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18$^{\text{th}}$ INTERNATIONAL SHIP AND
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VOLUME 1

COMMITTEE I.2

LOADS

COMMITTEE MANDATE

Concern for environmental and operational loads from waves, wind, current, ice, slamming, sloshing, weight distribution and operational factors. Consideration shall be given to deterministic and statistical load predictions based on model experiments, full-scale measurements and theoretical methods. Uncertainties in load estimations shall be highlighted. The committee is encouraged to cooperate with the corresponding ITTC committee.

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KEYWORDS

Ships and offshore platforms, cables and risers, damaged ship structures, wave loads, slamming and springing, sloshing, ice loads, fatigue loads, design waves, hydroelasticity, CFD, model and full scale tests, uncertainties.

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18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

CONTENTS

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)
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1 INTRODUCTION

The content of this committee's report is dictated by its mandate, as well as the expertise of its membership. Its structure and content follow along similar lines to those adopted in previous ISSC reports (e.g. ISSC 2009). Wave-induced loads on ships are dealt within two different sections, namely 2 and 3. Section 2 focuses on two- (2D) and three-dimensional (3D) methods, dealing with linear and nonlinear methods and including applications of the so called CFD (Computational Fluid Dynamics) methods. Section 3 reviews specialist topics such as slamming and green water loads as well as loading on damaged ships. Wave-induced loads on offshore structures are reviewed in sections 2 and 4, the former dealing with single and multi-body interactions, including a note on the effects of current and bathymetry. On the other hand section 4 focuses on specialist topics, such as cables and risers, vortex-induced vibrations (VIV), offshore lifting and installation and submersibles. As with previous reports, current state of progress in short- and long-term predictions and fatigue loads is examined, focusing on applications to ships and offshore structures. Finally, uncertainties in experimental and full-scale measurements and computational methods are discussed.

2 COMPUTATION OF WAVE INDUCED LOADS

2.1 Zero Speed Case

2.1.1 Body Wave Interactions

Traditionally the prediction of wave loading of zero speed body wave interactions has been based on potential flow solutions (ISSC 2009). Consideration of viscous effects has been commonly restricted to specific problems such as, the calculation of slow drift motion of offshore structures, the evaluation of rolling response close to the roll resonance of ships or barges or the evaluation of the resonant motions of the confined fluid between side-by-side arrangements of floating bodies.

Pescoa *et al.* (2011) presented an experimental investigation of the first and second order wave exciting forces acting on a body of simple geometry subjected to long crested irregular waves. The body is symmetric about the vertical axis, like a vertical cylinder with a rounded bottom, and it is restrained from moving. Second order spectral analysis was applied to obtain the linear spectra, coherence spectra and cross bi-spectra of both the incident wave elevation and of the horizontal and vertical wave exciting forces. The linear and quadratic transfer functions (QTF) of the exciting forces were obtained from the analysis of irregular wave measurements. The results have been compared against experiments in bichromatic waves and with numerical predictions from a second order potential flow code. Whereas the agreement of the experimental and numerical results was shown to be satisfactory for the linear forces, it was concluded that the measured wave exciting forces include a significant non linear contribution for the low frequency range.

Recent research results have been presented in the area of bottom founded structures (e.g. single or multi-array cylinders, wind turbine foundations, gravity support structures (GBS) etc.) show a trend toward the use of CFD simulations and approximate nonlinear diffraction models. For example, Morgan and Zang (2010) investigated the use of the open source CFD software suite OpenFOAM for the simulation of focused wave packets interacting with a vertical bottom mounted cylinder. Wave elevation in the vicinity of the cylinder was compared to experimental data. In a parent paper, Zang *et al.* (2010), investigated the higher-order diffraction effects on the loading and demonstrated that the method leads to reasonable agreement with experiments.

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Bredmose and Jacobsen (2010) reported investigations on a typical bottom-mounted offshore wind turbine foundation, also using the OpenFOAM suite. In this study special emphasis was attributed to the wave generation process. The fluid loading obtained from the CFD calculations was compared to results given by a combination of the 'Wheeler stretching technique' for the incident wave kinematics, and 'Morison equation' for the fluid loading. Comparisons between empirical and computational results were shown to be satisfactory. Roos *et al.* (2009, 2010) reported on the experimental study of wave impacts on elements of a GBS composed of submerged storage caissons combined with four surface piercing vertical cylinders, in relatively shallow waters. The authors indicate that larger impact loads to those measured on the underside of the deck (e.g. wave in deck impact loads, loads on vertical columns etc.) may be recorded successfully.

The recent expansion in the market of Floating Offshore Installations (FOIs) has introduced the need to direct research towards understanding the effects of varying water depths and associated high frequency responses of such structures in waves using advanced methods. For example, Johannessen (2011) revisited the problem of the high frequency resonant response of offshore structures in irregular waves, using approximate nonlinear diffraction models. The author concluded that provided the incident wave spectral properties are carefully represented, such models allow for a good representation of the resonant response of stationary large offshore structures. Yan *et al.* (2010) conducted fully nonlinear analysis of a moored FPSO vessel in shallow water waves using the Lagrangian-Eulerian finite element method. Investigations were also carried out on the effects of water depth on forces and wave run-up. The numerical results suggest that the induced forces decrease. However, the nonlinear components may be more significant as the water depth decreases. Lee and Kim *et al.* (2010) calculated motions of two floating bodies (FSRU and LNGC) in shallow water. The authors concluded that whereas the horizontal surge motion is significantly affected by the wave deformation, the surge motion is considerably amplified in low frequency waves by nonlinear wave-wave interactions.

Park *et al.* (2010) studied the motions and loads of a LNG-FPSO considering the effects of sloshing. The methodology is based on a coupled model of sloshing and motion in the time domain. It was confirmed that the sloshing impact pressure depends on the wave period, the number of filled tanks and the tank filling level. Ryu *et al.* (2010) studied sloshing loads in partially filled LNG tanks for an FLNG at different headings and sea states. They described the effect of wave heights on the sloshing loads, especially for partially filled LNG tanks.

2.1.2 Effects of Varying Bathymetry

When shallow water operation is considered, the influence of the seabed bathymetry variation on the loads acting upon the floating body needs to be examined. De Hauteclocque *et al.* (2008) presented a method to eliminate the interference caused by the wave reflection on the boundaries of the truncated bathymetry using the classical diffraction theory. Their method applies semi-transparent panels to the region of the bathymetry boundaries. The radiation coefficients were compared with those obtained when only an opaque bathymetry is considered. The wave kinematics calculated by the diffraction code were compared to those obtained by a shallow water code based on Green-Naghdi theory. The study concluded on good comparisons against semi-analytical solutions (e.g. GNWave) of wave kinematics along a slopped seabed. Further numerical studies for the case of a barge floating over a horizontal bathymetry

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and for a LNG over a slopped seabed demonstrated that the interference effect of variable bottom on the wave loads may be important.

Molin *et al.* (2010) and Liu *et al.* (2011) addressed the problem of determining apriori whether the shoaling of the accompanying long wave to an irregular wave system may lead to significant corrections with regards to the flat bottom model. These studies assume that the bathymetry is constrained in way of a constant depth zone that is followed up by a rectilinear ramp. The authors compared their results with those of a flat bottom. It was concluded that low frequency second order loads are strongly reduced as compared to their flat bottom reference values.

Athanassoulis *et al.* (2009) studied the problem of transformation of the spectrum of an incident wave system over a region of strongly varying bottom topography within the context of linearity. This work focused on cases where the typical wave length and the characteristic length of the bottom profile variations are comparable and the waves propagate in intermediate-to-shallow water depth. It was concluded that the approach permits the consistent transformation of the full incident wave spectrum over variable bathymetry regions and the calculation of the spatial evolution of point spectra of all interesting wave quantities at every point in the domain. Belibassakis (2010) presented a nonlinear hybrid domain decomposition method with application to the problem of roll response of ship-hull sections of general shape floating in general bathymetry regions. The idealisation is based on a BEM for the representation of the nonlinear potential wave motion around the floating body and a vortex particle method for the generation of vorticity in way of the boundary layer. Results of reasonable accuracy are presented. It is concluded that in those cases where the viscous effects associated with boundary layer separation may be significant, mixing of boundary integral and particle methods may be useful in the evaluation of ship-hull characteristics in rolling motion.

Ferreira *et al.* (2009) discuss the importance of modelling the effects of significant variation in bottom depth along the length of large LNG carriers. In this work, comparisons between simplified and advanced numerical models idealising in detail the bathymetry changes due to a sloping bottom in way of the ships' parallel body are generally speaking small. Hence, reasonable estimates of the heave and pitch motions were obtained using the average depth along the length of the ship. The authors concluded that differences in depth at the bow and stern do have a substantial effect on the cross-coupling coefficients. Thus, the phases of the heave and pitch motions and associated loads are not as well approximated by computations assuming constant depth.

De Hauteclocque *et al.* (2010) formulated a radiation - diffraction theory to calculate the wave kinematics, motions and loads of a floating body in areas of varying bathymetry. The method presented could be useful in the context of LNG terminals where the depth is quite shallow and the bathymetric variations significant. The bathymetry is modelled as a second body. A modified formulation of the BEM is introduced to model accurately the opaque bathymetry. Numerical results are shown to be satisfactorily compared to a 3D shallow water code based on Green-Naghdi theory. The differences with the constant depth calculations are shown to be significant, due to the modified incident wave field, modified added mass and radiation damping terms. More recently, Pinkster (2011) also addressed the same problem by introducing a modified diffraction method based on a multi-domain approach capable of handling different water depths in each domain. In this work it is shown that the multi domain approach can also be used for subdividing large domains.

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2.1.3 Multi-body Interactions

Multi-body hydrodynamics became a relevant topic of research over the last years as the offshore activities grow and diversify. Many of the developments have been motivated by the operation of side-by-side, or tandem, offloading of LNG from the floating production unit to a shuttle tanker. Other examples of multi-body systems include the classical problem of multiple surface piercing vertical cylinders, very large floating structures and wave energy converters. The calculation of the hydrodynamic interactions is important in order to assess the operability of the coupled systems, estimate the loads on the structure and on the mooring lines (e.g. lines connecting the bodies and on the articulations). The current practice is to use frequency domain potential flow linear BEM to calculate the wave-body interactions. For computational economy the Higher Order Boundary Element Method (HOBEM) is preferred for multiple bodies. If nonlinear mechanical interactions need to be included, frequency domain results are used to calculate hydrodynamic linear impulse response functions. The equations of motions and loads are consequently solved in the time domain by combining linear and nonlinear forces. There are specific problems which require nonlinear hydrodynamic methods (e.g. resonant free surface motions in a narrow gap between two fixed or floating structures).

Lewandowski (2008) presented a systematic investigation of the hydrodynamic coefficients, free surface elevation and motions of two side-by-side rectangular barges. The author confirms that standing waves between the hulls occur at critical frequencies and they may have a significant effect on the hydrodynamic forces and loads. Different methods to reduce the standing wave elevations have been proposed as reported by ISSC I.2 (2009). However, some energy dissipation in the form of a damping term, must be assigned by the analyst. Since the loading calculations of moored floating structures often need to be carried out in the time domain, the author discusses the effects of the critical frequencies on the floater motions by memory functions. Such functions become inherently lightly damped, which leads to truncation errors in the evaluation of the convolution integrals. Bunnik *et al.* (2009) proposed a variation of the damping lid method introduced by Chen (2005) to reduce the unrealistically high resonant wave elevations between two floating structures positioned side-by-side. The damping lid method was chosen as it adds some damping to the free surface between the vessels. The results from the new method were compared with experimental data for two similar LNG ships in head regular waves. It was concluded that the new approach compares well with available experimental data for the in-gap wave motion and the wave induced drift forces.

Kristiansen and Faltinsen (2009) applied 2D linear and nonlinear BEM to investigate the pumping mode induced by incoming waves on an LNG carrier berthed near a gravity based structure in shallow waters. The results were compared with experimental data to conclude that both the linear and nonlinear predictions overestimate the resonant free surface elevation, although nonlinear results are closer to the experiments. In a more recent publication from Kristiansen and Faltinsen (2010) the flow separation of bilge keels was modelled by an inviscid vortex tracking method. It was concluded that while the nonlinear free surface effects have a small effect on the resonant free surface elevation prediction, the damping effect from the flow separation is large and in fact the predictions of the complete nonlinear model are quite good.

A 2D viscous flow numerical method has been applied by Lu *et al.* (2010a, 2010b) to calculate the wave motion in the narrow gap between rectangular cross sections, restrained from moving when subject to harmonic waves. In this work the Navier-Stokes

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

equations are solved with a finite element method, while the free surface is captured with a VOF method. The viscous flow results are compared against experimental data for the wave elevation in the gap showing good agreement. It is concluded that a 2D linear potential flow method is able to predict correctly the resonant frequencies but overestimates the free surface elevation amplitudes.

Hansen *et al.* (2009) presented an analysis of the motions, mooring lines and fender forces on two LNG carriers moored side-by-side in irregular seas and shallow water. The motions are calculated in the time domain accounting for the nonlinear mooring effects, while the multi-body hydrodynamic problem is solved with WAMIT. The Boussinesq wave model is applied to simulate the irregular sea states in shallow water. The comparisons with experimental data show good agreement for the first order motions and reasonable agreement for the forces on the mooring lines and fender connecting the ships. On the other hand, de Wilde *et al.* (2010) presented an experimental investigation with scaled models of the LNG stern-to-bow offloading with a shuttle tanker behind a weather vaning platform in irregular waves, wind and currents. Different options were assessed, namely passive tandem mooring, taut hawser and full dynamic positioning (DP). It was concluded that the DP shuttle tanker option significantly reduces the relative motions between the vessels.

The operability of the LNG offloading with tandem configuration can be assessed with the support of commercial computer codes. For example, Wang *et al.* (2010) used the software ARIANE 7.0 to carry out a systematic investigation of the time domain responses of a floating production platform and a tanker in tandem configuration. Clauss *et al.* (2009) presented an LNG transfer system based on new flexible cryogenic pipes where the shuttle tanker is towed between the mooring wings of a turret moored platform. The system was analyzed with WAMIT and related impulse response functions and with AQWA in the time domain, to calculate the relative motions and mooring forces. Excellent operability in the North Sea environment was reported. Brake *et al.* (2009) proposed to separate the floating LNG production platform in two vessels, the first for the production, process and storage of crude oil and the second for the storage of LNG and LPG. The vessels were moored with spread lines and connected with a yoke system in a tandem configuration. The relative motions and forces on the mooring lines were calculated with WAMIT for the multi-body hydrodynamics and OrcaFlex for the nonlinear coupled mooring analysis.

Within the reporting period new linear and nonlinear methods have been proposed to calculate the hydrodynamic interactions between vertical cylinders. Siddorn and Taylor (2008) presented an exact algebraic method to solve the diffraction and radiation of linear waves by arrays of independently moving truncated cylinders. This method is an alternative to BEM and since it does not require discretization of the boundaries, the solution is fast. Mavrakos and Chatjigeorgiou (2009) solved the second order diffraction problem of two concentric surface piercing cylinders subjected to harmonic waves with a semi-analytical formulation. Wang and Wu (2010) applied a finite element method to calculate the potential flow fully nonlinear interactions between incident waves and arrays of fixed cylinders in a numerical tank. At each time step the FEM was used to determine the velocity potential and then a finite difference method was implemented to calculate the velocity of the free surface and track its movement. A structured mesh was used near the wave maker. This was combined with an unstructured mesh around the cylinders.

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

2.2 Foreword Speed Case - Overview of Methods

A large variety of different nonlinear methods for the forward speed problem have been presented in the past three decades. One may distinguish between methods based on potential theory and those solving the Reynolds-Averaged-Navier-Stokes (RANS) equations. The majority of methods for ships at forward speed still belong to the first group. Within this group there is a large variety of methods ranging from linear theories to fully nonlinear methods. Between these two extremes there are many partially nonlinear, or blended, methods, in which one aims at including the most important nonlinear effects. As per ISSC 2009 in the subsequent discussion these methods are classified using 6 different levels namely: Level 1(linear); Level 2 (Froude-Krylov nonlinear); Level 3 (Body nonlinear); Level 4 (Body exact - weak scatterer); Level 5 (Fully nonlinear - Smooth waves) and Level 6 (Fully nonlinear).

2.2.1 Level 1: Linear Methods

In linear methods, the wetted body surface is defined by the mean position of the hull under the corresponding position of the free surface where the free surface boundary conditions are applied. The hydrodynamic problem is solved in the frequency domain by either 2D, 2.5D or 3D idealisations. One may distinguish between three levels of refinement in representing the steady flow field when the equation system for the unsteady flow is established. Those are:

- The Neumann-Kelvin (NK) method where the base flow is approximated by a uniform flow with velocity equal to the ship speed (U).
- The Double-body (DB) method where the base flow is approximated by the flow obtained when a mirror condition is imposed on the plane defined by the mean free surface.
- The Complete method where the complete steady flow, including the steady wave elevation, is used.

In problems with low speed and relatively high frequencies, the interaction with the steady flow in the Free-Surface Boundary Condition (FSBC) can be neglected and the only interaction appears as a U-term in the Body Boundary Condition (BBC). The solution of the boundary value problem can then be divided into a zero-speed solution and correction due to the forward speed. Such a speed correction approach is used in the classical strip theory (Salvesen *et al.*, 1970) and it is also quite common in 3D methods. One example is the so-called pulsating-source (PS) Green's function methods.

A recent comparison of frequency-domain 3D Green's function methods based on pulsating source (PS) and translating-pulsating source (TPS) is presented by Chapchap *et al.* (2011a). The authors studied the heave and pitch motions of the S175 container ship at Froude number 0.2 - 0.275 in head regular waves. The PS method produced better results than the TPS for this case; a trend that has also been observed for other hull forms at relatively high Froude numbers (Bailey *et al.*, 1999). The forward speed Green's function is significantly easier to evaluate in time-domain than in frequency domain, and many linear 3D methods utilise this fact. For example, Datta *et al.* (2011) have increased the robustness and the overall efficiency of the method of Datta and Sen (2007) to enable calculation of motions of fishing vessels. The simulations were compared with results from the 3D WAMIT code (Korsmeyer *et al.*, 1988) and a strip theory code for the zero-speed and forward-speed cases, respectively. The method compares generally well with WAMIT for zero speed

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for 3 fishing vessels, while the agreement with strip theory varies depending on the Froude number (in the range 0 to 0.42) and the hull form.

A systematic study of the influence of various degrees of refinement in the modelling of the forward speed-effects has been presented by Zhang *et al.* (2010). The authors compared hydrodynamic coefficients, excitation forces and heave and pitch motions calculated by three interaction scenarios between (a) uniform flow in BBC and FSBC (Neumann-Kelvin method) (b) double-body (DB) flow in BBC and uniform flow in FSBC and (c) DB flow in BBC and in FSBC (Double-body method). Comparisons against experimental measurements were carried out for the Wigley I hull of Journee (1992) at Froude number 0.3 and a Series 60 hull at Froude number 0.2 (Gerritsma *et al.*, 1974). It was concluded that for the hydrodynamic coefficients, A35, A53, A55 and B55, including the DB-flow in the BBC gave the most significant improvement. For B35, including DB-flow in the FSBC was the most important, while for B53, including DB-flow in BBC and in FSBC were of almost equal importance. For the excitation forces, the effect of including the DB-flow was small. For heave and pitch motions the double-body method produced significantly better results than the Neumann-Kelvin method.

In order to accurately compute the m-terms, involving interactions between the base flow and unsteady flow fields in the BBC, Qiu and Peng (2007) introduced a panel-free method for frequency domain forward speed problems. More recently, Peng and Qiu (2009) have applied their method to the Wigley III monohull of Journee (1992) at Froude numbers 0.2 to 0.4 in head seas. The calculated heave and pitch motions generally compare well with the experimental results; except for pitch at the highest Froude number. The heave resonance peak of the Wigley III at Froude number 0.3 was well predicted by the Neumann-Kelvin method of Peng and Qiu (2009), while Zhang *et al.* (2010) demonstrated that the Neumann-Kelvin method gave a relatively large overestimation of the heave resonance peak of the Wigley I at the same speed. This indicates that it is still difficult to draw firm conclusions regarding the required refinement level when including forward speed effects in the boundary value problem.

Shao and Faltinsen (2011) presented a time domain Higher Order Boundary Element Method, which is based on cubic shape functions, to study the linear seakeeping problem. Their validation results include the amplitudes and phase angles of a Wigley hull subject to heave and pitch motions in head seas, and the corresponding added resistance. Finally, they studied the 2nd order wave diffraction problem of the Wigley hull and showed that the second order velocity potential is dominating over the quadratic terms in the wave induced excitation of nonlinear ship springing.

Du *et al.* (2011) discussed the problem of irregular frequencies in forward speed seakeeping analyses with singularity distribution methods. For the majority of ship-like structures these irregular frequencies lie outside the range of practical interest for rigid body motions but they may create difficulties for the analysis of flexible bodies, multi-hulled vessels and when using frequency-domain data to create impulse-response functions for subsequent simulation of vessel responses in the time-domain (Bailey *et al.*, 2001). A rectangular box and a Series 60 hull form were analysed at zero and non-zero forward speed. It was concluded that more practical numerical approaches are required to overcome the problem of irregular frequencies.

Wu *et al.* (2010) applied the VERES/WINSIR strip theory based hybrid hydroelastic method of Wu and Moan (2005) to study the heave/pitch motions and vertical bending moments (VBM) for an ultra large container ship progressing at the Froude number

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0.22 in head seas. Comparisons were made with results from model tests and with the 3D WASIM code. For RAOs of heave, pitch and VBM, both computer codes agreed quite well with the experimental data. However, it could not be concluded that one code is superior to the other.

Some linear seakeeping methods have recently been modified to enable analysis of special vessels, such as high speed craft (HSC), multihulls, air-cushion vehicles (ACV), foil-assisted craft and SWATH-like vehicles. De Jong and Van Walree (2009) extended the work of Lin and Yue (1990) and van Walree (2002) to present a linearised time-domain Green's function method for analysis of HSC. Predicted heave, pitch and vertical accelerations are compared with experimental data for two high speed monohulls in head irregular waves. Results in terms of standard deviations compared well, but the numerical method tends to underpredict the extreme vertical accelerations. Milewski *et al.* (2009) presented a practical simulation model for seakeeping analysis of air-cushion vehicles. Saito and Iwashita (2009) applied a frequency domain Rankine panel method to calculate the motions, pressures, vertical shear forces (VSF) and VBM for a slender high speed vessel with aft outriggers in head seas. The Froude numbers 0.31, 0.5 and 0.69 were studied. Good agreement with experiments was reported, but the strip theory method was shown to give almost as good results for the heave and pitch motions. For VSF and VBM at the two higher speeds, the 3D method provided better agreement against experiments. Experimental results for a trimaran, a monohull and two SWATH types at Froude numbers 0.43-0.50 were given by Kihara *et al.* (2009). Comparisons against strip theory calculations for the monohull and the SWATHs has shown that additional damping due to lift and drag may be accounted for in a quasi-steady manner as suggested by Lee and Curphey (1977). Hydrodynamic interactions between hulls were neglected in their calculations. However, the strip theory calculations generally agreed well with the experiments for hydrodynamic coefficients, excitation forces and heave/pitch motions.

2.2.2 Level 2: Froude-Krylov Nonlinear Methods

In Level 2 methods, the disturbance potential is calculated as in the linear case. The incident wave forces are evaluated by integrating the incident wave pressure and the hydrostatic pressure over the wetted hull surface defined by the instantaneous position of the hull under the incident wave surface. Level 2 methods are very popular, since they capture many important nonlinear effects with only a fraction of the computer time required for the Level 3 methods. It is common to use linear analysis to calculate the frequency response or Retardation Functions (RF). The linear frequency response functions are transformed to time domain, yielding the RFs. The time domain response will contain a convolution integral with the RF to account for the memory effects. Another common starting point is to solve the problem directly in the time domain using the time-domain (transient) Green's function, which also involves convolution integrals (e.g. Lin *et al.*, 2007; Weems *et al.*, 2007). In the next step, various nonlinear modification forces can be included in the time domain equations of motion in addition to nonlinear Froude-Krylov and restoring forces in order to account for slamming and green water.

Within the reporting period the Level 2 time domain 3D formulation LAMP-2 has been applied to a semi-displacement mono-hull by Ibrahim *et al.* (2009). The authors incorporated lift and damping effects from the hull by adopting a formula from Thwaites (1960). Lift and drag forces due to trim tabs were also included. It was demonstrated that these lift-effects are small for Froude numbers below 0.3. On the

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other hand, at higher Froude numbers the effects of including these additional forces become noticeable. However, when comparing against experiments it is not yet clear that lift and drag force idealisations give more accurate results.

Bruzzone *et al.* (2009) applied a Level 2 method to a hard-chine and a round-bilge catamaran, running at Froude numbers 0.5 and 0.3, respectively. A 3D Rankine panel method was used to calculate the steady flow and linear radiation and diffraction forces in the frequency domain. Interaction with the steady flow was included in the FSBC. Relatively good agreement with experiments was obtained for the vertical motions. Liu and Papanikolaou (2010) presented a hybrid, time-domain domain potential theory method and applied it to a variety of seakeeping problems. The validation included steady flow, wave resistance calculations and studies of nonlinear motions and loads in waves. Their results agree well with experimental data for the wave making resistance of a Wigley hull, heave and pitch motions of the S-175 container ship in head sea under different wave conditions and the added resistance of various ship hulls. In a more recent publication the efficiency of calculations was enhanced by use of a Chimera-type, overlapping grid schemes on the free surface (Liu and Papanikolaou, 2011).

The hybrid hydroelastic nonlinear strip theory of Wu and Moan (2005) was applied for the case of a 294 m long container ship by Drummen *et al.* (2009). Numerical results were compared against experimental results derived from a flexible model in head seas. The nonlinear strip theory agreed quite well with the experimental results. It was demonstrated that sagging and hogging moments in head seas increase and become more nonlinear when the high-frequency vibrations due to hull flexibility are accounted for. It was also shown that springing is often excited by nonlinear wave loads that oscillate at a frequency that is an integer multiple of the wave encounter frequency. The same theory was applied to a 366 m container ship by Wu *et al.* (2010) and compared with experimental results from a flexible model in head seas. The calculated hogging and sagging moments generally agreed quite well with experiments. However, it was concluded that the wave-frequency sagging moments are over predicted, while the whipping sagging moments are under predicted. Hence the 2D momentum slamming model could be replaced by a more refined model in order to predict the whipping moments more accurately.

Another nonlinear hydroelastic analysis of a 336 m container ship was reported by Lee *et al.* (2011a, 2011b). The calculated VBM were compared with results from model tests with a flexible model in head seas. The time-domain analysis used linear hydrodynamic coefficients obtained with a 3D panel method. Momentum-based slamming forces were included in addition to the nonlinear Froude-Krylov and hydrostatic forces. The theoretical method captured the springing and whipping vibrations reasonably well, but it was shown that there are some regular wave periods for which the vibration magnitude is not correctly predicted.

2.2.3 Level 3: Body-nonlinear Methods

In Level 3 methods, the disturbance potential is calculated for the wetted hull surface defined by the instantaneous position of the hull under the mean position of the free surface. This requires regridding and recalculation of the disturbance potential for every time step. The computational costs will therefore increase dramatically as compared to Level 2 methods. No publications regarding the Level 3 methods appeared during the reporting period.

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2.2.4 Level 4: Body-exact Methods (Weak Scattered Methods)

These methods are similar to Level 3, but the wetted hull surface is defined by the instantaneous position of the hull under the incident wave surface. For Green's function methods, this increases the complexity, since the commonly used time domain Green's function satisfies the free surface condition on the mean free surface and not on the incident wave surface. The later can be circumvented by mapping the geometry into a computational domain where the incident wave surface becomes a flat plane (e.g. Lin *et al.*, 1994). Level 4 methods are sometimes referred to as "weak scatter methods", since the disturbed, or scattered waves, caused by the ship are disregarded when the hydrodynamic boundary value problem is set up. It is assumed that the scattered waves are small compared to the incident waves and the steady waves.

Recently, Mortola *et al.* (2011a,b) presented a time-domain method where the restoring, Froude Krylov and diffraction forces are calculated at each time-step for the exact position of the hull under the incident wave surface. The diffraction forces were calculated with the strip theory approach (Salvesen *et al.*, 1970). Hydrodynamic coefficients for the correct instantaneous draft for each section were applied during the simulation. These coefficients were calculated beforehand by strip theory for relevant combinations of section immersions and heel angles. This approach implies that forward speed effects are accounted for only in a simple manner. It is shown that the method predicts RAO-values of heave, pitch and midship VBM for the S175 in head regular waves that, for the zero speed case, compare quite well with predictions from linear 2D and 3D frequency-domain codes.

2.2.5 Level 5: Fully Nonlinear Methods (Smooth Waves)

In these fully nonlinear methods, the scattered waves are no longer assumed to be small, and they are included when the boundary value problem is set up. In the MEL (Mixed Eulerian-Lagrangian) method the Eulerian solution of a linear boundary value problem and the Lagrangian time integration of the nonlinear free surface boundary condition is required at each time step. These methods assume that the waves are "smooth", i.e. there is no wave breaking or fragmentation of the fluid domain. Computations are typically forced to stop based on a wave breaking criterion. The stability of the free surface time-stepping can also be a problem (e.g. Bandyk and Beck, 2008).

Lin and Kuang (2009) applied the 3D fully nonlinear method presented by Lin and Kuang (2006) to a fast vessel. Heave and pitch motions seem to agree well with experimental results in head irregular waves, but only short time-series for two different speeds have been presented. Sun and Faltinsen (2009) extended their fully nonlinear 2.5D theory to account for non-prismatic hull forms. Only calm water results have been presented, but the theory is also applicable to the problem of forced heave and pitch motions. Yan and Liu (2010) presented a fully nonlinear 3D method. An efficient MEL-based time-domain computational method was developed using the pre-corrected Fast Fourier Transform algorithm based on a quadratic BEM. The method was used to study wave radiation of a heaving sphere, wave diffraction of a fixed vertical cylinder, and wave generation of a forward moving ship hull. Calculated results generally compared well with available experimental data, although discrepancies still remain in the predictions of the wave elevation near the bow of the ship hull. More recently, in order to overcome some of the problems associated with the MEL description of the fluid flow and enhance its applicability, Chapchap *et al.* (2011b) described the geometric domain by means of signed distance functions, which considerably simplify the mesh generation procedure.

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2.2.6 Level 6: Fully Nonlinear Methods

The boundary integral methods used in potential theory cannot handle breaking waves, spray and water flowing onto and off the ship's deck. Moreover, viscous forces are not part of the solution and must be obtained by other methods. With the increasing power of modern computers, methods solving the RANS equations are becoming increasingly popular. In these methods, the water/air volume is normally discretised, and a finite difference, finite volume or a finite element technique is used to establish the equation system. Within the reporting period particle methods, where no grid is used, have also been applied to solve the Navier-Stokes equations. Examples are the Smoothed Particle Hydrodynamics (SPH), the Moving Particle Semi-implicit (MPS) and the Constrained Interpolation Profile (CIP) methods, with the latter believed to be more suitable for violent flows.

The unsteady RANS code CFD Ship-Iowa V.4 has been applied to a catamaran advancing in head regular waves by Castiglione *et al.* (2009). In this code the free surface is captured using a single phase level set method and turbulence is modelled by a blended $k-\epsilon/k-\omega$ model. The equations are discretised using a finite difference approach. The authors concluded that calculated amplitudes and phases of heave and pitch motions agree well with experimental results at Froude numbers 0.45, 0.6 and 0.75. A modal hydroelastic analysis, using CFD Ship-Iowa V.4 for the fluid calculations and the commercial FEM code ABAQUS for calculation of mode shapes, was presented by Paik *et al.* (2009). The S175 container ship at Froude number 0.2 in head regular waves was studied. Different ways of fluid-structure coupling were investigated. Heave, pitch and VBM compared quite well with experimental data obtained with a flexible segmented model (Ramos *et al.* 2000).

Lin *et al.* (2009) used the FANS (Finite-Analytic-Navier-Stokes) code developed by Chen and Yu (2006) together with the Froude-Krylov nonlinear 3D potential theory code LAMP-2 to calculate motions and wet deck slamming loads on a high-speed catamaran. In this work LAMP was used for the flow solution in the outer region and FANS was used to model the local flow region immediately around the ship for nonlinear free surface and 3-D impact effects. FANS uses a level-set method for interface capturing. The paper presents some computational results obtained with this new hybrid method but no comparison is made with experimental data.

Hu *et al.* (2010) applied the CIP-based code RIAM-CMEN to a post-Panamax container ship at Froude number 0.179 in head and bow regular waves. RIAM-CMEN uses a Cartesian grid covering the whole computation domain, the CIP combined and unified procedure as the flow solver, a VOF-like Tangent of Hyperbola interface capturing technique and a Lagrangian method for solid body motion, in which the fluid structure interaction is treated by an immersed boundary method. Calculated heave, pitch, pressures, VBM, horizontal bending moments (HBM) and torsional moments (TM) were compared against experimental results for a segmented model (Miake *et al.*, 2004) and with results from a linear Rankine panel method and a linear strip theory. The results from RIAM-CMEN generally compared better with experiments than do the potential theory codes. This was particularly the case for hydrodynamic pressures on the hull and for heave and pitch motions. For HBM strip theory results compared equally well with the experiments, and for VBM amidships strip theory seemed to compare slightly better than RIAM-CMEN. None of the methods could predict the torsional moments in bow waves with good accuracy.

The same CIP method was applied to a $270\,m$ container ship at Froude number 0.24 in head regular waves by Huijsmans *et al.* (2010). Calculated heave, pitch, VSF

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and VBM were compared with results obtained with a segmented model. The CIP-method predicted pitch motions with quite good accuracy, while heave motions were underestimated. Generally, for VBM and VSF the discrepancies between computed and experimental RAO's were relatively large, although for the peak RAO-values of the VBM amidships and the VSF at the fore quarter length the agreement was fairly good.

2.3 Offshore Wind Loads

Wind loads are often considered as secondary with regards to the overall loading of marine structures. This may be considered acceptable as long as the magnitude of the mean wind forces and moments are only a fraction of the total loading. For situations such as cyclonic storms (e.g. hurricane Katrina), for offshore offloading and operations or helicopter landing the magnitude of wind loading is considered critical and should be accounted for in the design.

Wind coefficients used in offshore structures load analysis are often taken from literature or from wind tunnel measurements. Engineering studies are usually focused on the prediction of the global motion analysis and not in the definition of the wind load itself. Accordingly, the wind, wave and current combined motion analysis effects are analysed by numerical models and validated by model tests. The approach used in model tests may be either used to generate wind directly by fans or to simulate wind loads using a dynamic winch. Wind load time series are then derived based on wind tunnel tests as reported by Liapis *et al.* (2010) for the Perdido spar.

With the advancement of computers complex computational methods (e.g. CFD) are used as a cost-effective alternative to wind-tunnel tests. For example, Wang *et al.* (2010) performed a wind load analysis for a semi-submersible platform using CFD analysis and compared the results with wind tunnel experiments. The model used was a semi-submersible drilling unit with a length of $114\,m$ and a main deck height of about $38\,m$. The analysis was performed for a 1:192 size model. The platform was modelled by using the FLUENT commercial CFD algorithm and standard turbulence models were investigated by Large Eddy Simulation (LES). It was concluded that the dynamic sub grid scale (SGS) model provides best results regarding pressure coefficients, drag and lift forces as compared to model tests. The $k-\epsilon$ model results showed acceptable force prediction but could not predict exactly the effects of turbulence. Wnęk *et al.* (2012) presented an analysis of the aerodynamic forces acting on a floating LNG platform and an LNG carrier. The investigation focused on understanding the approach manoeuvre of the ship to the platform. This is the effect of platform shadow on the vessel during operation under wind conditions. Results from using the commercial CFD ANSYS CFX code were compared with experimental measurements performed in a wind tunnel. Numerical and experimental results, presented in a form of coefficients for the drag, lift components and yaw moment, reached approximate agreement. The biggest discrepancy occurred for lateral forces, where CFD underpredicts by about 50 % the experimental results.

Within the reporting period special interest has been attributed to loads emerging from extreme events (e.g. cyclonic tropical storms, hurricanes etc.). For example, Jang *et al.* (2010) identified the effects of damages on wind turbines due to tropical storms and analysed these effects on a wind turbine tower. Yang *et al.* (2009) analysed the loads on drilling rig tie down systems during hurricane conditions. The authors attributed special effort in analysing the dynamics of the structures. The wind force time series were calculated in a classic manner and applied as collinear to the wave and

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current actions. In a similar type of work Mücke *et al.* (2008) and Mücke *et al.* (2010) have analysed high frequency wind speed time series measured at the GROWIAN site at the German North Sea coast. In comparison with the standard models used for load analysis of structures and wind turbines their models have shown a higher probability of extremes. The analysis of probability density functions of wind speed amplitudes showed a non-Gaussian distribution with flatter tails. Adjusted wind turbulence models as the one proposed by Kleinhans (2008) were used to numerically analyse loads on wind turbines resulting in significantly higher load fluctuations.

In those cases where the wake behind a simple object may be roughly estimated using wind coefficients coming from experiments or empirical formulas, CFD simulations can be valuable to simulate the wake field astern complex ship structures. For example, Koop *et al.* (2010) investigated the applicability and accuracy of CFD analysis to derive wind loads for an FPSO tandem offloading configuration. This work was performed within the OO1 Joint Industry Project and analysed the wind load on a fully-loaded barge-shaped FPSO with 5 square blocks on the deck and a ballast loaded shuttle tanker at a distance of 450m. For the tandem configuration the FPSO was modelled with a 30° misalignment to the mean wind direction while the shuttle tanker was fully aligned to the wind direction. The analysis was performed using the MARIN in-house CFD code ReFRESCO and the CFX commercial software on block structured and unstructured computational grids. Steady state forces on the structures were derived. Computational results were compared against wind tunnel measurements using segmented models. For FPSO or shuttle tanker standard configurations different numerical analysis codes provided force coefficients within a bandwidth of the order of 15 % to 30 % of the measurements. However, in the tandem configuration numerical analysis showed large differences compared to wind tunnel measurements. Trends in forces and moments were opposite from measurements, a fact that led to an unexpected increase in the drag force of the shuttle tanker. It was concluded that model scale effects may influence the wake behaviour and grid adjustments. CFD models therefore should capture more accurately the vortices generated by the FPSO boxes.

A similar type of analysis was performed by Tannuri *et al.* (2010) on a typical shuttle tanker when offloading an FPSO moored in a spread mooring system. In that work shielding effects when the shuttle is shifted to a tandem position, aligned to the FPSO, were analysed. Two identical FPSO and shuttle tanker structures (length 300 m) were tested for wind directions of 15° and 30°. The steady state condition was analysed using the commercial CFX algorithm and the model was calibrated using wind tunnel measurements. The results showed accuracy of the order of 10 % to 40 % depending on the load components and conditions. For yaw moments large discrepancies were observed for those cases where the absolute value of the moment is very small.

De Carvalho (2010) simulated the flow over a helideck in way of the complex topsides geometry of an FPSO. The numerical investigation was performed using CFX for a typical Brasilian FPSO of about 340 m length. During the preliminary tests comparative simulations were carried out using the $k-\epsilon$ and Shear Stress Transport (SST) turbulence models. SST results were in line with the wind tunnel experiments performed for a 1:200 scale model. Particle Image Velocimetry (PIV) and hot wire measurements compared well against the flow field numerical analysis measurements. Comparisons against modelling guidelines resulted in the conclusion that new turbulence criteria may have to be developed in the future.

A special topic in wind load analysis is the loading of offshore wind turbines. Currently, numerical schemes accounting for the coupled dynamics of the wind inflow,

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aerodynamics, elasticity, and controls of the turbine, along with the incident waves, sea current, hydrodynamics, and foundation dynamics of the support structure are being developed. Jonkman *et al.* (2010) and Vorpahl *et al.* (2010) reported some of the results from a benchmark study carried under the International Energy Agency (IEA) Wind Task 23 on aero-servo-hydro-elastic codes. In this work complex load cases were defined and run to trace back differences against simulation results. Different phases analysing the response of a 5 MW turbine on (a) a monopile with fixed foundation, (b) a monopile with flexible foundation, (c) a tripod and (d) a floating spar buoy were studied and an adaptation of the codes to those developments was enabled. The comparisons, in general, agreed quite well. All codes used blade element theory to account for rotor aerodynamics and the Morison equation to consider the wave actions. The structural dynamics were modelled by FEM methods or multi body formulations that are acknowledged to have influence on higher order eigen-frequencies. Some differences in the results obtained from different structural or hydro-structural models were identified.

The influence of wakes within a wind farm may significantly influence wind turbine loading. The standard approach is to artificially increase wind turbulence intensity to account for added vorticity and wind speed decay due to upwind wind turbines as shown by Frandsen (2007). Madsen *et al.* (2010) proposed the use of a dynamic wake meandering (DWM) model. Accordingly, by using CFD computations simplified engineering equations were derived considering basic physical mechanisms in the wake i.e., the velocity deficit, the meandering of the deficit, and the added turbulence. The model has been validated by Hansen (2009) and implemented in the HAWC2 and the Bladed codes by Schmidt *et al.* (2011).

In the field of floating offshore wind turbines the coupling of the rigid body motion (due to wave forces) and the elastic behaviour of structure/blade with the aerodynamic loading may be significant. Jonkman (2009) described the dynamics of offshore wind turbines for load analysis. Cordle (2010) and Matha *et al.* (2011) provided a complete overview of the state of the art and existing codes as well as the requirements for floating offshore wind turbine load analysis. Regarding aerodynamic loading one interesting finding is that the large low frequency platform motions experienced by floating wind turbines may result in complex flow conditions in those cases where the rotor is traversing back over its own wake.

2.4 Loads from Abnormal Waves

In the field of abnormal or freak (or rogue) waves some investigations deal with the nature, as well as physical and numerical generation of these waves, whilst others with the effects of waves on floating structures. The former falls within the remit of Committee I.1; hence, the focus of this section will be on the latter.

The concept of rogue waves and their effect on ships and offshore structures was first brought to prominence by Draper (1964, 1971) through observations of the addition of many wave components to form a larger wave during a world voyage. In more recent decades the phenomenon has grown in consequence in the marine industry as a result of high-profile encounters recorded by vessels. For example, Haver (2000) reported on the effects of a $30\,m$ high rogue wave that broke over the superstructure of the Queen Elizabeth 2 during gale conditions in 1995. Stansberg (2000) discussed the case of the FPSO Schiehallion that suffered plate deformation of the order of $15-20\,m$ above the mean waterline, due to severe bow slamming experienced as the result of an impact from a $20\,m$ high wave crest. Haver and Andersen (2000) reported on the event that

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occurred at the Draupner oil platform on 1st January 1995 when a 26 m high rogue wave occurred in a 12 metre sea state, causing damage to the accommodation deck on the platform. More recently, Berlotti and Cavaleri (2008) discussed the incident where the passenger ship Voyager encountered a rogue wave in 2005. This event caused severe roll motion, control room flooding and a loss of electrical systems. From these known encounters information about rogue waves is available in the form of crew observations and, in the case of the Draupner platform, a wave record from a downward facing laser. Unexplained ship losses have also been attributed to rogue wave encounters. For example, Kjeldsen (2000) reported on the cases of M/S Anita and M/S Norse Variant; Kharif and Pelinovsky (2003) discussed the effects of rogue waves in relation to the loss of MV Derbyshire.

The effect of freak waves on marine structures, in general, has also been focused on the effect on stationary offshore fixed structures. For example, Guedes Soares *et al.* (2008) presented an approach to determine the global load effects induced on ship structures by abnormal, freak, or episodic waves. The authors refer to a procedure that can be used for the determination of extreme values of wave-induced responses, including the recent advances of adopting time series of wave elevation, as reference design condition to calculate the wave-induced structural loads on ships in heavy weather. It is shown how this procedure can be extended to account for abnormal or episodic waves. It is suggested that at the present stage of knowledge it is possible to determine the loads induced by abnormal waves similar to ones that have been measured at various ocean locations and that are thus realistic. Although this information cannot replace the wave-induced loads calculated with the presently established procedures, it can serve as guidance for the design. Fonceca *et al.* (2010) investigated the vertical motions and bending moments of an Floating Production Storage and Offloading FPSO platform in several design storms with duration of three hours which correspond to the 100 years return period of the North Sea. Experimental data were systematically compared with numerical results from a nonlinear time domain strip method and they were found to underestimate the relative motions at the bow. The authors concluded that the discrepancies were related to the nonlinear effects on the incident waves, resulting in larger crests than troughs, and the run-up of the wave as it encounters the hull. The maximum bending moments obtained experimentally in the design storms were compared with the Rule reference values and they were found to surpass the later by around 30 %.

Following the work of Clauss and Henning (2004) on the assessment of rolling and capsising of ships in large waves, more recent investigations focused on understanding the behaviour of moving vessels in severe random seas. For example, Dramen *et al.* (2009) and Clauss (2009) addressed an experimental and numerical studies for a Container Ship, a bulk carrier and a Ro-Ro ship responses in severe seas. In these works it is recognised that having chosen a rogue wave type, known repeatable rogue waves need to be produced in an experimental towing tank. It is also addressed that nonlinear fluid structure interaction techniques including the physics of wave formation and the wave kinematics should be developed and validated. The later may include the nonlinear Schrodinger equation introduced by Onorato (2005) and the numerical wave tank approach suggested by Clauss *et al.* (2005). Recently, Rajendran *et al.* (2011) present direct comparisons between experimental time records and linear and nonlinear time domain simulations for a 117 m container ship in extreme sea conditions. Predefined wave traces, corresponding to the New Year Wave and a freak wave measured at North Alwyn, were reproduced in the tank. It is shown that the calculated response motions

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compare well with the experiments. However, the VBM amidships calculated using a linear method tend to underestimate the sagging peaks and overestimate the hogging peaks.

The work by Denchfield *et al.* (2009, 2010) concentrated on investigating the encounter between a rogue wave and a Lender Class Frigate in irregular head waves, including the influence of forward speed, through a combination of experimental investigations and numerical models incorporating the effects of hull flexibility. Predicted motions were compared with test measurements from a rigid model and two options for generating rogue waves, namely the first order optimisation approach and the New Wave approach. Results have shown that as the significant wave height and hence the rogue wave height increases, the experimental wave traces exhibit greater second order characteristics in the vicinity of the rogue wave peak. Comparisons in terms of heave and pitch motions become more severe with the introduction of a rogue wave into a seaway. The 2D linear model shows good agreement at low and mid-range speeds but at high speeds it shows some considerable discrepancies against experiments. It was concluded that this is likely to be due to the extreme "tunnelling" motions usually observed at high speed and in large seas during experiments.

2.5 Hydroelasticity Methods

Wu and Cui (2009) presented an overview of the developments and achievements of linear and nonlinear 3D theories of ships and the corresponding numerical and experimental techniques. In the proceedings of the 5th International Conference on Hydroelasticity in Marine Technology Temarel and Hirdaris (2009) presented a number of theoretical developments and applications of hydroelasticity methods on the design of ships and offshore structures. Hirdaris and Temarel (2009) discussed a number of recent applications of 2D and 3D hydroelasticity theories for ship design along with future ideas on the development and implementation of fully nonlinear fluid-structure interaction models, including CFD based methods, for the improved modelling of ship wave load predictions.

Following some initial work by Uğurlu and Guedes Soares (2008), Uğurlu and Ergin (2009) proposed a 3D hydroelasticity method for studying the response of surface piercing elastic structures using a higher order BEM approximation. The effects of approximation order and boundary surface discretisation on the removal of irregular frequencies were investigated by applying the extended boundary integral equation method of Lee *et al.* (1996). The frequency dependent hydrodynamic coefficients were calculated for a freely floating half-submerged elastic circular cylindrical shell. It was shown that the process of removing the irregular frequency effects becomes inefficient for higher frequency values. Notwithstanding, repeating the analysis with a higher number of free surface elements or by using a higher order approximation may be useful.

Mikami and Kashiwagi (2008) derived a nonlinear hydroelastic strip theory capturing the geometric nonlinearities in the hydrodynamic restoring and Froude-Krylov forces in waves. The frequency dependence in the radiation and diffraction forces was accounted for by using convolution integrals. The hull was modelled using a Timoshenko beam approach. The calculations were performed for a 716 TEU container ship and comparisons against model test results were shown to be satisfactory for symmetric distortions.

Kim *et al.* (2009a) studied the springing response of the flexible S175 ship using a Vlasov beam finite element method for the motion of the flexible structure and a

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higher-order Rankine panel-based boundary element method to simulate the fluid motion around the flexible body. The solution was sought by strongly coupling these boundary integral equations and FEM implicitly in the time domain. The structural domain was modelled by beam finite elements, able to capture the coupling effect between torsion and bending as well as warping distortion. Comparisons between symmetric wave loads derived by the Rankine-panel based time domain approach and a Green-function based frequency domain approach compared generally well (Kim *et al.*, 2009c).

Hirdaris *et al.* (2009b) discussed a method for the dynamic analysis of beam-like ships with large deck openings and associated structural discontinuities. The authors employed different numerical models to assess the influence of the discontinuities and the effect of other structural parameters. They concluded that the inclusion of structural discontinuities may have an important influence on natural frequencies, mode shapes and modal internal actions. However, it is difficult to establish a pattern of influence in terms of torsion or bending dominant mode shapes or a particular modal characteristic. In a similar type of work, Senjanović *et al.* (2009) investigated the hydroelastic responses of a $7800\,TEU$ container ship by coupling a beam structural model with a 3D hydrodynamic model. The analysis demonstrated reasonably good results for symmetric wave loads. However, the structural responses in way of the hatch corners were underestimated.

Riyansyah *et al.* (2010) employed the Euler-Bernoulli beam theory and boundary element method to solve the beam equation of motion and the governing equation of fluid motion, respectively, for the hydroelastic response behavior of a two floating beam system. The authors investigated the relative beam stiffness on the hydroelastic response behavior. They observed that an increase in the flexural rigidity may change the characteristics of the floating beam system. It may also change the pressure distribution along the floating beam system.

Kaydıhan *et al.* (2010) presented a hydroelasticity study investigating the response of six bulk carriers with different load carrying capacities. The ships selected for this investigation were two Handysize, one Panamax and two Capesize bulk carriers. The authors calculated dry and wet natural frequencies and associated modes as a function of the non-dimensional parameters. They also presented hydrodynamic modes, such as generalised added mass and hydrodynamic damping, as a function of wave frequency, and wave excited responses.

Tian *et al.* (2009) investigated the rigid body motions and structural responses of an $180{,}000\,dwt$ bulk carrier traveling in regular and irregular head waves. The numerical predictions were obtained by using the programs THAFTS and NTHAFTS that are based on linear and non-linear 3D hydroelasticity theories respectively. The predicted linear hydroelastic responses are illustrated, together with the investigation and discussion of the forward speed effect on the hydroelastic responses. The successive second order nonlinear hydroelastic analysis was also performed. It was shown that the springing behavior is clearly exhibited by the linear and nonlinear predictions. The influences of the forward speed effect and the nonlinear hydroelastic actions on the motions and structural loads of this large bulk carrier were quantitatively discussed.

Itamura *et al.* (2009) studied the hydroelastic vibrations including springing and whipping of an ore bulk carrier, and their influences on fatigue damage. A fully 3D time-domain method was employed to analyze the hydroelastic response. That is, shell finite elements were employed to account for the complex deformation behavior of the

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ship to predict global and local stress distributions while linear and nonlinear forces were considered with an extension of 3D potential flow theory. Springing responses in regular and short-term irregular waves were discussed by different ship speeds and wave heights.

Taghipour *et al.* (2009) presented an alternative method for hydroelastic analysis of marine structures by using state-space models. The method was applied to a very flexible barge, and the dynamic response of the barge due to regular waves as well as its transient response after release from an initial displacement was simulated. It was concluded that state-space models may replace the convolution integrals.

2.5.1 Slamming Loads

The hydrodynamic loads imposed upon the water entry of a flat plate were investigated by Iafrati and Korobkin (2008). The authors developed a 2D potential flow theory accounting for variable entry velocity. A theoretical estimate of the loads during the early stage of the water impact by the method of matched asymptotic expansions compared well against numerical predictions.

Dessi and Mariani (2008) implemented the Von-Karman theory with a water up-rise correction to calculate the sectional loads acting on the V-shaped bow of a fast-ferry. The authors considered the effects of variable water-entry speed, the presence of knuckles and the contribution of 3D terms given by the variation of ship sections by implementing a BEM. The theoretical load prediction used seakeeping experimental data as input for the calculation. The sectional loads were spatially integrated along the ship length and compared with the vertical force measured on the physical model segments in order to avoid errors on the relative body motion derived from the theoretical analysis.

Tveitnes *et al.* (2008) investigated the constant speed water-entry of wedges at different dead rise angles. The authors measured both loads and wetted length uprise during impact. They concluded that careful investigation of results in way of water entry and exit conditions may be useful for the refinement of 2D slamming load theories. In a subsequent publication, Sun and Faltinsen (2009) dealt with the 2D water entry of a bow-flare ship section with constant heel angle by means of a BEM. Non-viscous flow separation from the knuckles of the section or from the curved bottom was taken into account. The numerical calculations were compared with drop tests available in literature. It was shown that as long as the heel angle is increased, high localised pressures arise on the impacting flare area. Thus, the flow separation for large heel angles may significantly affect the pressure along the impacting bottom and its relevance seems much more related to non viscous than to viscous effects.

Lee and Park *et al.* (2010) exploited the moving particle semi-implicit method to study the effects of an incompressible violent flow over structures. The method exploits a more efficient algorithm and is used for solving various highly nonlinear free-surface problems, to evaluate the slamming loads on rigid plates with various incident angles. It was shown that without using the Eulerian approach or the grid system, the convection terms and time derivatives in the Navier–Stokes equations can be calculated more directly without any numerical diffusion, instabilities or topological failure. The method also allows for the derivation of numerical results that are in good agreement with available experimental data.

Greco *et al.* (2010a, 2010b) analysed the problem of bottom slamming for very large floating structures using 2D potential flow theory without and with coupling between

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the global behaviour of the platform and local actions. Whereas a linear solver was adopted to investigate the global behaviour, a nonlinear approach was implemented to predict locally the slamming forces. For large platform motions an iterative time-decomposition strategy was developed to examine the resulting coupling. The effect of air entrapment was taken into account along with a detailed description of pressure and stresses on the platform bottom using beam theory to model the equivalent floating structure.

Korobkin (2011) discussed a refinement of the well-known generalized Wagner model to improve the hydrodynamic forces measured on 2D impacting bodies. Wagner models provide higher accuracy with respect to other semi-analytical methods (e.g. modified Logvinovich Model) as they are able to predict better the pressures on the body contour. However, they fail to integrate correctly the pressure distribution due to lack of adequate numerical treatment. To avoid this drawback, Korobkin (2011) employed rigorous analytical calculations by separating the singular components of both the flow velocity and the pressure. By reducing the original problem to two non-linear integral equations, where one of them serves to evaluate the conformal mapping and the second one to compute the position of the contact point, improved prediction of the pressure and hydrodynamic forces was achieved.

Another interesting application of Wagner's water impact theory was provided by Qin and Batra (2009). They investigated the local slamming problem of a deformable sandwich wedge by taking into account hydroelasticity effects. The novelty of their work resides upon the use of a sandwich panel theory, that incorporates the transverse deformations of the core, with the Kirchhoff plate theory for modelling of the face sheets. A numerical procedure to solve the nonlinear system of governing equations, from which both the fluid load and the structure deformations can be simultaneously computed, has been developed and verified. The hydroelastic effect on the hull deformations appears to be noticeable and the core shows to absorb a considerable part of the strain energy due to transverse shear deformation implying that the core can be effectively used for slamming impact alleviation.

Maki *et al.* (2011) highlighted the need to develop a practical tool for the computation of slamming loads. Taking advantage of the method developed by Paik *et al.* (2009) the authors recommended using an one-way coupling method to model fluid structure interactions. Accordingly, the open source CFD solver OpenFOAM and the dynamic finite element method were employed and the exchange of numerical data was facilitated by a grid matching algorithm. The fluid-dynamic simulation was carried out on a rigid body in the time domain and the modal equations of motion were numerically integrated to yield the structural response in time. Acoustic elements were used to account for the added mass due to flexible modes. The procedure allowed solving the impact of a rigid and an elastic wedge. Hanbing Luo *et al.* (2011a,b) studied the hydroelastic responses of complex stiffened panels. A steel wedge with complex stiffened panels was designed with a dead rise angle of 22° and a series free-drop model tests were carried out. The explicit FEA commercial algorithm LS-DYNA was used to simulate this coupled hydroelastic impact problem. Comparisons of the numerical and the experimental results have shown generally good agreement on the acceleration and stress responses. However, more research is required to understand the influence of high frequency oscillations on the measured accelerations and the local hydroelastic effects.

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2.5.2 Experimental Hydroelasticity

Over the last three years two major international Joint Industry Projects (JIPs) concentrated on the validation of the effects of springing and whipping on Container Ship Structures. In the first one Classification Societies, CeSOS and MARINTEK carried out model tests with the ultimate aim to investigate how wave induced vibrations affect the fatigue and extreme loading at different cross sections (Storhaug *et al.*, 2010a, and Storhaug *et al.*, 2010b). The second international project namely WILS currently enters its third phase; it is led by the Korean industry (KORDI and Korean Shipyards) and is supported by all major Classification Societies (Kim *et al.*, 2010, Lee *et al.*, 2011a,b). To date the main conclusions of both JIPs can be summarised as follows:

- With regards to the impact of the wave-induced vibrations on structural design, the tank test results seem consistent with each other to the point that the fatigue damage is increased due to the wave-induced vibration when the fatigue damage is estimated by using the Rainflow counting method and the Palmgren-Miner's rule. However, the validity of the fatigue damage estimation method for the combined load is yet to be confirmed against fatigue tests under combined high-frequency and low-frequency loads that may be used to clarify the effects of wave-induced vibrations on fatigue damage;
- The scaled model techniques for the wave-induced vibrations of hull girder in torsional mode have been developing and there is still space for improvement. Scaled models need to have similarities in modal shapes as well as the natural frequencies. The consideration of the position of the shear centre, which is normally located lower than the keel, and measurement methods of the torsional moments seem to be some of the directions where fundamental understanding needs to improve;
- Numerical simulation methods need to be validated in further against tank tests and full scale measurements until they become an established tool for predicting the wave-induced vibrations of a ship's hull girder;
- Slamming impacts seem to be a source of large uncertainty.

Drummen *et al.* (2009) presented an experimental and numerical study of the responses of a container ship in severe head seas. In this work it was demonstrated that hull flexibility could increase the vertical bending moment by up to 35 %. Comparisons of experimental bending moments against nonlinear hydroelastic strip theories provided reasonably good agreement. Kim *et al.* (2009b) (see Kim, 2009a,b,c) investigated the responses of a floating and flexible barge. The experimental measurements were carried out in different wave heading angles, from head waves to beam waves with angle increments of 30 degrees. different irregular waves were generated based on the JONSWAP spectrum with different significant wave heights and wave periods. Resonses were obtained by processing the irregular motion time history using Fourier analysis.

Coppotelli *et al.* (2008) determined the operational vibration modes of an elastically scaled ship using the frequency domain decomposition method. By exploiting the ambient mode excitation in head waves they have determined the mode shapes as well as the associated frequencies and damping. In furthering this work, Dessi *et al.* (2009) presented the preliminary results relative to the correlation of model scale and full scale tests, for determining the bending response of a naval vessel in waves. The tests were carried out at the INSEAN towing tank with a segmented-hull elastic model

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scaling the mass, sectional moment of inertia and shear area. The vertical bending moments measured on board the ship during the full scale trials were compared with those determined with the segmented-hull tests and with the simulations using 2D and 3D FEA models of the ship structure.

Dessi *et al.* (2010) also explored the bow and stern slamming events experienced by a cruise ship comprising of five-segments. The authors demonstrated that slamming intensity occurring in way ot the ship stern in following wave conditions may be potentially larger than the one relative to the bow in head waves. The response level was evaluated as the time average of the envelope of the high-pass filtered bending moment, obtained experimentally from the strain-gages for different sea states, wave directions and forward speeds. The mean bending moment was then related to the number of impacts per minute and to the impact severity. Some global trends between the observed variables were identified and were found to be similar to those determined for other ship types. More recently, the underlying requirement of broad-band excitation has been clarified by Dessi (2011). The author applied the proper orthogonal decomposition under the same hypothesis to determine not only the modal shapes of the same physical model but also the energy associated to each identified mode in the response. This method is based on the construction of a correlation matrix among the measured degrees of freedom with accelerometers or strain-gages. It allows for deciding how many wet modes may be required to perform simulations in certain conditions (e.g. forward speed and sea-state).

Iijima *et al.* (2009) developed a scaled model design technique to tune the natural frequencies in torsional mode as well as vertical and horizontal bending modes. A backbone beam approach with several cut-outs was shown to be effective in giving an appropriate torsional stiffness as well as vertical and horizontal bending stiffness by selecting the configuration of the cut-outs. The natural frequency was measured in wet conditions. Vertical and horizontal bending and torsion moments were also measured by using longitudinal and shear strains calibrated prior to the tank tests. By using this scaled model, the hydroelastic vibrations in torsion as well as vertical bending in head/oblique seas were measured. Springing response to linear/nonlinear loads and whipping response to slamming impacts in both vertical bending and torsion were reported.

Oka *et al.* (2009) carried out a series of tank tests in regular and irregular waves using a segmented model for a large container ship, with backbone. It was verified that estimated torsional moment by means of FEA was strongly consistent with measured torsional moments. Ship motions, accelerations, wave-induced bending moments and torsional moments were measured in various seakeeping conditions. The relation of wave loads of a large container ship with respect to waves and ship speed was examined. Derbanne *et al.* (2010) reported on the springing measurements of a flexible large container ship. The model was made of 12 segments attached to a squared section steel rod with total length of $4.42\,m$. The steel rod was located just under the baseline of the ship in order to have the centre of torsion as low as possible. The tests were run without forward speed, in regular head and oblique conditions. Linear springing response in torsional mode and coupled resonance of the horizontal bending were found to be strongly coupled.

Stenius *et al.* (2011) considered the hydroelastic interaction involved in panel-water impacts for a high speed craft. Hydroelastic panel-water impacts were simulated by using the FEM code LS DYNA and a simplified in-house developed method. It was shown that hydroelastic effects can both increase and reduce the panel responses

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depending on the impact envelope considered. Thomas *et al.* (2011) studied the slam events experienced by high-speed catamarans with a segmented model capable to measure the whipping induced load responses in way of the centre bow. Wet-deck slamming events were identified by analysing the load time-history provided by strain-gages and their intensity was related to the relative vertical motion (immersion and velocity) at the same section. As expected, the slam intensity showed a tendency to increase as long as the deck impact velocity became higher. The experiments also highlighted an evident dependency of the slam location on the forward speed.

2.5.3 Full Scale Measurements

Within the reporting period the work published on full-scale measurements of ocean going ships has clearly shown that wave induced stress components may vary in way of the two node hull girder frequency e.g. Okada *et al.* (2006), Miyahara *et al.* (2006), Heggelund *et al.* (2010), Ito *et al.* (2010), Hirdaris *et al.* (2009). These stress components show both transient (whipping) and more continuous (springing) variations.

For example, Hirdaris *et al.* (2009) presented a summary of an investigation into the effects of hull flexibility when deriving an equivalent service factor for a single passage of a Great Lakes Bulk Carrier from the Canadian Great Lakes to China. It was shown that the long term wave induced bending moment predicted using traditional 3D rigid body hydrodynamic methods is augmented due to the effects of springing and whipping by including allowances based on two-dimensional hydroelasticity predictions across a range of headings and sea states. The analysis results were correlated with full scale measurements that are available for this ship. The combined effects of springing and whipping responses on the wave-induced VBM results were predicted to enhance the design VBM and the service factors by up to 37.7 %. This prediction, although conservative, was considered necessary to ensure a suitable design margin for the possible sea states that might be expected. Comparisons against full-scale measurement data also showed that achieving good agreement between predictions and measurements, both for ship-wave matching and springing, depend on the parameters of the wave spectra as well as the estimation of structural damping for the latter and any uncertainties involved in measuring such data.

Miyake *et al.* (2010) presented the whipping measurement results of an ultra large 12,000 TEU container ship both in regular and irregular seas. The authors reported on the relationship between the maximum vertical bending moment amidships and the wave amplitude for various combinations of wave/ship length ratio in regular head seas. The non-dimensionalised hogging moments were almost constant and equivalent to the first harmonics of the hogging moments in small wave amplitude. However, the non-dimensionalised sagging moments increased with the increase of the wave amplitude. Discrepancies in sagging and hogging moments were also observed in irregular seas with differences more prominent for the values whose exceedance probability is lower.

Drummen *et al.* (2009) demonstrated that hull flexibility can increase the vertical bending moment by up to 35 % in sea states relevant for design. They also compared measurements and calculations of high frequency induced stress components and have shown that their developed hydroelastic model slightly over-predicts the increase of the bending moments due to hull flexibility.

Jensen *et al.* (2009) and Pedersen and Jensen (2009) have described a simplified calculation procedure for the probability distribution of the combined wave and whipping induced stresses. Reasonable agreements with full-scale measurements have been achievable provided that the pertinent parameters related to the estimation of the

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impulse slamming loads are chosen with care. More detailed procedures based on the solution of nonlinear hydrodynamic strip theory formulations coupled with a Timoshenko beam model of the hull girder have been presented in Iijima *et al.* (2008), Drummen *et al.* (2009), Wang *et al.* (2009) and Vidic-Perunovic (2010).

2.5.4 Specialist Structures

Santos *et al.* (2009a,b) studied the symmetric response of a fast patrol boat using unified hydroelasticity analysis. 2D and 3D idealisations were adopted to predict the structural response behavior. The fluid-structure interaction effects were calculated using 3D potential flow analysis in a variety of seakeeping conditions. This work demonstrated the inherent limitations of the applicability of beam idealisations to vessels with a small length/beam ratio using either the Prohl-Myklestad methodology or an FEA model. It was concluded that structural discontinuities (e.g. deck openings) and the long superstructure that is not aligned with the ship's sides are additional factors affecting the applicability of 2D hydroelastic models.

Ikoma *et al.* (2009), and Van Kessel and Huijsmans (2009) studied the hydroelastic response behavior of aircushion supported structures in waves. In the former study, the motion reduction effect of aircushion was confirmed from theoretical calculations with zero draft assumption. In the latter one, a new method that takes into account the fluid-air-structure interaction of aircushion supported structures in waves was derived.

Damaren (2010) examined the hydroelastic properties of the vibration modes of a thin plate floating on the surface of an incompressible, inviscid, irrotational ocean of infinite extent. The results demonstrated that the modes of the plate of optimised shape exhibit large damping coefficients. Van Kessel (2010) presented the results for validation of a new hydroelastic code for flexible floating structures moored in waves. Numerical results were validated by model experiments of a flexible barge in waves from different headings. In addition, the obtained results were compared with results from other existing hydroelastic programs. In general it is shown that numerical results show good agreement with experimental values.

Milgram (2007) addressed the importance of evaluating the unsteady forces and moments on an underwater vehicle in finite-depth water, at small enough submergences for it to be influenced by sea waves. This study has employed strip theory, including the effects of finite depth and lift forces on fins to predict the unsteady seakeeping forces on streamlined underwater vehicles close to the surface. Comparisons with experiments have shown errors within the range of application of strip theory to ships.

Can and Ergin (2010) presented experimental data and theoretical calculations on the dynamic response behavior of a flexible submarine pressure hull model vibrating in air and water. Different representative to submarine hull aspect ratios were selected. Jagadeesh *et al.* (2011) presented a towing tank-based experimental study on forces and moments on Autonomous Underwater Vehicle (AUV) hull forms in the vertical plane. A five component force balance was used to measure the variation of axial, normal, drag, lift and pitching moment coefficients. The obtained results point out a relevant sensitivity on the parameters, especially for axial and normal force coefficients. As in a previous paper by Sulin *et al.* (2009) the authors used CFD tools (ANSYS-Fluent) to estimate the hydrodynamic coefficients of AUVs. However, the complex shape of the body under investigation provided a more challenging case. Because of the block-like structure of this underwater vehicle, the relationships between the hydrodynamic loads and the translational and rotational velocity of the vehicle are nonlinear. Although comparison against experiments appeared encouraging, the simplifying assumptions

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employed to carry out the simulation and the successive interpretation of the results, were not as straightforward as in the case of streamlined bodies. Saout and Ananthakrishnan (2011) proposed a theoretical methodology to determine the open-loop directional stability of a near-surface AUV. They used an approach similar to that carried out for surface ships that is based on solving the coupled sway and yaw equations of motion. The stability derivatives were obtained numerically through simulation of motions corresponding to planar motion mechanism model tests. For the numerical simulation, a boundary-integral method based on the mixed Lagrangian–Eulerian formulation was developed. The presence of the free surface, through radiation damping, was found to suppress unsteady oscillations and thereby to enhance the directional stability of the vehicle. The shape optimisation of an AUV required to operate at snorkelling condition close to the free surface, where torpedo-like shapes present some drawbacks, was studied by Alvarez *et al.* (2009). They dealt with this problem using a first-order Rankine panel method to compute the wave resistance on different axial-symmetric bodies moving close to the free surface, constrained to have the same overall volume. The optimised shape exhibited experimentally a smaller resistance than the reference one.

3 SHIP STRUCTURES – SPECIALIST TOPICS

3.1 Loads Versus Operational Guidance

Many new-build ships have extensive data collection systems that are used for continuous monitoring of engine and hull performance, for voyage performance and evaluation, etc. Often, such systems are, or could be, expanded to include also procedures for stress monitoring and for operational guidance, where statistics of the most critical wave-induced ship extreme responses and fatigue damage accumulation can be estimated for hypothetical changes in ship course and speed. The focus on goal-based standards (Papanikolaou *et al.*, 2010, Papanikolaou (Ed.), 2009, Skjong and Guedes Soares, 2008) implies that future developments of operator guidance systems should be based on numerical models that introduce probabilistic and risk-based approaches. Further remarks and discussions about risk-based methods for operational guidance have also been outlined by Shigunov *et al.* (2010), Bitner-Gregersen and Skjong (2009) and Nielsen *et al.* (2009).

The current state of the art in operational guidance typically relies upon mathematical models in which the on-site wave environment is automatically estimated. Ongoing developments in EU FP7 WATERBORNE project Handling Waves (2011) are driven by the development of systems that could be used for monitoring in real time the actual ship responses and associated structural loads due to weather changes and to possible changes in course or speed. The research programme supports the notion that the calibration of load predictions and the development of simplified numerical models that are accurate and fast is necessary in order to ensure that information and guidance are given with sufficient time to the ship's master. This is, for example, in further investigated and demonstrated in the work by Nielsen *et al.* (2009) and Nielsen (2010). In these investigations the horizontal acceleration and the racking failure mode of containers stowed on ships in heavy weather are studied. A procedure which can be used to obtain up-crossing rates for an inherent nonlinear ship response, such as the racking force in containers, is derived. It is also shown that first and second order reliability based formulations (FORM/SORM) and associated procedures may be significantly faster than more crude simulations (e.g. Monte Carlo). The motion simulation of container stacks on deck is considered also by Wolf and Rathje (2009).

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The authors deal with a (refined) numerical model from which knowledge about the dynamic forces acting on container stacks can be attained. The numerical findings and results of this work could be useful for establishing decision support criteria with respect to container and lashing loads. Considerations of computational efficiency in relation to calculation of fatigue damage rates in the ship hull girder and operator guidance have been presented by Ito *et al.* (2010) and Nielsen *et al.* (2011).

Typically, the underlying approach for operational guidance builds on a pure mathematical model, where the seakeeping characteristics of a ship, often given in terms of response amplitude operators (RAOs), are combined with information about the on-site sea state using linear spectral analysis to make statistical predictions of future responses to be expected. However, the on-site estimation of sea state parameters at the location of an advancing ship forms a crucial and fundamental problem to which a perfect solution has not been established. For this reason, concepts of a novel procedure for operational guidance have been proposed by Nielsen and Stredulinsky (2010) and Nielsen and Jensen (2011). The purpose of the procedure presented is to increase the reliability of the given guidance. Thus, predictions of future response levels are based on an integrated model using a mathematical model that has as input the estimated sea state parameters, and using also past measurements of the considered response(s). Both works include an analysis of full-scale motion measurements and the approach shows promising results.

3.2 Ice Loads

Environmental changes, harsher winters in the area of Baltic Sea and climate changes in other Arctic and Sub-arctic zones create new challenges for further exploration of Northern Regions including demands for more and environmentally safer ice-strengthened vessels. The following discussion reviews some key publications in the area of ice loading on ships and offshore structures that have been presented over the reporting period.

Bekker *et al.* (2009) described some of the characteristics of the drifting of ice cover and the associated scenarios of ice loads. Their study looks into the mathematical simulation of the physical process of interaction between the ice cover and the offshore engineering objects at Sakhalin offshore zone in terms of simulation and statistical methods. By taking into account the dynamics of an ice cover in the Sea of Okhotsk, the authors simulate various design cases of combined effects on marine structures from drifting ice features and ice fields. In a more recent study, Bekker *et al.* (2011) explored the results derived from a statistical modelling of ice loads on the ice-resistant platforms in Piltun-Astohsky and Lunsky oil and gas fields. The authors made a comparative analysis of ice loads on various types of gravity-based concrete structures according to the standards, procedures and guidelines imposed by different design codes. Comparative analysis of ice loads from level ice fields and from ridges show a wide range of load prediction variations. It is suggested that this scatter is caused by the various approaches and models for load estimation. Comparisons of the existing codes demonstrated that it is necessary to carry out long-term experimental and theoretical investigations including full-scale measurements on existing offshore structures.

Bjerkås *et al.* (2009) presented a case study employing direct simulation and empirical methods on the lighthouse Norströmsgrund in the Gulf of Bothnia. In this study design ice loads have been compared to existing code recommendations. It was concluded that the lighthouse was designed for a load level of 110 % higher than what is proposed

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by the recently issued ISO 19906 (2011) design code. Hence, it was suggested that separate dynamic analyses should be performed instead of simply adding amplification factors which is common practice in the prediction of static loads. On the other hand, Gürtner *et al.* (2009) simulated ice actions by means of a finite element model. In their approach fracture of the ice sheet was accounted for by the cohesive elements placed at internal FEA mesh boundaries in order to track traction versus separation forces. The simulation results indicated that the proposed numerical method derives comparable global ice loads to the lighthouse to those of the selected ice event.

Comparisons against the ISO 19906 (2011) standard for offshore installations are also provided by Masterson and Tibbo (2011). Their work looks into the determination of ice loads due to crushing on vertical structures and for bending loads on sloping structures. It is concluded that load calculations based on large scale measurements are preferable and more reliable than those made using small scale data which are then factored for full scale applications. It is also recommended that ISO 19906 could be the preferred guideline for determining loads on offshore structures placed in ice covered waters. Jordaan *et al.* (2011) presented a probabilistic load prediction model of the ice environment in the northeast Caspian Sea. Once again the methodology is consistent with approaches outlined in ISO 19906. The software used for the analysis included modules for season length, ice thickness and movement events, as well as ice crushing strength for vertical structures and models for flexural failure including rubble formation on sloping structures. A Monte Carlo approach has been used to simulate ice-structure interaction events on an annual basis. As a result a distribution of annual maximum forces from which n-year design loads can be extracted has been arrived.

Murray *et al.* (2009) reported the results from 1:30 and 1:50 model scale ice tests for the prediction of loads of an ice resistant spar design. They compared mooring and ice loads measured in fixed and compliant conditions. A limited number of tests were carried out at the two model scales in the same ice conditions to investigate scaling effects. The study indicated that the model scale testing methodologies employed, assuming the structure is fixed, provide good estimates.

Frederking (2010) described field data from operations of the CCGS Louis S. St-Laurent during a period of icebreaking escort operations in the Gulf of St. Lawrence in March 1985. The bow of the ship was strain gauged to measure ice impact loads. Forces, operational conditions (ship speed and power), and ice conditions (ice concentration, ice thickness and floe size) were recorded. From these data, time series of measured loads were used to obtain the maximum force of each measured impact, as well as the impulse associated with it.

Su *et al.* (2010) introduced a numerical method to simulate ship maneuvers and associated loads in level ice. The coupling between continuous ice forces and ship motions has been considered and the three degree-of-freedom rigid body equations of surge, sway and yaw have been solved by numerical integration. The numerical analysis results have been validated via comparison with the ship performance data from the ice trails of icebreaker AHTS/IB Tor Viking II. More recently, Su *et al.* (2011) derived an ice loading prediction process that has a clear stochastic nature due to the variations in the ice conditions and in the ice breaking processes of ships. The statistical characteristics of local ice loads were studied by field measurements. A numerical method was applied to simulate a ship moving forward in either uniform or randomly varying ice conditions where the thickness and strength properties of the ice encountered by the ship were assumed to be constant or randomly generated using the Monte Carlo

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method. To validate the numerical results, an icebreaking tanker, MT Uikku, has been modelled and the ice loading process was stochastically reproduced. The calculated amplitude values of the ice-induced frame loads were compared against the field measurements.

Haase *et al.* (2010) reported on the interaction between a conical structure and unconsolidated ice rubble that was simulated by a 3D discrete element simulation method. The failure process of the simulated ridge keels was studied by observing the rubble displacement during the simulation run. The simulation results were compared to full scale data and to results from an analytical ridge load model for cones.

Wang *et al.* (2011) described the development of a procedure for determining design ice loads on Arctic offshore structures using a first order reliability method (FORM) incorporating the uncertainties in the underlying ice floe and environmental parameters. In this work level ice and ice ridges were considered as major load sources interacting with the offshore structure in the ice regime. The geometric parameters of ice floes were assumed as random variables in the probabilistic approach. Specific site data were then used to demonstrate the results which are comparable to Monte Carlo simulations. It is concluded that the FORM approach is computationally economic and becomes increasingly accurate for rarer events.

Määttänen *et al.* (2011) reported on near full-scale ice crushing tests that were conducted in Aker Arctic test basin. An 1:3 scale ratio test rig was designed to allow ice to be crushed in controlled conditions against a stiffened plate presenting a typical full size ship or offshore structure plating. It was shown that contrary to expectations the plate compliance played no role in crushing pressure distribution. This differs from what is assumed in some ice rules, where the highest pressure is idealised at the location of stiffeners. The results also indicated that the ice crushing pressure in the design of plating thickness should be constant regardless of stiffeners.

Wille *et al.* (2011) presented a numerical model for drifting level ice interacting with a moored downward conical structure. The goal of this development has been to get better insight into the key processes that are important for the interaction process between moving ice and a floating structure. The level ice was modelled as a moving Euler-Bernoulli beam, whereas the moored offshore structure was modelled as a damped mass-spring system. It was concluded that the motions of the moored floating structure do not significantly influence the bending failure process of level ice. Also the influence of the in-plane deformation and the heterogeneity of ice on the bending failure process were found to be negligible. As a consequence, the dynamic response of the structure has been for the biggest part, determined by the ice failure process. Although the response of the structure can be dynamically amplified due to resonance for some particular ice velocities, no frequency locking of the ice failure onto one of the natural frequencies of the structure was observed. The model output showed qualitative agreement with model test results. It was however concluded that beamlike models of level ice sheets cannot accurately predict loading frequencies on downward conical moored floating structures because the ice blocks that break off are too long. Modelling level ice in two dimensions using plate may give better results, since it takes into account the curvature of a structure and both radial and circumferential ice failure.

3.3 Loads on Damaged Ship Structures

The principal difference between wave load effects employed for intact and damaged ships is driven by environmental conditions and exposure times after damage. While

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for intact ships the North Atlantic wave environment is usually adopted, local scatter diagrams are proposed, as applicable, for the reliability assessment of damaged ships (e.g. Luis *et al.,* 2009). Reduced exposure time to environmental conditions after damage should also be considered before salvage to a safe location. For example, Teixeira and Guedes Soares (2010) proposed a time period of one week as the voyage duration of a damaged ship to the dry-dock. They concluded that the mean extreme VBM of a Suezmax tanker is about 15 % lower when the exposure time is reduced from one year in the North Atlantic to one week in European coastal areas.

The magnitude of the loads on damaged ships is also subject to the extend and overall location of the damage. For example, Folso *et al.* (2008) and Rizzuto *et al.* (2010) have performed seakeeping computations on a damaged ship by the 3D linear hydrodynamic code PRECAL. For the case of the flooded ballast tank amidships, they obtained RAOs of the VBM worse than those evaluated in intact conditions. The correlation between sea states and occurrence of the accident is partly addressed in accordance to the IACS North Atlantic scatter diagram ($H_S \geq 7.5\,m$). The authors concluded that the VBM of the damaged ship reduces by 19 % of its mean extreme value when the vessel is exposed for one day in a truncated North Atlantic wave environment.

Hearn *et al.* (2008) also presented a study on the hydrodynamic and dynamic motion analysis of a damaged ship. In this work damaged ship statistics were used to provide the likely damage scenarios and particular emphasis was attributed on modelling the effects of water ingress when hydrodynamic and hydrostatic influences of the internal free surfaces as well as the aerostatic influences of the air contained within the damaged hold are accounted for. The change of the mean position of the internal surface as a consequence of the relative phasing of the motions of the ship and the internal free surfaces was also modelled.

Zaraphonitis and Samuelides (2009) addressed the loading induced on grounded hulls of bulk carriers. The determination of the loading included the influence of dynamic effects and the interaction of the hull with the sea bed in the grounding area.

An experiment on forced oscillation of a damaged ship section was presented by Drake *et al.* (2009). The authors simulated a damage of the keel by a longitudinal orifice. Various widths of orifice were investigated, with the damaged hull form in two configurations, open and airtight (to investigate the effect of trapped air stiffness). The hull was forced to oscillate for a range of amplitudes and frequencies and measurements of hydrodynamic force and internal free surface elevation are discussed.

Recently, Lee and Chan *et al.* (2011) developed a computational tool for the prediction of hydrodynamic loads of damaged ships. The results of the theoretical method and experimental tests were compared over a variety of design conditions. Whereas for the loads in intact condition, the prediction with a duration of 20 years at sea state 5 was used, for loads in damaged conditions, the prediction with 96 hours of exposure time at sea state 3 was employed. It was concluded that the maximum values of the most probable extreme amplitudes of dynamic wave-induced loads in damaged conditions are much less than those in intact condition because of the reduced time. An opening could change the distribution of not only still-water bending moment but also wave-induced bending moment. It is also observed that although some cross-sections are not structurally damaged, the total loads acting on these cross-sections after damage may be dramatically increased compared with the original design load in the intact condition.

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3.3.1 Still Water Loads of Damaged Ships

A review of stochastic models of still water bending moments applicable for damaged ships has been presented by Teixeira and Guedes Soares (2010). The simplest way to take into account consequences of the damage is to modify the still water load combination coefficient. Luis *et al.* (2009) proposed values of 1.1 and 1.5 to analyse the impact of the increased still water loads on the reliability of a grounded oil tanker. In most cases, flooding of ballast compartments in midship area is critical for double hull tankers, as this causes increase of sagging moments. Hussein and Guedes Soares (2009) calculated the effect of the flooding of ballast compartments of a double hull tanker and found increases of 30 % and 46 % for one side and both side damages respectively. Rizzuto *et al.* (2010) calculated asymmetrical flooding of the midship ballast tank on one side only of the Suezmax tanker. The still water bending moment corresponds to 152 % of the intact value for the same loading condition. They proposed to use coefficient of variation in reliability assessment of damaged ship slightly higher than for the intact ship. This is explained by additional effect in damaged conditions seen in water inflow and outflow through the damaged hull that is not accounted either in static or wave load analysis.

Santos and Guedes Soares (2008b) presented a time-domain theoretical model capable of predicting the behaviour of a damaged ship subject to progressive flooding in still water conditions. Their approach provides information in each stage of flooding, concerning the ship motions, the amount of water in each flooded compartment and shear forces and bending moments acting along the ship's length. Applications on a passenger Ro-Ro ship and a tanker led to the conclusions on the time required to reach the most critical conditions and the increase in global loads in damage condition. They also demonstrated that during the intermediate stages of flooding, floodwater distributions can be generated. Those may cause significantly higher shear forces or bending moments than the ones present in the final equilibrium damage condition.

3.3.2 Structural Integrity and Stability of Ships

Whereas computational methodologies and regulatory developments provide improved means for the assessment of the damage stability of ships in waves, there is still a long way to go before a variety of open issues, including combined loading and dynamic response matters, are fully satisfactorily addressed.

Papanikolaou (2007) reviewed the recent scientific and regulatory developments on the damage stability of ships and identified trends on the way ahead. Developments of numerical simulation methods for the prediction of damaged ship motions and associated loads in waves were discussed on the basis of related ITTC benchmark studies and the most significant open issues for further research were briefly addressed. In a more recent paper Papanikolaou *et al.* (2010) discussed the new probabilistic damaged stability regulations for dry cargo and passenger ships (SOLAS 2009), which entered into force on 1st of January 2009. Whereas these regulations represent a major step forward in achieving an improved safety standard through the rationalisation and harmonisation of damaged stability requirements there are serious concerns regarding the adopted formulation for the calculation of the survival probability of passenger ships, particularly for ROPAX and large cruise vessels. In Papanikolaou *et al.* (2011), the most recent progress of the work under the EU FP7 project GOALDS (Goal Based Damaged Stability, 2009-2012) is outlined. A thorough analysis and review of collected data of most recent grounding statistics of damages resulted to important new knowledge regarding the location and extent of grounding damages, both for passenger and

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cargo ships. A review of updated data of collisions damages, in which most recent ship damages were included, led to a confirmation of the validity of the currently used probabilistic modelling of collision damages for passenger ships, as considered in SOLAS 2009. Following the 1st international benchmark study of the 24th ITTC Specialist Committee on Stability in Waves (Spanos and Papanikolaou 2004), a 2nd international benchmark study on the performance of computer codes for the assessment of the stability of the damaged ships in waves was presented by Papanikolaou *et al.* (2008) under the work of the EU funded project SAFEDOR. Comparison of benchmark codes led to the conclusion that whereas the performance of standard computer codes remains unchanged the divergence of the numerical predictions for the damaged survivability of ships in waves is notable.

Santos and Guedes Soares (2008a) presented an application of shallow water theory to describe the motion of floodwater inside a damaged rolling ship in waves. A time domain hydrodynamic approach was applied to study the behaviour of a passenger Ro–Ro ship in regular beam seas and the characteristics of the floodwater motion were studied for a number of different wave frequencies. The dynamic floodwater roll moment was also compared against the static roll moment. The effects of parametric variations of different factors in the ship's survivability were addressed in a consecutive publication by Santos and Guedes Soares (2009). Numerical results were presented for a passenger Ro–Ro ship under a damage condition involving the main engine room. The permeability of this compartment was taken in consideration by modelling the engines as intact blocks. The ship's survivability in irregular waves has been assessed with respect to: the vertical location of the centre of gravity, the spectral description of the seaway, the roll damping factor and discharge coefficients, the depth to main deck, the double-hull in the main deck and the initial heel angle.

A **H**olistic **A**ssessment of Ship **S**urvivability **a**nd **R**isk after **D**amage was studied in the project EU project HASARD (SURSHIP, 2011). A comprehensive calculation procedure useful for quantitative assessment of damaged ships survivability (incorporating structural collision resistance, structural stability and collapse, time simulation of ship flooding and stability in waves) was developed. Results from systematic simulations through this calculation procedure (risk assessment/FSA) could be used in recommendations for future IMO rule making. Results of this project were published by Schreuder *et al.* (2010), following an interdisciplinary calculation procedure encapsulating the chain of events of ship collision, flooding, and loss of stability within given time. The presented method concerned the interaction between structural and damage stability computations and has been used to study the influence of various parameters such as the significant wave height and size of damage opening on a RoPax-ferry damaged in a collision with a ship of similar size.

The time dependent survivability of Ro-Pax vessels was also investigated by Spanos *et al.* (2010) by use of numerical simulations of ship motion and of flooding in waves. The study re-confirmed that a Ro-Pax ship may capsize fast when sustaining damages. The time dependent survivability may be estimated by applying a Monte Carlo probability simulation but may be limited within short times after the damage event.

Simonsen *et al.* (2009) presented the analyses and results of a study aiming at developing damage stability requirements which take into account the structural vulnerability to grounding damage, i.e. the kinetic energy available to generate damage and the structural resistance. The paper presents the analysis of new damage statistics in order to determine impact scenarios, in particular in terms of impact speed, impact location, and width and height of damage. A new empirical damage prediction formula

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was developed based on a combination of full-scale testing and extensive non-linear finite element analyses. This deterministic prediction method was validated against grounding experiments and then used in a probabilistic (Monte Carlo) simulation framework. It was concluded that the grounding damage statistics for all ships can be characterised by a single parameter namely the Grounding Damage Index (GDI) which includes the ship kinetic energy and its structural resistance to grounding damage. Simple, closed-form expressions were developed for the GDI and it was shown how the probability of exceeding a box-shaped damage is a simple function of the GDI and the size of the box. The paper therefore gives the background and the results for a new generation of damage stability rules where the structural crashworthiness is taken into account and where the passive safety level is explicitly expressed. It furthermore gives simplified prediction tools and data for actual ships, i.e. a toolbox that is readily available for risk analysis regarding grounding damage.

Kvon *et al.* (2010) addressed the coupled problem of loss of stability and structural integrity due to progressive flooding and structural failure by linear elastic fracture mechanics and the ‘Paris Law’ (Paris and Erdogan, 1963) crack propagation assessment methods. The authors considered the impact of wave induced loads on the deterioration of damaged ship strength. They applied adopted methods to the analysis of a sample ship mid-ship section sustaining collision or grounding damages and found both methods promising for concluding on the deterioration and the ultimate ship’s strength after damage.

3.4 Green water

Shipping of green water occurs when the deck of the ship or a floating structure is immersed in the water. The green water constitutes in a certain sense a counterpart of the slamming problem provided that the water column impinges the structure from above. However, since the green water problem shares with sloshing similar flow features the computational approaches are in closer relationship with those applied to sloshing than to slamming phenomena. Within the reporting period research efforts concentrated on defining new methods that combine the straightforward calculation of pressure and loads of the techniques based on mesh definition (like FEM or BEM) with the interesting property of mesh-less methods, like SPH, that do not suffer large domain deformations or fragmentation.

Le Touzé *et al.* (2010) applied the SPH method to predict the fluid behaviour for two different dynamic flooding scenarios. The first is the interaction between a vessel and travelling waves. The second is the transient flooding behaviour that occurs during and immediately after a side collision between two vessels. Water heights were measured close to the point of impact within the vessel. Shibata *et al.* (2009) have proposed an incompressible variant of the SPH method known as moving particle semi-implicit method (MPS). In this paper, they compared the estimated pressure with the experiments of Tanizawa *et al.*, where the ship is towed in head waves. The investigation has shown that there is still some lack of agreement in terms of both pressure and forces acting on the deck due to relevant oscillations in time.

Chen and Kai (2009) developed a level set numerical method for the simulation of violent flows. In their approach Navier-Stokes equations were coupled with an interface preserving technique for the simulation of green water effects. Accordingly, the free surface flows were modelled as two phase (air/water) flows and represented by the zero level set function. Large eddy simulation (LES) and Smagorinsky models were employed to account for the effects of turbulence introduced by the violent free surface

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motions. The technique was employed for the simulation of slamming on a hemisphere and wet deck slamming of an X-Craft. Numerical results indicated that such an approach is able to deal with violent flows involving breaking waves, water droplets, trapped air bubbles and wave current interactions.

Zhu *et al.* (2009) developed a numerical program to model green water occurrence on floating structures based on a commercial CFD code. In their work a combination of numerical programmes is presented in which the motions of an FPSO are calculated by potential theory and CFD tools are used to investigate the details of green water impacts. A technique of dynamic mesh has been introduced in a numerical wave tank to simulate the green water occurrence on the oscillating vessels in waves.

Colicchio *et al.* (2010) proposed a 3D domain-decomposition strategy where a linear potential-flow seakeeping analysis of the vessel was coupled with a local nonlinear rotational-flow investigation. The Navier-Stokes solver was applied in the region close to the ship bow.

Lu and Yang *et al.* (2010) developed a numerical time domain simulation model to study green water phenomena and the impact loading on structures. A Volume of Fluid (VOF) technique was used to capture the violent free surface motion. The incompressible Euler Navier Stokes equations, written in an Arbitrary Lagrangian-Eulerian (ALE) frame, were solved using projection schemes and a finite element method on unstructured grids.

Lee and Lim *et al.* (2010) analysed and compared experimental results of green water on the deck of three different FPSO bow shapes in regular head waves. They established a database for CFD code validation and proposed some design considerations. The so called marker density method has been applied to capture the extremely complicate free-surface, including breaking, associated with the differentiated nonlinear governing equations.

Kendon *et al.* (2010) considered results from a 2D model test setup and compared the measured vertical loading on the deck against two simple potential theory based methods and against results from a commercial CFD code. The results demonstrated that a second impact event closely following a first impact event can have a much flatter free-surface profile (and stronger water entry force) as a result of its interaction with deck diffracted waves. They concluded that for isolated impact events the simple potential flow based models, which do not consider the influence of one impact event on another, are adequate to predict vertical loading. Extending the same strategy Colicchio *et al.* (2011) worked on the modelling of green water loads within seakeeping codes. They used a domain decomposition method and a potential flow analysis solver so as to determine the Navier Stoke inflow conditions. A similar problem was considered by Hu and Kashiwagi (2009) who studied the 2D water on deck problem with a constrained interpolation profile (CIP) based method. For the validation of the simulation, a new experiment involving a floating body of rectangular section in a wavy channel was designed. Reasonably good agreement was obtained with regards to body motions and the amount of water shipping, whereas still minor indications were given about local loads acting on the deck or the superstructure. The Natural Element Method (NEM) developed by Afansiev *et al.* (2011) employs both these features to solve the dam-break problem promising to be a valid alternative to other approaches for green water simulation.

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3.5 Sloshing

Sloshing is a phenomenon of fluid movement in a partially filled containment system that may be subject to nonlinear and possibly extreme external excitation. Over the course of the reporting period numerical solutions and model tests have been developed extensively with the aim to reliably capture aspects of sloshing behaviour on modern LNG vessels. In this particular case, due to the motion of the ship in waves, the LNG sloshes around the tank generating very high impact pressures on the containment system and the supporting hull structure. Recent advances concentrate on aspects of hull flexibility, model scale validation, use of advanced fluid dynamic methods for sloshing modelling or coupling with overall hull girder loads.

3.5.1 Model Experiments

Kuo *et al.* (2009) reviewed the relevant Exxon Mobil's sloshing assessment methods. In this work it is also highlighted that among the most significant developments is the introduction of a probabilistic based framework that facilitates modelling of the high variability of sloshing impact pressures due to sloshing physics and insulation materials.

Marès *et al.* (2009) described the main features into GTT's methodology for sloshing assessment. In an accompanying paper Pillon *et al.* (2009) presented how GTT developed and validated its numerical models to obtain a proper representation of the complex and nonlinear motions of the containment system. The authors explain that for the validation of numerical results model tests are necessary in order to analyse the behaviour of critical response components under different conditions related with the tank statics, dynamics or ambient and cryogenic temperatures. Gervaise *et al.* (2009) described recent GTT state of the art knowledge and developments on hardware improvements, assumptions for sea-keeping calculations, loads and strength evaluations.

Hirdaris *et al.* (2010) discussed some of the recent advances in model test tank investigations and reviewed the relevance of allowing unrestricted fill levels in LNG membrane tank ships. The assessment presented in this work allowed for a reduction in the barred fill range from 80 % to 70 % of the internal height of the tank. Model tests reviewing the loads on pump towers revealed that there are several issues related to the application of loads derived from model tests, namely (a) scaling issues due to the use of water and air (or some other ullage gas); and (b) suitable representation of the near boiling LNG liquid and vapour in the ullage space.

Brosset *et al.* (2009) provided an overview of the SLOSHEL Joint Industry Project along with information on experimental set ups, the parameters tested and numerical approaches employed. In furthering this work Bogaert *et al.* (2010a) and Zheng *et al.* (2010) highlighted aspects on scaling issues and summarised the key findings from model and full scale tests. Bogaert *et al.* (2010b) utilised a database of large scale impact tests and discussed in detail the behaviour of Mark III corrugated primary membrane systems under breaking wave impacts.

Bunnik and Huijsmans (2009) described a study of model test experiments on a large scale 2D section (scale 1:10) of an LNG carrier in various loading conditions without depressurisation. Using high speed video observations the wave front formed by the bore of the LNG in resonance was related to measured impacts on the tank hull. The loading on a hydroelastic hull panel with correctly scaled structural properties was also examined and the influence of the stiffness on the pressure pulse was found to be significant. Panigrahy *et al.* (2009) developed a liquid sloshing experimental setup to

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estimate the pressure developed on the tank walls and the free surface displacement of water from the mean static level. The pressure and displacements were measured on the basis of changing excitation frequency of the shaking table and fill level in the tank. The experiments were carried out without and with baffles.

Tabri *et al.* (2009) employed the numerical models developed by Godderidge *et al.* (2009) to study the sloshing induced liquid oscillation initiated by ship collision. Data about the dependence of accelerations, strain energy and tank water elevation on mass ratios and collision velocity were collected. Though only linear sloshing has been modelled comparisons between experimental trends and simulation analyses were reasonable.

Lugni *et al.* (2010a, 2010b) focused on the air cavity evolution during a depressurised wave impact, an event likely to occur not only in partially filled tanks but also in other violent flow phenomena like green water. Their underlying idea was to represent experimentally a repeatable impact event so as to distinguish its different stages and the main physical variables. It was concluded that air cavities may lead to the formation of highly localised pressures.

Xu *et al.* (2012) carried out sloshing model tests with 1:55 scale membrane-type LNG tank oscillating in regular harmonic motions. The purpose of this study has been to investigate the characteristics of free surface motions, impact pressures and structural responses. The structural features of the insulation layer were simulated by a plywood box equivalent to a $1.1\,m \times 1.1\,m$ simply supported panel and then scaled to a $20\,mm \times 20\,mm$ bronze sheet of $0.3\,mm$ thickness. A bidirectional strain gauge was disposed at the centre of each bronze sheet to measure dynamic stress responses. Impulsive spikes were presented in the temporal curves of structural strain records due to the sloshing impact pressures.

3.5.2 Hull Flexibility

Lee and Tan *et al.* (2010) investigated the coupling effect between a flexible ship and sloshing in beam regular waves by evaluating the added mass contributions due to liquid motions in partially filled tanks. Recently, Malenica *et al.* (2011) developed a modal (hydroelastic) method for assessing the influence of the dynamic motion of the liquid cargo in containment systems. Maguire *et al.* (2009) and Hirdaris *et al.* (2010) considered numerical simulations of fluid loading by CFD and structural response by FEA. The simulations described demonstrate that two different philosophies, namely the decoupled (or one way coupled) and coupled (or two way coupled) approaches are achievable. Accordingly, the effects of the transfer of pressures from the fluid code to dynamic FEA and the resulting instantaneous deformation response of the containment system boundary being transferred back to the CFD solver have been investigated. The later, although it may be computationally expensive, it allows for the use of the instantaneous deformed tank shape to evaluate the pressure at the each time step. However, it is computationally expensive.

Lee and Park *et al.* (2010) investigated the influence of hull flexibility on the hydrodynamic forces and moments associated with liquid sloshing and vice versa, as well as the dynamic characteristics (e.g. resonance frequencies) of the whole system. The method was validated by comparing hydrodynamic forces from sloshing obtained using rigid and flexible body approaches. The coupling effect between flexible ship and sloshing in partially filled tanks was investigated for an idealised LNG Carrier in beam regular waves, considering different partial filling scenarios.

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3.5.3 Advanced Numerical Methods

Gavory and de Seze (2009) reviewed the current status of the numerical methodologies used for sloshing assessment. Their work concluded that inviscid methods are still broadly used as an intermediate benchmark of validity against other available nonlinear computations. Cao *et al.* (2010) presented the range of validity of potential flow models by comparing the predictions with those by other CFD simulations and experimental measurements of the liquid motion in an oscillating tank.

Peric *et al.* (2009) demonstrated the application of a procedure to predict internal sloshing loads on partially filled tank walls of LNG ships subject to realistic wave excitations. A moving grid approach was employed and a finite volume solution method was designed to allow for arbitrary ship motions. An interface capturing scheme that accounts for overturning and breaking waves was used to compute the motion of liquid inside the tanks. Liu and Lin (2009) developed a Navier-Stokes numerical model to study the 3D liquid sloshing in a tank with a baffle. The numerical results were validated against available analytical solutions and experimental data. Another experimental study was performed by Wu and Chen (2009) who developed a 3D time independent finite difference method to study the sloshing waves and resonant modes of a fluid in a 3D tank. In this work, five distinct types of sloshing waves were observed and they were closely related to the excitation frequency.

Delorm *et al.* (2009) investigated experimentally the 2D shallow water sloshing phenomenon under forced rolling motion conditions by the SPH method. The numerical model depicted reasonably well the free surface shape obtained from tests and assisted in reproducing the pressure trends during a water impact, though overestimating the maxima. Lee *et al.* (2010) described an efficient and robust moving particle semi-implicit method to predict violent free-surface and floating-body motions as well as impact pressures. The floating-body-motions and the impact pressures induced by violent liquid sloshing motions were verified by comparing numerical results against conventional methods. It was concluded that the roll amplitudes could be significantly reduced for excitation frequencies away from the lowest sloshing natural frequencies.

Thiagarajan *et al.* (2011) applied a CFD method accounting for air/water interaction to the problem of sloshing in a rectangular tank. The fill levels varied from 10 % to 95 % of tank height, corresponding to a 1:30 scaled model of a prototype tank. The study employed the $k - \epsilon$ turbulence model to capture the features of the flow and a volume-of-fluid (VOF) model to track the sloshing free surface.

3.5.4 Coupling Sloshing with Motions

Faltinsen and Timokha (2009a, 2009b, 2011) presented an overview of sloshing in the tanks of ships with swash bulkheads. The authors highlighted that whereas nonlinearities are important for the assessment of sloshing excitations, ship hydrodynamics may be handled well by linear theory except for the motions and loads associated with viscous roll damping.

The use of simplified modelling of sloshing is also perceived as a mandatory approach when the interaction between global ship motion and partially filled tanks are investigated. This guideline was followed for instance by Lin *et al.* (2011) and Hirdaris *et al.* (2010) using a potential model for global ship motion coupled with a sloshing model for the prediction of LNG tank loads, the last one based on a RANS code with VOF surface tracking that exploits the open source CFD code OpenFOAM libraries.

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Hashimoto *et al.* (2010) reported on the use of nonlinear potential theory and particle based hydrodynamics for the coupled formulation of the sloshing/seakeeping problem. Bunnik and Veldman (2010) compared the results on RAOs of roll motions obtained linear and particle based hydrodynamics approaches against the experimental results reported by Molin (2008). They concluded that whereas linear potential theory shows a reasonable agreement there is a slight difference with the experiments near the sloshing peak frequency in terms of the spread of the peak as well as the shift of the peak frequency. The use of nonlinear potential flow hydrodynamics may allow for good agreement in all frequency ranges for both low and high sea states.

Huang *et al.* (2009) discussed the global force acting on the tank under coupled internal liquid and LNG carrier sway motions based on numerical and experimental results. They showed that the coupling between the tank sloshing and ship motions can be predicted by a linear potential theory as the global forces induced by the liquid sloshing are relatively periodic and deterministic whereas the local sloshing pressures are highly nonlinear and do not affect the ship motions.

Lee and Kim (2010) investigated the coupling and interactions between ship motions and inner-tank sloshing by a potential-viscous hybrid method in the time domain. For the time-domain simulation of vessel motions, the hydrodynamic coefficients and wave forces were obtained by a potential theory based 3D diffraction/radiation panel program in the frequency domain. The corresponding simulations of motions in the time domain were carried out using the convolution integral method. The liquid sloshing in a tank was simulated in the time domain by a Navier-Stokes solver. A finite difference method with SURF scheme assuming the single-valued free-surface profile was applied for the direct simulation of liquid sloshing. The computed sloshing forces and moments were applied as external excitations to the ship motion.

Nam *et al.* (2009) considered the motion responses of floating bodies in waves coupled with sloshing-induced internal forces and their effects on sloshing-induced impact loads. The linear ship motion was solved by using an impulse-response-function method. The nonlinear sloshing flow was simulated using a finite difference method. Two models were considered namely (a) a liquid natural gas floating production, storage, and off-loading unit with two partially filled tanks and (b) a modified S175 hull with an anti-rolling tank.

Tabri *et al.* (2009) studied the sloshing interaction in ship collisions both experimentally and numerically. Sloshing affects the collision dynamics and reduces the amount of energy available for structural deformations. An understanding of the interaction phenomenon was obtained by a series of model-scale experiments, in which a striking ship, with two partially filled tanks, collided with an initially motionless struck ship without any liquid on board. The simulation model was validated with experimental results and good agreement was achieved in the case of medium filling levels in the tanks. Tan *et al.* (2010) on the other hand investigated the influence of hull flexibility on the hydrodynamic forces and moments associated with liquid sloshing and the effects of sloshing on wave induced responses. It was observed that the liquid sloshing has an influence on the response of distortional as well as rigid modes, i.e. wave-induced motions and loads.

Bunnik and Veldman (2010) employed the following two different models to take into account the effect of sloshing on ship motions: (a) a linear diffraction method in which both the liquid motions in the containment system and the liquid motions outside the vessel are described by linear potential flow in the frequency domain; (b) a time-domain coupling method in which the sloshing liquid in the containment system is

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computed by CFD (Volume of Fluid method) and the ship hydrodynamics by means of linear diffraction theory. Both methods were applied to model tests described by Molin (2008), in which he measured the motion response of a barge with a partially filled water container on deck.

3.5.5 Design Assessment Procedures

Over the reporting period, procedures to predict sloshing loads and evaluate structural strength have been introduced by most Classification Societies. For example, Lloyd's Register (2009) developed a comprehensive sloshing assessment guidance document with recommendations on the procedures that can be applied for the assessment of sloshing loads on LNG tanks. The procedure comprises of three parts namely (a) ship motions analysis and determination of the design sloshing loads (b) structural analysis and (c) assessment criteria.

Wang and Han (2009) and Wang and Arai (2010) conducted a dynamic structural analysis, considering fluid-structure interaction, to determine the design strength capacity for the No. 96 containment system using sloshing model tests in terms of selected environmental conditions, vessel configurations and loading conditions. In these studies spatial, temporal and statistical characteristics of the measured sloshing loads were investigated. Linear transient FEA of the No. 96 containment system including both the structure and the LNG was performed to obtain structural responses at predefined critical locations under short duration triangular pulse which is referred to as Triangular Impulse Response Function (TIRF). In the FEA model orthotropic material properties for plywood and acoustic medium for LNG were considered. Statistical analysis results of peak stress values in each component of the containment system were used as the basis for determining design sloshing loads or strength assessment of the No. 96 containment system.

4 OFFSHORE STRUCTURES – SPECIALIST TOPICS

4.1 Offshore Lifting and Installation

Understanding of the loads imposed upon operating offshore floating cranes has been of interest for many years (e.g. Schellin *et al.*, 1989). The analysis of offshore crane vessels can be largely divided in two main categories namely structural analysis and hydrodynamic analysis.

In recent publications, Al-Sweiti *et al.* (2007), Ren *et al.* (2007) and Cha *et al.* (2010) reviewed the literature and reported on the effects of undesired crane load motions. The common approach applied assumes that the excitation is simply a prescribed motion of the pivot point of a hoisting rope. This assumption leads to a dynamical model with parametric excitation while the motion of the vessel is neglected. Although such an approach may be justified for vessels in sheltered basins and if the load to vessel ratio is very small, it is certainly not appropriate for large moored floating cranes operating offshore. The dynamics of such vessels is affected by strong coupling between vessel and load motions and depend on the characteristics of the mooring system. Along these lines, Al-Sweiti and Soffker (2007) developed mathematical tools for modelling and control of elastic ship cranes which have the Maryland Rigging system. Their study was extended by Ren *et al.* (2007) who demonstrated the effects of lifting cable length, reeling and unreeling speed of cable and wave frequency on cargo dynamic response. Cha *et al.* (2010) performed a more rigorous numerical analysis to identify the effects of nonlinear static and dynamic response of a floating crane and a heavy block that are connected using elastic booms and wire ropes. In

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their work two mathematical models of different levels of complexity have been used to systematically determine the responses of the vessel payload systems to periodic forcing of waves. One technique is the multiple scales method which allows for the investigation of the nonlinear dynamical system in frequency domain and results in an analytical solution. The other technique applies numerical path following methods to trace bifurcations (parameter values for which a qualitative change in the dynamics can be observed) of periodic solutions.

4.2 Cables, Risers and Moored Structures

The publications concerning cables risers and mooring systems during the reporting period deal primarily with the coupled floater mooring global response. It is also evident that there is still a great deal of interest for issues that influence the nonlinear dynamic behaviour of mooring lines and the slow drift motion of the moored floaters. Recent developments on the later were highlighted in section 2.1.3 (e.g. Hansen *et al.*, 2009; Clauss and Sprenger *et al.*, 2009; Brake *et al.*, 2009).

The purpose of coupled analysis is to accurately predict the loads on mooring lines and risers at extreme design conditions. Chan and Ha (2008) used a fast domain coupled analysis along with a frequency domain mooring analysis to predict the first order slowly varying drift motions of an FPSO in design conditions. The line tensions predicted in the time domain were compared with the frequency domain solutions. Chen *et al.* (2008) used the coupled analysis to assess the effect of two different top tensioned riser configurations, one with buoyancy cans and one with tensioners on the motion responses of a truss spar in ultra deepwater. Nonlinear spring properties of tensioners and hydrodynamic loadings on the risers and the mooring lines were calculated.

The coupled analysis requires extensive computational efforts. Hence there is a need for the development of more simplified methods for use in practical design applications. Within the reporting period efforts concentrated on developing a highly efficient frequency domain approach in which the drag forces are linearised. For example Low and Grime (2011) have shown that the geometric nonlinearity of the mooring lines/risers may be insignificant. This was demonstrated by applying statistical techniques in conjunction with frequency domain analysis to predict the extreme responses of the coupled system. The crossing rates for surge, sway and yaw obtained were found to agree well with those extracted from the time domain simulation, whereas the result for yaw is less favourable.

4.3 Vortex Induced Vibrations (VIVs) and Wake Induced Oscillations (WIOs)

VIVs are highly nonlinear motions induced by flow periodical irregularities. Over the last few decades, significant progress has been made in understanding the VIVs of long circular cylinders by means of numerical simulations and physical experiments. The following discussion highlights some recent operational considerations as well as theoretical developments in the area of VIVs and Wake Induced Oscillations (WIO).

From an operators' perspective it is today far more desirable to eliminate or reduce VIVs than it is to amplify their effects. For example, Tongarelli and Taggard (2008) reported on the hydrodynamic performance of various offshore units and production platforms. The measured data presented in this work shed some light on the physical details of full scale riser response omitted from predictive riser design tools. They were also used to establish performance indicators for some VIV suppression devices that are currently in use.

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A comprehensive review of VIV prediction methods was presented by Williamson and Govardhan (2008). The authors summarised fundamental research results presented over the last two decades. Many of those are related with the push to understand and, as applicable, implement very low mass and damping mechanisms in existing and forthcoming experimental and computational techniques. The authors focused on vortex induced dynamics and energy transfer phenomena that may give rise to dynamic loads. More recently, Kevlahan (2011) employed potential flow and 2D Navier Stokes calculations to investigate the role of vortex shedding in the non resonant flow induced vibration of periodic tube arrays. This dual approach untangles the effects of potential and vertical flow. The negative damping theory is shown to be inconsistent with the Navier Stokes simulations allowing only a single degree of freedom in tube motion. Whereas the later is thought to significantly overestimate the simulation of critical velocities, the results presented assist to untangle the role of vortex shedding and potential flow in way of the non resonant fluid elastic instability of tube arrays.

Investigations on flow interaction with moving circular cylinders have always been carried out in 2D because of the unaffordable computational effort that 3D simulations may demand. There are a number of publications in this topic. For example, Prasanth (2006) studied the laminar flow induced vibration of a circular cylinder at low Reynolds numbers. On the other hand Wanderley *et al.* (2008), and Al Jamal and Dalton (2004) adopted RANS and LES turbulence models to simulate the VIV response at moderate Reynolds numbers. Such studies have also been extended to cases of two circular cylinders. For example, Prasanth and Mittal (2009) built upon the work of Schulz and Kallinderis (1998) and Papaioannou *et al.* (2008) and reported on the shielding effect of upstream cylinders in laminar flow induced conditions.

In contrast to VIV problems understanding of the downstream effects in WIO is relatively lagging behind. This is probably because of the technical difficulties to approximate the large amplitude motions that mooring and riser cylinder like structures suffer from. Recent studies mainly focus on model measurements. For example, Okajima *et al.* (2007) studied the stream-wise oscillation of two tandem circular cylinders in different arrangements. On the computational developments front Meneghini *et al.* (2001), Jester and Kallinderis (2003) reported on 2D laminar flow interactions between two fixed circular cylinders. Carmo and Meneghini (2006), Deng *et al.* (2006), Kitagawa and Ohta (2008), Palau-Salvador *et al.* (2008) performed 3D numerical simulations at different Reynolds numbers using approximation models (e.g. LES methods) that are able to simulate turbulence effects.

4.4 Spars and TLPs

The successful design and operation of floating production units requires appropriate evaluation of the environmental loads that prevail during transportation installation and operation. To this end recent research also concentrated on spars and Tension Leg Platforms (TLPs).

A numerical prediction of the spar motions in waves, wind and current was carried out by Liapis *et al.* (2010). The predictions were based on the COSMO/WAMIT commercial software and compared well with model test results. Special line members were included to take the viscous loads and damping into account. Koo *et al.* (2010) studied the motions and loads for the float-over installation of spar topsides. The numerical analysis involved multi-body hydrodynamic interaction, simulation of impact forces and validation studies. In the transportation analysis it was found that the predicted

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catamaran barge global motion statistics were slightly conservative in comparison with those of the model tests.

In the past three years research on TLPs concentrated on experimental and numerical studies. The aim has been to improve their design by damper mechanisms that may reduce the loads on the tendons. For example, Heidari *et al.* (2008) presented a study on the design of a dry-tree FourStar TLP operating in a 4300 ft water depth. Bian *et al.* (2010) presented the design of an integrated ultra-deepwater TLP with an air spring type vibration absorber to suppress the vertical resonance motions. Jayalekshmi *et al.* (2010) investigated the effect of tether-riser dynamics on the response characteristics of deepwater TLPs in water depths of 900 m and 1800 m and in random waves. The nonlinear dynamic analysis of deep water TLPs was carried out by using FEA and results were reported in the form of statistical responses. These values increase with water depth and a significant increase was observed when risers were included in the analysis. Taflanidis *et al.* (2008) also explored the idea of using mass dampers for the reduction of dynamic loadings and hence the protection of offshore platforms. To achieve greater vibration suppression appropriate tuning of the parameters of the dampers was necessary. The later was achieved by a stochastic design approach.

Srinivasan (2010) addressed the use of TLP in ultra deepwater to support dry-tree in oil and gas production. To reduce the effects of the wave loading, truss-pontoons were used. A technically feasible and cost-effective artificial sea-bed was used to ease the tendon design in deepwater and harsh environment. As a result a simple and slim hull, which is easy to design, fabricate, transport and install, was obtained. Lee and Lim (2008) studied the fatigue induced loads on a TLP by using a frequency domain analysis coupling the effects of first order wave, mean drift and linearised viscous forces. Survivability analysis was then carried out in the time domain where the second order wave and nonlinear viscous forces were considered. The optimisation process led to a hull form with improved dynamic performance and minimised top tension of the tendon.

4.5 Semi-submersibles

The study on loads of submerged bodies has received considerable attraction for many years. The interaction between gravity monochromatic waves and a fixed submerged horizontal circular cylinder with its axis parallel to the crests of the incident wave was first studied by Dean (1948) who used a linearised potential theory and a conformal mapping technique. The first experimental study related to this phenomenon was undertaken by Chaplin (1984) who calculated the nonlinear forces of the reflected and transmitted waves originated by a fixed submerged horizontal cylinder. His study revealed the nonlinear components of these forces with frequencies up to 3 times the fundamental wave frequency.

Over the last few years the analysis of hydrodynamic performances of submerged bodies has become increasingly important with the growing interest in offshore activities related with the generation of ocean wave energy via wave induced motion of oscillating submerged bodies. For example, numerical and experimental studies by Kent and Choi (2007) suggested a solution for the velocity potential imposed upon submerged bodies by a multi pole expansion. More recently, Conde (2009) studied the fully behaviour of a 2D horizontal cylinder by a nonlinear diffraction analysis theory. Guerber *et al.* (2010) extended a 2D fully nonlinear potential flow numerical wave model to include a submerged horizontal cylinder of arbitrary cross-section. The in-

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teraction between the free-surface flow and the surface tension for a circular horizontal cylinder has been investigated by Moreira and Peregrine (2010). Yan *et al.* (2010) has investigated the fully nonlinear interaction between freak waves and 2D submerged cylinders and Bai *et al.* (2010) has studied the 2D submerged dikes interaction with viscous free surface waves using the Cartesian cut cell approach.

Matsumoto *et al.* (2010) carried out wave basin tests for a large semi-submersible. They observed relatively large low-frequency motions in heave, roll and pitch, which affected the dynamic air gap measurements and loads. Hussain *et al.* (2009) discussed the requirements for a floating vessel designed to support top tensioned risers. Mansour (2009) introduced the performance of a new conceptual semi submersible design that provides motion response similar to a Spar. It was concluded that the use of a free-hanging Solid Ballast Tank (SBT) may significantly increase the heave natural period while controlling the heave response in the wave frequency range.

Current loads on stationary submerged vessels have been investigated by Vaz *et al.* (2009). Model-tests, semi-empirical models and CFD methods were used to predict these loads. Two key issues affecting the modelling accuracy, the location of the transition to turbulent flow and the control of the numerical errors were identified and discussed. Their field measurements indicated that the design guidance derived from model tests, as presented by Rijken and Leverette (2008), result in very conservative estimates motions. It was also observed that the flow field around the columns may cause oscillations along one of the vessel's main diagonals under particular conditions.

Simos *et al.* (2009) showed that semi-submersible hulls may be subjected to second order slow motions in heave, pitch and roll. These resonant motions are directly related to the large dimensions and relatively low natural frequencies of the floating systems. Their paper discussed the evaluation of the 2nd order wave induced motions of a large-volume semi-submersible platform using the WAMIT second order module. It was shown that the hydrodynamic forces induced by the 2nd order potential affects significantly the resonant response. Matos *et al.* (2010) studied the scale effect of the slow drift motions in vertical plane of a large volume semi-submersible platform. The importance of considering the resonant roll and pitch motions in the seakeeping analysis of large-volume semi-submersible platforms was demonstrated.

5 UNCERTAINTIES IN WAVE LOAD PREDICTIONS

Specification and quantification of uncertainties related to environmental models, load predictions and response calculations is important part of the risk-based assessment, design and operation of marine structures. To date, load uncertainties have been specified by reliability based code formats (e.g. Bitner-Gregersen *et al.*, 2002) and for development of decision support systems that may be useful for navigation guidance (e.g. Spanos *et al.*, 2008; Bitner-Gregersen and Skjong, 2009). Bitner-Gregersen and Skjong (2009) suggested to divide uncertainties into two groups namely (a) aleatory (natural and physical) and (b) epistemic (knowledge based). According to the authors the information about uncertainties should be introduced in the reliability analyses in the form of random variables. Aleatory uncertainties represent a natural randomness of a quantity, also known as intrinsic or inherent uncertainty, e.g. the variability in wave intensity over time and cannot be reduced or eliminated. Epistemic uncertainties represent errors which can be reduced by collecting more information about a considered quantity and by improving the methods of measuring it. These uncertainties may be classified into: (a) data related (b) statistics related and (c) model related.

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Data uncertainties appear due to the imperfection of an instrument used to measure a quantity, and/or a model generating data. If a considered quantity is not obtained directly from the measurements, but some estimation process is interposed (e.g. the significant wave height), then the measurement of uncertainty must be combined with the estimation of model uncertainty by appropriate means. Statistical uncertainty, often also referred to as estimation uncertainty, is due to limited information such as a limited number of observations of a quantity and also due to an estimation technique applied for the evaluation of the distribution parameters. Model uncertainty is due to imperfections, simplifications and idealisations made in physical model formulations for an event as well as in choices of probability distribution types used in the representation of uncertainties. The accuracy of a quantity characterises the extent to which a measured quantity agrees with the true value. To characterise the later it is necessary to indicate a systematic error (also known as bias) and a precision (or random) error. The systematic error, or bias, of an estimator for a quantity considered refers to a systematic deviation from the true value of the quantity. The precision of the quantity considered refers to random variations, and is usually summarised by the standard deviation. A normal distribution is commonly adopted to describe the precision.

Significant efforts have been made by ISSC in recent years to explain uncertainty in predicted extreme wave loads on ships (e.g. ISSC, 1997, 2000). Roughly, uncertainty in wave loads may be divided into uncertainty of wave loads calculated under linear assumptions and uncertainty of nonlinear effects. Uncertainties of linear wave load predictions refer to the shape of wave spectra, the choice of wave scatter diagram, transfer functions, methods for prediction of long-term extreme values and human actions. Uncertainty of nonlinear effects in wave loads may comprise different sagging and hogging bending moments mainly due to non vertical ship sides and influence of slamming and whipping on extreme vertical bending moments.

The traditional approach for assessing the wave induced loads in intact ships structures assumes that the sea states are dominated by wave systems generated by local winds. However, in many situations marine structures are subjected to the combination of more than one wave system and in this case the frequency spectrum exhibits two peaks. Double-peaked wave spectra can be observed when a swell system combines with wind-generated waves. For example, Teixeira and Guedes Soares (2009) have demonstrated that, for a trading ship of non-restricted operation, the long-term distributions of the wave induced vertical bending moment for combined sea states do not change significantly when compared with the ones obtained from sea states of a simple component. In their work it is recognised that double peaked wave spectra can have a significant impact on the design and operability of fixed and offshore platforms. They suggest that it would be important to assess damaged ships since collisions and groundings may occur in sea areas with swell dominated sea states and the manoeuvrability may be affected as a consequence of the accident.

Ivanov (2009) proposed a method for calculating the hull girder bending stresses following the procedure in the class rules but in probabilistic terms. In this work the still water and wave-induced hull girder hogging and sagging loads are presented in probabilistic format as one phenomenon, i.e. using bi-modal probability density functions. The probabilistic distribution of the total hull girder load is calculated using the rules of the composition of the distribution laws of the constituent variables. Parunov and Ćorak (2010) investigated the influence of environmental and operational uncertainties on the long term extreme vertical wave bending moment of a container ship assuming rigid hull. As the long term distributions of vertical wave bending moments

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are highly dependent on the assumed environmental and operational parameters, their different combinations are considered. Results are compared among themselves as well as with the IACS rule vertical wave bending moments. Statistical parameters which may be useful for reliability-based design of container ships are quantified. Shu and Moan (2009) studied the effect of the heavy weather avoidance on the long-term wave-induced pressure along the midship transverse section of a VLCC and a bulk carrier. They proposed a practical model to consider the effect of heavy weather avoidance on the wave pressure along a mid-ship transverse section. Mohhamed *et al.* (2009) discussed the basis of a cross-spectral formulation that could be used to assess the combined effects of wave loads on hull girder strength. The methodology accounts for long term probability distributions and considers phase relationships between narrow banded load processes.

Jensen (2009) discussed useful stochastic procedures for wave load problems covering the range from slightly linear to strongly non-linear (bifurcation) problems. The methods employed were (a) Hermite transformation, (b) Critical wave episodes and (c) First Order Reliability Method (FORM). The procedures are illustrated by results for the extreme vertical wave bending moment in ships. Another simplified procedure for determining the long term distribution of wave hull girder loads acting on container ships including transient loads such as slamming and green water effects has been presented by Jensen *et al.* (2009). The authors combined high frequency transient loads with lower frequency wave induced loads and the entire simplified solution is presented in closed-form solution. For non-linear processes a good estimate for the mean out-crossing rate was found using FORM. An interesting – but not general – property with the FORM analysis for the specific problem of the extreme bending moment is that the associated reliability index is inversely proportional to the significant wave height for fixed values of other operational parameters. As pointed out by Jensen (2010) this means that the computational efficiency of Monte Carlo simulations for the specific problem can be increased drastically by introducing a scaling of the significant wave height; a phenomenon previously investigated by Söding (1986). Gaidai *et al.* (2010) described a method for the prediction of extreme whipping stresses measured in deck amidships a container vessel during operation in harsh weather. Whipping response time series were analysed for two different voyages of the same ship, similar route and similar season month. Two different statistical methods were applied and compared with respect to the extreme response estimate. Parunov *et al.* (2011) investigated long-term distribution of slamming loads of container ships accounting for different types of environmental and operational uncertainties. In this work the uncertainties studied were (a) the choice of the wave scatter diagram, (b) the effect of the avoidance of heavy weather, (c) the effect of the manoeuvring in heavy weather and (d) the method for predicting the long-term extreme slamming pressures.

6 FATIGUE LOADS FOR SHIPS AND OFFSHORE STRUCTURES

6.1 Fatigue Analysis of Ships

In recent publications the contribution of high frequency whipping and springing vibrations to the fatigue damage in the hull girder is extensively studied by Storhaug (2007) and Storhaug and Moan (2007). It was concluded that the high frequency components could be as important as the contributions from the wave frequency range. Similar observations have been found from full-scale measurements in container ships and LNG vessels, e.g. Storhaug and Moan (2007), Heggelund *et al.* (2010) and Nielsen *et al.* (2011). As noted by Storhaug (2007) it is difficult to distinguish be-

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tween springing and whipping vibration components in full-scale measurements and their individual contribution to the fatigue damage cannot be assessed easily from such measurements. In total they might, however, typically increase the expected fatigue damage by 20 – 50 % depending on the sea state, loading condition, speed and heading. Based on both full-scale measurements and model tests, the following general conclusions can be made with respect to fatigue damage accumulation in the hull girder of ships:

- The correlation between significant wave height and fatigue rate is strong, and most fatigue damage is accumulated in head or following sea (Heggelund *et al.*, 2010);
- It is necessary to further study the effect of safety margin between hull girder capacity and loading by a more refined approach (Storhaug *et al.*, 2010a);
- Whipping and springing-induced fatigue accumulation is a complex phenomenon, which is not properly included in design rules yet (Storhaug *et al.*, 2010b; Boutillier *et al.*, 2010);
- The only way to progress in the understanding of fatigue phenomena is to combine all the available tools including model tests, full-scale measurements and numerical models/simulations (Storhaug *et al.*, 2010b).

In a slightly different line of work, Garbatov *et al.* (2010) studied the combined effects of vibration and wave induced loads on fatigue. Their analysis considered local and global loads due to wave actions and cargo effects by means of the hot spot fatigue analysis approach. Detailed FEA was used to determine the critical hotspots and the stress distributions on the hull structural joints. As a result of the performed analysis the stress concentration factors have been defined and used for fatigue damage calculation by taking into account the combination of low-frequency wave induced loads and transient loads. It was concluded that the calculated local stresses around the structural singularities depends on the structural idealisation, the element types used and the mesh subdivision. In a subsequent publication Garbatov and Guedes Soares (2010) reported on the importance of assessing fatigue life prediction related uncertainties by discrete, closed form and spectral approaches. This work analysed the influence of various factors (e.g. ship main characteristics, operational profile, wave climatic data, heading distributions) and considered the random origin of structure born deviations (e.g. mean stress effect, imperfection, weld shape improvement, hot spot calculation and resulting notch stress concentration factor) to the fatigue life of a butt welded ship structural component. It has been observed that there is significant difference between the mean fatigue damage pairs of the heading direction and distribution. Also, different fatigue damage calculation approaches may introduce different level of uncertainties resulting in different means and standard deviations of fatigue damage.

A number of studies have recently been dedicated particularly towards onboard monitoring of fatigue damage rates. Models and procedures have been developed to evaluate fatigue damage accumulation in the hull girder both for short-term (30 minutes to 3 hours) decision support, (e.g. Nielsen *et al.*, 2011) and for long-term voyage planning (e.g. Mao *et al.*, 2010a and Mao *et al.*, 2009). These studies present comparisons between measurements and predictions of fatigue damage rates and promising results are obtained. As uncertainties related to fatigue damage analysis can be profound independently of the prediction period, it should be considered to use risk-based approaches for the evaluation of fatigue damage rates. This has not been attempted until now, but ideas may be gained from the studies by Mao *et al.* (2010b) and Choung *et al.* (2010).

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6.2 Fatigue Analysis of Offshore Structures

Fatigue is one of the most significant failure modes for offshore platforms which are mostly made of metals (Bengtsson and Rychlik 2009, Cui *et al.* 2011). Metal fatigue has been studied for more than 170 years. However, the fact that fatigue life prediction methods are not based on Fatigue Crack Propagation (FCP) theories remains a concern. Cui *et al.* (2011) outline their idea to develop a unified fatigue life prediction (UFLP) method for marine structures. The key issue for this development is to establish a correct crack growth rate relation. Hence, a new crack growth rate model based on the concept of partial crack closure is presented. It is concluded that their improved model shows strong capability in simulating the crack growth curves under different load ratio of various metal materials. Moreover, the model has been successfully applied for simulating some special fatigue phenomena such as compressive to compressive loading effect and overload retardation effect.

The importance of uncertainty in fatigue life prediction of marine structures subjected to Gaussian loads has been discussed by Bengtsson and Rychlik (2009). In particular, they discussed how general types of environmental loads (that often vary with time) can be included in a stochastic by computing a measure of risk for the fatigue of a structural components during a specific time period. In their model, the combination of different types of uncertainties was facilitated by use of a calculated safety index. Another study which deals with uncertainty related to the analysis of fatigue data has been presented by Guida and Penta (2010) who introduced the concept of Bayesian inference. In their study a Bayesian analysis of SN fatigue data is outlined for estimating material properties and for establishing fatigue design curves from small size samples.

Recently, two practical approaches for fatigue life assessment have been presented. The former by Low (2010, 2011) presents an approach for calculating the fatigue damage from a stochastic bimodal process, in which the High Frequency (HF) and Low Frequency (LF) components are of narrow band Gaussian format. The novelty of this method is claimed to be its ability to incorporate two critical effects, which have been unrecognised in prior studies; the reduction of the small-cycle amplitudes caused by the LF process, and the offset between the HF and LF peaks. The approach is found to produce highly precise damage estimates ($\sim 1\,\%$ error) when benchmarked against simulations made as a number of case studies of theoretical multimodal processes (with no particular attention to where the process may derive from). On the other hand the approach by Jia (2011) looks at the calculation of wind induced fatigue of tubular structures by taking into account the effects of the wind direction, across wind and wind grid size. It is argued that calculation procedure has the merit of reducing uncertainties without degrading a required safety level, which may lead to a positive economic impact with regard to construction and maintenance costs.

7 CONCLUSIONS

7.1 Wave Induced Loads on Offshore Structures

Traditionally, the prediction of wave loading of zero speed body wave interactions has been based on potential flow solutions for the prediction of global loads imposed upon FOIs. Research results have also been presented in the area of bottom founded structures. There is clearly a trend towards the use of CFD based methods and nonlinear hydrodynamic diffraction approaches. However, these models require further experimental verification.

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When shallow water operation is considered, the influence of the seabed bathymetry variation on the loads needs to be examined. Current research is directed towards understanding the effects of varying water depths and associated high frequency responses of FOIs in waves by using nonlinear diffraction models, Langragean – Eulerian methods and hybrid methods for the assessment of sloshing motions in the time domain. Once more these approaches require further experimental verification.

Side by side configurations that are used in offloading operations drive developments in the area of multi body interactions. Within the reporting period the calculation of loads is performed mostly by linear and partly non linear boundary element methods with the aim to assess operability of the coupled systems and assess the loads on the structure, the mooring lines as well as lines connecting the bodies and articulations. Accordingly, the publications concerning cables, risers and mooring systems deal primarily with the so called coupled floater mooring global response. Time and frequency domain mooring methods are employed to predict the first order responses in extreme weather conditions. Considering that coupled analysis requires extensive computational efforts more efficient computation schemes are needed for use in practical design.

Whereas significant progress has been achieved in the area of VIVs investigations of wave induced oscillations on downstream circular cylinders are relatively lagging behind probably due to the technical difficulties to approximate large amplitude motions. It would be useful to expand research efforts in this area.

7.2 Wave Induced Loads on Ships

A large variety of nonlinear methods for the forward speed problem was reported. One may distinguish between methods based on potential theory and CFD based methods. Between those extremes there are various methods such as partly nonlinear or blended methods in which different modelling assumptions are used to approach selectively nonlinear effects. Further verification of available techniques against experimental measurements is necessary.

Understanding hydroelastic responses of ships is recognised as an important design verification tool. Whereas linear hydroelastic theories have reached a degree of maturity 3D nonlinear theories are still under development. The primary difficulty in applying CFD is related with the computational efficiency as well as the implementation of free surface flows particularly for large scale free surface effects around ships. In any case the use of CFD based methods (e.g. CIP or RANS) looks promising and should be investigated in further.

The need for quality benchmark data is as great as ever, particularly relating to the measurement of global loads from model tests. Within the reporting period experiments on elastically scaled models have been broadened and it would be useful to see this trend continued and expanded. Whereas full scale measurements provide the most robust form of validation in terms of realism of the data collected the number of investigations is limited and worthwhile to be expanded.

Evaluation of rogue wave induced loads continues to be dealt using partly non linear methods and comparing prediction against model tests. It will be interesting to apply fully nonlinear methods, including CFD based methods, to this type of approach. The potential flow formulation of slamming problems has continued to raise interest. Recent research studies focused on the evaluation of slamming loads on symmetric and asymmetric sections using the Wagner approach. There is some rise in the use of

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hybrid CFD based methods (e.g. RANS or SPH) using commercially available solvers. However, it would be interesting to carry out further validation studies.

7.3 Specialist Topics

Typically the underlying approach for operational guidance builds on combined theoretical seakeeping models and linear spectral analysis used for statistical predictions. Recently, concepts of novel procedures for operational guidance have been proposed to increase the reliability. The approach shows promising results. Specification and quantification of uncertainties related with environmental models, load predictions and response calculations is important part of risk based assessment for design and operation of marine structures. Load uncertainties have been specified for the improvement of reliability based code formats and for the development of decision support systems for onboard navigation. It is recognised that both model experiments and sea trials are providing the most reliable data for the validation of numerical codes. In the future it is hoped that more data will be publicly available.

Whereas there is currently some focus on developing fluid structure interaction models that simulate flooded damaged ship dynamics, the use of reliability methods and the broader implementation of available methods within the context of risk based design and assessment are strong trends that will be impacting on future research and development. With reference to sloshing loads recent advances concentrate on aspects of hull flexibility, model scale validations and implementation of advances CFD methods and tools to study the effects on the hull girder response. Perhaps, amongst the most important developments is the introduction of a probabilistic based framework that facilitates modelling the high variability of sloshing impact pressures due to sloshing physics.

The issues of fatigue analysis of offshore structures are by and large similar to those for ships. Within the reporting period efforts were focused on including nonlinear effects in fatigue predictions. Important properties are the non-Gaussian broad band width of the nonlinear response and the sequence of loads. Further investigations are necessary in order to clarify to what extend transient and hydroelastic effects need to be considered in fatigue analysis and structural design of ships.

Whereas a number of models and procedures have been developed to evaluate fatigue damage accumulation in the hull girder for decision support, probably the best way to proceed in understanding the phenomenon is to combine all available tools including full scale measurements and numerical simulations.

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