Prediction of TLP Responses: Model Tests vs. Analysis", OTC, Houston, paper no. 1658.

16.2 Nomenclature

BOSS	Behaviour of Offshore Structures Conference
DOT	Deep Offshore Technology International Conference
ISOPE	International Offshore and Polar Engineering Conference
IWWWFB	International Workshop on Water Waves and Floating Bodies
OMAE	International Conference on Offshore Mechanics and Artic Engineering
OTC	Offshore Technology Conference
PRADS	International Symposium on Practical Design on Ships and Other Floating Structures

APPENDIX A: QUESTIONNAIRE ON MODELLING / SIMULATION OF WIND ENVIRONMENTS

A questionnaire on modelling/simulating the wind environments was distributed to monitor the state of the art practices and procedures in model basins. Thirteen institutes responded to the questionnaire but two of them don't operate wind force modelling devices. The list of the institutes that participated in the questionnaire is given in Table A.1 Contents of the questionnaire are presented in Table A.2 Modelling methods of wind forces in model tests are summarised in Table A.3 and numerical simulation methods are summarised in Table A.4. The name of institutes is arbitrarily symbolised from A to M.

Most of institutes (8 out of 11) use arrays of fans to simulate wind forces caused by wind field. The remaining three institutes use fans mounted on the model deck. Spring-weight-wire systems seem to be used as a complementary method to the previous two methods. Most of the institutes (10 out of 11) use RPM control for adjusting wind forces. About half (6 of 11) of them simulate wind spectra in the basins.

The force matching method and Froude scaling method are equally used for generating wind forces. Wind drag coefficients are obtained from wind tunnel tests and other empirical data, but CFD results are not accepted yet.

All the institutes doing numerical simulations use empirical formula proportional to square of the wind velocity and, if they simulate wind spectra, the harmonic superposition method for generating time series. Only three participants answered that they consider non-stationary properties such as squall, which causes significant changes of wind in time and space.

Table A.1- List of participation institutes.

Name of Institutes	Country	Remarks*
CEHIPAR(Canal de Experiencias Hidrodinamicas de El Pardo)	Spain	M/S
DHI(Danish Hydraulic Institute)	Denmark	M/S
Delft Hydraulics	Netherlands	None
Hiroshima University	Japan	None
KRISO/KORDI (Korea Research Institute of Ships and Ocean Engineering, KORDI)	Korea	M/S
MARIN(Maritime Research Institute Netherlands)	Netherlands	M/S
MARINTEK	Norway	M/S
NMRI(National Maritime Research Institute of Japan)	Japan	M/S, 2 facilities
NRIFE(National Research Institute of Fisheries Engineering)	Japan	M/S
Offshore Model Basin	USA	M
OTRC(Offshore Technology Research Center)	USA	M/S
The University of Tokyo	Japan	M
IOT(Institute for Ocean Technology)	Canada	M

M: Model tests, S: Numerical simulation

Table A.2- Contents of the questionnaire on modelling/simulation of wind environments.

Questionnaire on Modelling/Simulation of Wind Environments (I)

Name of Institute (wave basin):

Modelling method of generation of wind force in the wave basin

-Wind force generation mechanism
Array of fans ( )
Fans mounted on the model deck ( )
Spring-weight ( )
Other (No equipment)
For case of (1) or (2), control of
-Fan RPM ( )
-Blade pitch ( )
-Other ( )
-Wind spectrum modelling
(1) Yes ( )
API( ), NPD( ), Davenport( ), Harris( ), Ochi-Shin( ), Kaimal( ), (Other:)
(2) No ( )
-Wind speed in model scale
(1) Force matching ( )
Use CD from wind tunnel test ( ), data base such as OCIMF ( ), CFD ( ),
other ( )
(2) Froude scale ( )
(3) Other ( )
-Brief description of the wind force calibration procedure

Questionnaire on Modelling/Simulation of Wind Environments (II)

Name of Institute (wave basin):

Modelling method of generation of wind force in numerical simulation

-Wind force generation mechanism
(1) Empirical formula ( ) : $F \sim V^2$
Use C_D from wind tunnel test ( ), data base such as OCIMF ( ), CFD ( ), other( )
Direct calculation by CFD ( )

-Wind spectrum modelling
(1) Yes ( )
API( ), NPD( ), Davenport( ), Harris( ), Ochi-Shin( ), Kaimal( ), (Other:)
(2) No ( )

-Wind velocity time series
(1) Harmonic superposition ( )
(2) Filtering method such as ARMA ( )
(3) Other ( )

-Consideration of non-stationary property
(1) Yes ( )
(2) No ( )
If yes, what do you consider? ( )
-Additional comments

Table A.3- Summary of the questionnaire on modelling of wind environment.

(1) Wind force generation and control system

Institutes*	A	B	C	D	E	F	G	H	I	J	K	L	M
(Mechanism)													
Array of fans				✓	✓	✓	✓		✓	✓	✓		✓
Spring-weight	✓			✓					✓		✓		✓
Fans mounted on the deck	✓	✓						✓					
Other													
(Control)													
Fan RPM	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓
Blade pitch		✓											
Other													

* Name of institutes is arbitrarily symbolised in alphabet character

(2) Spectrum modelling

Institutes	A	B	C	D	E	F	G	H	I	J	K	L	M
(Spectrum model)													
API				✓				✓	✓		✓		
NPD				✓				✓	✓		✓		
Davenport	✓			✓					✓				
Haris				✓					✓				
Ochi-Shin				✓									
Kaimal				✓									
Other*		✓		✓				✓	✓				
(No spectrum model)					✓	✓	✓			✓			✓

* any form of wind spectrum provided from clients

(3) Wind speed in model scale

Institutes	A	B	C	D	E	F	G	H	I	J	K	L	M
(Force matching)		✓		✓				✓	✓		✓		✓
CD from wind tunnel test		✓		✓				✓	✓				✓
CD from data base (e.g.,OCIMF)		✓		✓									✓
CD from CFD													
Other*				✓					✓		✓		✓
(Froude scale)	✓				✓	✓	✓	✓	✓		✓		
(Other)													

* empirical formula or client specified CD

Table A.4- Summary of the questionnaire on simulation of wind environments.

(1) Wind force generation mechanism.

Institutes	A	B	C	D	E	F	G	H	I	J	K	L	M
(Empirical formula ~V^2)	✓	✓				✓	✓		✓				✓
CD from wind tunnel test		✓		✓		✓	✓		✓				✓
CD from data base(e.g.,OCIMF)				✓									✓
Other				✓									✓
(Direct calculation by CFD)													

(2) Wind spectrum.

Institutes	A	B	C	D	E	F	G	H	I	J	K	L	M
(Spectrum model)	✓			✓		✓			✓				✓
API				✓					✓				
NPD				✓					✓				
Davenport				✓					✓				
Haris				✓					✓				
Ochi-Shin				✓		✓							
Kaimal				✓									
Other*				✓									✓
(No spectrum model)							✓						

* any form of wind spectrum provided from clients

(3) Wind velocity time series.

Institutes	A	B	C	D	E	F	G	H	I	J	K	L	M
Harmonic superposition	✓			✓		✓			✓				✓
Filtering method such as ARMA													
Other							✓						

(4) Consideration of non-stationary property.

Institutes	A	B	C	D	E	F	G	H	I	J	K	L	M
(Yes)		✓		✓									✓
time				✓									✓
space													
(No)	✓					✓	✓		✓				

APPENDIX B: NONLINEAR EFFECTS IN STEEP 100-YEAR RANDOM WAVES (BENCHMARK STUDY)

This Appendix describes the specification and the data sets of a benchmark study carried out by the 24th ITTC Ocean Engineering Committee. Final results from the study are presented in Section 13 of the main Report.

B.1 Purpose

- To compare extreme wave and crest heights from different independent storm wave simulations and prediction models, using state-of-the-art laboratory and numerical methods.
- To identify and discuss non-linear effects and variability in results, with possible consequences on the modelling of extremes in a 100-year storm sea state.

B.2 Specification

- *Reference storm*: *Hs*=15m, *Tp*=16s (100-year Northern North Sea)
- *Sea states*: Cover a range of steepness around the reference case; also 1-year and 10000-year storms (see Fig. B.1)
- *Reference spectrum details:*
  Single-peaked JONSWAP spectrum, γ (Gamma) = 2.0.
  Water depth: 150m.
  No current
  Unidirectional.
- *Deviations from reference details:* Actual contributions may deviate from above details, but must be documented and may be treated separately
- *Simulation / prediction methods*: Laboratory modelling; numerical simulation; statistical models.
- *Storm duration*: 3 hours (full scale). More than one realisation may be included – however, results for each should be given.

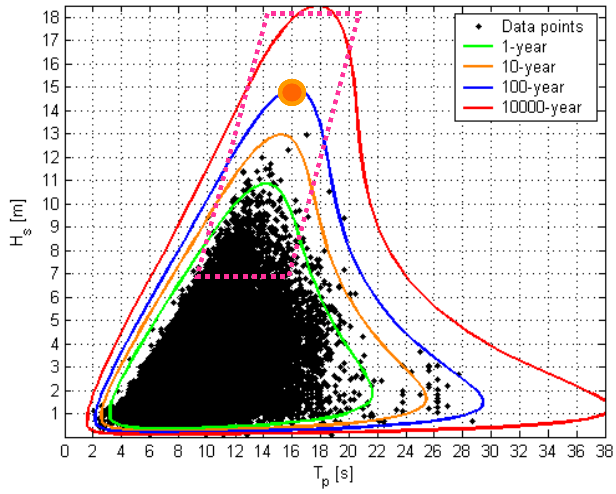


Figure B.1- Scatter diagram, Northern North Sea (Stansberg et al., 2004). Additionally, the “Reference” 100-year sea state and suggested sea state range for the OEC extreme wave benchmark are indicated.

B.3 Documentation of data for bench marking analysis

- *Primary data from measurements*: Significant wave height H_S (= H_{m0}), Peak and zero-crossing periods TP, TZ, 3-hour maximum wave and crest height Hmax, Amax (specify if sample maxima or fitted estimates)

- *Supplementary information*:
  Type of lab (basin, narrow tank, size etc.)
  Model scale.
  Measuring location.
  Spectral shape (plots; ASCII or Excel tables).
  Statistical data: Skewness; kurtosis; mean values; standard deviation, zero-crossing statistics.
  Probability distributions (plots; ASCII or Excel tables).
  Grouping information.
  Deviations from reference spectrum details.
  Special comments or information, if any.

B.4 Analysis and presentation of results

Main comparison. 3-hour extreme wave and crest heights, H_{max}, A_{max}, will be normalised by the corresponding significant wave height, H_{mo}, and presented versus the "sea state steepness", $s_p = H_{mo} / L_P$., where L_P is the wavelength corresponding to the spectral peak period, T_P. Non-linear effects and trends in the data will be identified and discussed.

Supplementary results. It is the intention also to consider possible explanations to observed effects and variations. Therefore some additional background info such as spectral shape, statistical characteristics, grouping, laboratory effects etc. will also be relevant in the analysis. For example, the spectral shape may influence the estimation of the effective steepness of the sea state.

B.5 Participating Institutes

The following four institutes contributed to the benchmark study (listed alphabetically):

- Institute of Ocean Technology (IOT), Canada
- Korea Ocean Research and Development Institute (KORDI), Korea
- Marin Research Institute Netherlands (MARIN), The Netherlands
- Norwegian Marine Technology Research Institute AS (MARINTEK), Norway

In the presentation of final results (main report), the different institutes are listed as Lab A-B-C-D, in a random order with no reference to the actual order above.

B.6 Contributed Data

Results from unidirectional irregular wave records of 3-hours full scale duration were submitted from the participating institutes. Model scales were in the range ≈ 1:50 – 1:70. Measurements were made in model basins normally used for offshore model testing, typically at a distance 5 -7 wavelengths from the wavemaker. All tests were run with single-peaked JONSWAP spectra, with the peak enhancement factor in the range 1.6 – 5.5. Full scale significant wave heights and peak periods were in the range 5.8m – 18.5m and 10.6s – 18.0s, respectively, which corresponds approximately with the area indicated in the scatter diagram in Fig. B.1. Most tests were run without current.