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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 prediction based on model experiments, full-scale measurements and theoretical methods. Uncertainties in load estimations shall be highlighted.

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KEYWORDS

Cables and Risers, CFD, Design Waves, Fatigue, Hydroelasticity, Ice Loads, Measurements, Moonpools, Multi-Bodies, Probabilistic Methods, Uncertainties, VIV, Wave Loads.

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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 that adopted in previous ISSC reports (ISSC 2006a), with one notable exception, namely impact loads due to slamming, sloshing and green water which, for this congress, fall within the remit of committee V.7. 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 so called CFD (Computational Fluid Dynamics) methods. Section 3 reviews measurements, ice loads and design loads in Classification Societies. Wave-induced loads on offshore structures are reviewed in sections 2 and 4, the former dealing with single and multi-body interactions, including effects of current and bathymetry. On the other hand section 4 focuses on specialist topics, such as cables and risers, vortex-induced vibrations (VIV) and moonpools. 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, with particular reference to benchmark data.

2. COMPUTATION OF WAVE-INDUCED LOADS

2.1 *Zero Speed Case*

2.1.1 *Body-wave Interactions*

Potential flow solutions formed the basis for evaluating wave loads on large offshore structures in most publications appearing during the reporting period. 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.

The solution of the first order diffraction and radiation problems achieved a level of maturity and the associated computer codes became reliable tools to provide Response Amplitude Operators (RAOs) of loads and motions. Most of the solutions for arbitrary geometries are based on 3D numerical methods. Analytical or semi-analytical methods that are usually based on matched eigenfunction expansions of the velocity potential in cylindrical coordinates have proven to be very efficient tools for treating the linear body-wave interaction problem in case of vertical cylinders (e.g. Garret 1971, Sabuncu and Calisal 1981) or arbitrarily shaped bodies of revolution with vertical symmetry axis

(e.g. Kokkinowrachos *et al* 1986). There is little work reported for bodies of arbitrary geometry out of the 3D numerical methods. For example Drobyshevski (2006) analyzed vertical-sided bodies, of arbitrary horizontal section, with flat bottoms and small under-keel clearance. Following the method of matched asymptotic expansions, the linear wave-body interaction problem is solved by matching the two “outer” flows with the “inner” flow near the structure’s edge. The 3D hydrodynamic problem is reduced to an integral equation in two dimensions formulated on the water line of the structure, simplifying the numerical implementation and reducing the number of subdivision elements. Numerical results are satisfactorily compared to analytical results. It is concluded that the proposed approach may provide an alternative to a complete 3D panel method, for analysis of vertical-sided structures in shallow water.

The extension of the matched axisymmetric eigenfunction expansion method for treating the mono- and bi-chromatic second order body-wave diffraction problem and evaluating the wave run-up in case of vertical truncated or compound cylinders, either floating or bottom-fixed, has been reported in a series of papers by Mavrakos and Chatjigeorgiou (2006a) and Chatjigeorgiou and Mavrakos (2006, 2007a, b). In the case of arbitrarily shaped bodies, Zang *et al* (2006) solved the second order scattering problem around a fixed ship-shaped body (FPSO: Floating Production Storage and Offloading vessel) in unidirectional steep waves by employing a quadratic Boundary Element Method (BEM). Very good agreement between numerical results and experimental measurements was reported. In addition, the significance of the second order free surface components at the bow of the ship in accurately predicting the wave-structure interaction was highlighted.

The recent installations of Liquefied Natural Gas (LNG) terminals in shallow water zone in proximity to the coast have raised some interesting problems. The wave kinematics in shallow waters appear to be rather more complex than in deep waters. The accuracy of the formulations used for the calculation of low frequency loads, already addressed by Naciri *et al* (2004), continued to receive attention. In the shallow water region, the second order potential contribution becomes important and the approximation of the low frequency loads based on the diagonal terms of the Quadratic Transfer Function (QTF), so called Newman’s approximation, is no longer satisfactory. Chen and Duan (2007) presented a new approximation for estimation of the low frequency wave loads obtained by developing the QTF in a Taylor expansion with respect to $\Delta\omega$. Chen and Rezende (2008) presented some new developments on this approximation and numerical results for a standard 138km³ LNG carrier. The approximation is shown to give satisfactory results for values of $\Delta\omega$ up to 0.06 rad/s and for any water depth, by comparison to the full QTF computation. It should be noted that the time reconstruction is made by single sums only, instead of double sums used for the full QTF.

The effects of wave directionality on the second order loads acting on a floating vessel has been readdressed during the joint industry initiative HAWAI (sHallow WATER Initiative) dealing with shallow water effects on LNG terminals. Rezende *et al* (2007),

extended the middle-field formulation, based on the use of a control surface for the estimation of the second order loads, to the case of cross waves. As in the case of unidirectional waves, the near-field formulation is shown to give results with poor convergence while the middle-field formulation provides accurate results for horizontal and also vertical load components. Renaud *et al* (2008) calculated the QTF using the middle-field formulation for two incident waves coming from two different directions and compared predictions with experiments in regular waves, showing agreement for most of the test conditions. In addition they carried out calculations for irregular waves, concluding that the long-crested condition does not necessarily lead to conservative results. In some specific conditions, the loads are increased with the increase of the spreading.

In addition to the perturbation based solutions, fully nonlinear methods are used for solving the diffraction and radiation problems. They are usually based on the Mixed Eulerian-Lagrangian (MEL) approach for updating the moving boundary surfaces in the time domain. For example, Bai and Eatock Taylor (2006), using a higher order BEM, predicted the nonlinear waves radiated by a forced oscillating vertical circular cylinder. Direct prediction of the potential's time derivatives was avoided by introducing some auxiliary functions. Bai and Eatock Taylor (2007) extended this method to tackle the fully nonlinear regular and focused wave diffraction around a vertical cylinder in a Numerical Wave Tank (NWT). Comparisons between numerical and experimental data are good. A NWT has also been used by Wang *et al* (2007a) to investigate the interactions between water waves and non-wall-sided cylinders by accounting for fully nonlinear boundary conditions on the free surface and the body surface. The Finite Element Method (FEM) is adopted together with a 3D mesh generated through an extension of a 2D Delaunay grid on a horizontal plane along the depth. Simulations are made for bottom-mounted and truncated cylinders with flare and the results compare very well with those of the second order solution in the time domain.

Sriram *et al* (2006) examined the estimation of forces and responses, due to the nonlinearities in wave loads, in the design of offshore structures. MEL requires the free surface to be smoothed or regridded at each time step due to the Lagrangian characteristics of the motion, which results in numerical diffusion of energy in the system after a long time. In order to minimize this effect, this 2D investigation fits the free surface using a cubic spline approximation with a FE approach for discretizing the domain. The efficiency of the method was illustrated for the standing wave problem.

Bunnik *et al* (2006) presented a formulation for the estimation of low frequency damping and quadratic wave drift force transfer function. Synthesized time series of the waves and low frequency motions were analyzed. Parameters influencing the stochastic nature of the QTFs and wave drift damping, such as length of time series, number of time segments and frequency resolution, were discussed. Two estimation methods were used. One is based on cross-bispectral analysis and another on a minimization scheme involving the quadratic transfer coefficients and the

reconstruction of the second order time series. The latter worked satisfactorily, thereby also providing an estimate for the wave drift damping coefficient. The procedure can be readily applied to low frequency motion time traces obtained from model test results or full-scale results.

2.1.2 *Effects of varying Bathymetry*

When shallow water operation is considered, the influence of the seabed bathymetry variation on the loads acting on the floating body needs to be examined. Buchner (2006) modelled the varying bathymetry as a second fixed body on the classical diffraction theory. The numerical results obtained were compared to experiments. It was observed that interference effects are too strong and the modelling of the bathymetry as a second body, without special measures, can not lead to correct results. 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. The method applies semi-transparent panels to the region of the bathymetry boundaries. The radiation coefficients obtained were compared with those obtained when only an opaque bathymetry is considered. In addition, the wave kinematics obtained by the diffraction code were compared to those obtained by a shallow water code based on Green-Naghdi theory. The results of the comparisons were considered satisfactory. Belibassakis *et al* (2007) presented a coupled mode technique for the prediction of wave induced set-up and mean flow in variable bathymetry domain. The model includes effects of bottom friction and wave breaking. Numerical results were compared with predictions obtained by the mild-slope approximation (Massel and Gourlay 2000) and experimental data.

Bingham *et al* (2007) reported on the development of a finite difference based numerical solution of the exact 3D potential flow problem for nonlinear waves and their interaction with fixed or floating structures. The work represents an intermediate stage of the development for which the final goal is to obtain highly efficient solutions on structured blocks on which the bottom variation is arbitrary but horizontal boundaries are uniform in the vertical and single-valued functions of the horizontal coordinate. Some results are presented for a rectangular bottom mounted structure and for a gap diffraction case.

Van der Molen (2007) presented a method for the calculation of waves in harbours and resultant ship motions. Calculation of the wave field requires an accurate description of the shape of the harbour and its bathymetry, whilst for ship motions the shape of the hull is important. Therefore, different methods are used for each problem. Propagation of incident waves is done through a Boussinesq-type wave model. The disturbance of the incident waves by the ship hull is treated using a panel based linear time domain diffraction model. The influence of nearby quay walls is taken into account. The superposition principle is used to consider the motions of the body in waves, i.e. the diffraction of the incident waves around the restrained body and the radiation problem are treated separately. This linearized approach is allowed as long as the motions are

small. Cornett *et al* (2008) described a large scale (1:50) physical model study conducted to investigate the movements of two LNG carriers moored at both berths due to the drawdown and wake created by a Suezmax tanker transiting the waterway. The physical model includes the effects of wind, river current and bathymetry. The drawdown and ship wake observed in the model was compared with site measurements. Strong influence of passing vessel speed on moored ship motions and mooring loads was identified. Christensen *et al* (2008) presented a method for simulating the motions and mooring forces of a ship under wave excitation. This method was applied both in open water and inside a harbour. The time domain simulation tool, called WAMSIM, applies the WAMIT® model to obtain the frequency domain hydrodynamic characteristics of the body. Diffraction forces are calculated using a Haskind relation and the wave input from a Boussinesq model taking into account the geometry of the harbour. However, the retardation functions are determined for an open water domain.

2.1.3 Multi-body Interactions

Recently, the side-by-side configuration for offloading operation has been often used, especially for gas transfer from one vessel to other. The accurate prediction of wave kinematics in the confined zone between the bodies is a crucial issue for the estimation of first and second order loads acting on the bodies. It is known that the wave kinematics is overpredicted by the classical potential theory. Different methods used aim to bring the resonant wave kinematics to more realistic levels. Fournier *et al* (2006) presented a series of results, using the flexible lid method and the “fairly-perfect” formulation, and model tests for two LNG vessels in side-by-side configuration. The distance between the two vessels was varied in the calculations. It was shown that the resonance in the gap affects not only the local wave field, but also the first order motions and the wave drift loads. Kristiansen and Faltinsen (2007) compared model test results (nearly 2D) with numerical calculations based on potential theory, both for the linear case and including nonlinear effects. Analogies to the moonpool problem were made in the treatment of the terminal gap. The results obtained showed that the wave kinematics in the terminal gap is overpredicted by both the linear and nonlinear potential methods. Pauw *et al* (2008) also compared model test results and numerical simulations, based on linear diffraction theory and lid methods (Chen 2007), on side by side LNG carriers in head waves. The damping parameter used for the lid between the two vessels is crucial for more realistic values of wave drift forces.

Kashiwagi (2008) described a method for multiple floating bodies in proximity. With an increase in the number of floating bodies, the calculation for wave-body interactions becomes formidable with the direct panel method. In such a case the Wave Interaction Theory (WIT) may be used which has a limitation, namely each interacting body must be far enough apart from the other bodies. In practice, however, WIT has been used successfully even for a case where the separation distance between the bodies is virtually zero. The authors investigated the applicability of WIT by considering 4 identical box-shaped bodies and comparing computed results with those obtained by

the higher order BEM. It was shown that the horizontal wave force, using WIT, compared favorably even when the separation distance is very small. This is not, however, the case for the vertical wave force.

Teigen and Niedzwecki (2006) calculated the second order wave amplifications around two identical side-by-side barges. It was observed that second order effects at the sum of frequency may cause intense wave amplification at certain zones. It should be noted that their results were obtained without including dissipation due to viscous effects. Therefore, in reality, one may expect that the wave amplifications are much less important, especially in case of second order waves. In the same context, Wang and Wu (2008) analyzed the second order resonant oscillations of liquid confined between two rectangular floating cylinders undergoing forced oscillations. FEM was used to obtain the velocity potentials at each time step. It was shown that when the oscillation frequency is equal to one half of the fluid's first order resonant frequency, the second order fluid's resonant motions became evident, a fact that requires further investigation. The influence of small gaps on hydrodynamic interactions obtained by the solution of the radiation problem among multiple floating bodies has also been studied by Zhu *et al* (2006). The study focused on the radiation problem in the frequency domain, using two box-shaped bodies. The effect that the gap's width and the depth have on the resonant frequency and the resonant amplitude of added mass and damping forces due to the radiation motions of the multiple bodies were discussed.

Another issue concerns the accurate calculation of low frequency wave loads acting on each body separately. The numerical problems suffered by the near-field formulation have been pointed out (ISSC 2006a). The new middle field formulation developed by Chen (2007) can be used as an alternative for multi-body computations, since it is capable of providing low frequency loads acting on each body of a multi-body system as shown by Chen *et al* (2007a). Their numerical results are in good agreement with experimental measurements on a FPSO and on side-by-side vessels. The formulation of the drift force based on Lagally's theorem has been reestablished by Ledoux *et al* (2006). This formulation can also provide individual drift forces in multiple body situations. Like the middle-field formulation, the results obtained by Lagally's formulation have less numerical problems than the near-field formulation in case of body with sharp corners. However, Lagally's formulation suffers from the effect of irregular frequencies.

The linear and nonlinear interactions of water waves with multiple cylinders was also investigated. For example Zhao *et al* (2007) studied the solitary wave scattering by an array of surface-piercing vertical circular cylinders using the Boussinesq approach for the description of the flow field and finite element formulations for discretising the governing equations. Numerical predictions for exciting wave forces and wave run-up on the cylinders were compared with experimental data of solitary wave reflection from a vertical wall and solitary wave scattering by a single vertical circular cylinder and an array of two and four cylinders, indicating very good agreement. Mavrakos and Chajigeorgiou (2006b) investigated the second order diffraction between

monochromatic second order waves and an arrangement of two concentric vertical cylinders. Second order wave loads on each constituent part of the two-body arrangement and corresponding wave run-up in the moonpool area, between the external toroidal body and the internal piston-like cylinder, were evaluated. The significance of the second order effects, especially in the frequency regions of fluid resonances in the moon pool were highlighted. Walker *et al* (2008) studied the diffraction of monochromatic waves by an array of four bottom mounted cylinders and a gravity-based structure using linear and second order theory. The phenomenon of near-trapping was investigated, allowing guidelines for air-gap design to be established. In doing so, a design wave, called New Wave, was proposed as a realistic model for large ocean waves in the wave-structure diffraction analysis.

Koo *et al* (2004) developed a 2D fully NWT based on BEM and MEL time marching scheme. Wave deformation and wave forces on submerged single and dual cylinders were investigated. The computed mean, first, second and third order wave forces on a single submerged cylinder were compared with experimental data, Ogilvie's second order theory and high order spectral method. The computed results agree well with measurements, but there exists notable discrepancy in the first order wave forces as the KC number increases, which can be attributed to viscous effects. The NWT simulations for submerged dual cylinders show that the interaction effects can be significant when the gap is small. In particular, the higher harmonic forces on the rear cylinder can be greatly increased due to already deformed incident waves by the front cylinder. A 2D fully nonlinear NWT in time domain is used. Koo and Kim (2007a) used a similar 2D NWT for the nonlinear interaction of stationary surface-piercing single and double bodies with surface waves. Mean and a series of higher harmonic force components were calculated and compared with the experimental and other numerical results, showing good correlation. Typical patterns of two-body interactions, shielding effect, and the pumping/sloshing modes of water column in various gap distances were investigated.

Interaction of linear waves and multiple porous structures was also investigated. For example, Silva *et al* (2006) presented a numerical method for analyzing the interaction of non-breaking waves with an array of vertical porous circular cylinders on a horizontal bed. The influence of the mechanical properties of the porous structures and the wave irregularity on wave transformation was examined. Results for unidirectional and multi-directional wave spectra were compared to those obtained for regular waves, providing a tool for engineering analysis. Sankarbabu *et al* (2007) investigated analytically the diffraction of linear waves around a group of dual porous cylinders, comprising a thin and porous outer cylinder with an impermeable inner cylinder, using an eigenfunction expansion method. The influence of the multiple interactions between the concentric cylinders in the group on the hydrodynamic forces, wave run-up and free surface elevation in the bodies' vicinity were examined.

A 2D solution method for the interaction of linear waves with an array of infinitely long horizontal circular cylinders in a two-layer fluid of infinite depth was presented by

Feng *et al* (2008). A multipole expansion method was used and analytical expressions for wave forces, hydrodynamic coefficients, reflection and transmission coefficients and energies were derived. The analytical results were compared with numerical ones obtained using a BEM, showing good agreement.

2.1.4 Body-wave-current Interactions

Several studies were carried out dealing with the body-wave-current interactions and the associated subject of wave drift damping evaluations. Among them Mavrakos *et al* (2007) investigated the second order wave drift damping on hydrodynamically interacting large bodies in the presence of monochromatic incident waves. The so called heuristic approach was applied for the evaluation of the second order wave drift damping in surge and sway modes of motion whereas mean wave drift calculations were carried out using the near-field formulation. Chatjigeorgiou and Mavrakos (2007c) investigated the effect that the square of current's velocity term, U^2 , has on the hydrodynamic forces acting on a vertical bottom-fixed and free surface piercing cylinder in the presence of a coexistent wave-current field. Figure 1 shows the importance of the U^2 terms, especially for higher wave frequencies and positive Froude numbers (Fn), i.e. waves and current acting in the same direction. For wave and current fields acting in opposing directions the effect of U^2 appears to be negligible. Jian *et al* (2008) presented an analytical solution for the diffraction of short crested incident waves propagating along the positive x-axis direction around a large circular cylinder in the presence of a uniform current. The important influences of currents on wave frequency, water run-up and wave force on the cylinder were investigated.

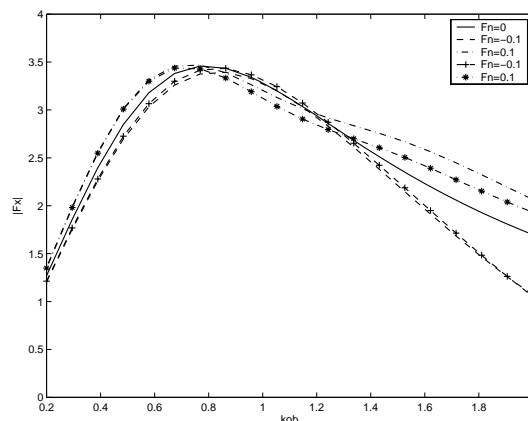


Figure 1: Horizontal exciting force on the cylinder for $F_n=0.1$ and $F_n=-0.1$. Lines with * and + symbols denote the combined contribution of both U and U^2 terms (Chatjigeorgiou and Mavrakos 2007c)

Koo and Kim (2007b) investigated nonlinear wave-current interactions with fixed or freely floating bodies by a 2D fully nonlinear NWT, based on a BEM with constant panels. MEL time marching scheme is used together with fourth order Runge-Kutta fully updated time integration, regriding, and smoothing techniques, as well as acceleration potential formulation and direct mode decomposition method. Specially

devised artificial damping zones were implemented to prevent wave reflection from the end wall and wave maker. Nonlinear wave-current interactions without bodies, with a stationary body and with a floating body were investigated for various wave and current conditions. Some of the simulations were compared with results from Boussinesq's equation and perturbation theory. It was noted that the NWT results reproduce the general trend of linear or perturbation theory in free surface profiles, run-up, forces, and motions. However, their magnitudes can be appreciably different from the perturbation based solutions, as wave steepness and current velocity grow.

2.2 *Forward Speed Case*

2.2.1 Overview of Methods

The focus of this section is on linear and nonlinear methods for prediction of ship motions and quasi-dynamic (i.e. ship treated as rigid body) hull girder loads. 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 vast majority of methods for ships at forward speed still belong to the first group and there is a large variety of methods ranging from linear theories to fully nonlinear methods, where the complete nonlinear potential flow problem is solved with as few assumptions as possible. Between these two extremes there are many partially nonlinear, or blended, methods, in which one aims at including the most important nonlinear effects.

A second order perturbation method in the frequency domain is well established for stationary wall-sided offshore structures, but such an approach is not strictly applicable to ships with forward speeds. Moreover, a second order method may not be sufficient to describe the nonlinear ship-wave problem, and proceeding beyond a second order theory will be complicated and not very practical. Hence, most of today's nonlinear methods produce results in the time domain. Fang and Chen (2006) however, used a second order method to calculate the added resistance and the mean lateral drift forces on a ship advancing in waves. Their method is similar to that of Salvesen (1978), but they use a 3D, rather than 2D, method for calculating the velocity potential with the zero speed Green's function. Comparisons are made with experimental data for a Series 60 hull. For the mean lateral force in oblique regular waves, the 3D method generally gives slightly better results compared to the 2D method. It appears that the 3D method may overestimate the heave motions around resonance. Results may be improved if a forward speed Green's function is used instead of the zero speed Green's function.

Although difficult, the different methods can be classified according to the level of nonlinearities included. Recently, Singh and Sen (2007a, b) used a classification with 4 levels. Two higher levels have been added and will be discussed in the next subsections. These levels are:

- Level 1: Linear
- Level 2: Froude-Krylov nonlinear
- Level 3: Body nonlinear
- Level 4: Body exact (Weak scatterer)
- Level 5: Fully nonlinear (Smooth waves)
- Level 6: Fully nonlinear.

The classification in Levels 2-5 is best suited for 3D potential theory codes, but strip theory codes will be included. Methods on Levels 2-4 are partially nonlinear methods, the most difficult to classify properly. Singh and Sen (2007a, b), presented results from a 3D panel code with different levels of nonlinearities, similar to the different levels of the LAMP code (Lin *et al* 1994). Singh and Sen (2007a) demonstrated that the different levels of modelling nonlinearities can give quite different results, as for example in the predicted relative velocity at the bow, which is important for slamming and whipping analyses. No experimental data are presented. Singh and Sen (2007b) compared Vertical Bending Moment (VBM) calculations from the different methods/levels with experimental data for the S-175 container ship in regular waves. It is shown that the linear method gives too low sagging and too large hogging moments.

In addition to the nonlinearities of the fluid-structure system, there is also the issue of nonlinearities in waves. For example, Kim (2007) reviewed the effect of sea severity on the vertical response of structures. It was noted that the vertical responses are consistently smaller in the higher seas than in the lower seas. The application and limits of the Volterra linear and quadratic models were examined. Impulse Response Functions (IRFs) were used to determine lateral and vertical motions. The developed numerical tool is limited to slow ship motion.

2.2.2 *Level 1: Linear Methods*

In the linear methods, the wetted body surface is defined by the mean position of the hull under the mean position of the free surface. The free surface boundary conditions are applied on the mean position of the free surface. The hydrodynamic problem is often solved in the frequency domain by either 2D, 2.5D or 3D methods. In the 2D methods, the ship's forward speed enters only in the body boundary condition, in the form of a speed correction. Such a speed correction method is also commonly used with the 3D Green's function (pulsating source) panel codes, to avoid computational difficulties. However, many 3D (as well as 2.5D) codes retain the forward speed term in the free surface boundary condition and solve for the forward speed Green's function (translating-pulsating source). 2.5D methods are limited to high speed problems, where the diverging waves dominate.

Fang and Chen (2008) adopted a 3D pulsating-source method to predict the significant wave loads for a trimaran travelling in waves. It was shown by Fang and Too (2006) that the pulsating source method can accurately predict the motion up to $F_n = 0.45$.

Based on a spectral analysis method, Fang and Chen (2008) obtained the significant wave loads including shear forces, bending moments, and torsion moments at different locations on the main hull and connected deck with respect to different outrigger arrangements (i.e. stagger and clearance). The calculations were performed for several ship speeds and wave headings. On the other hand, Inoue and Kamruzzaman (2008) developed a computer code, YNU-SEA, based on 3D Green's function method with forward speed for analyzing the radiation and diffraction forces and motion responses of high speed catamarans in waves. The numerical solutions were performed for the heave and pitch modes of motion. The calculated hydrodynamic coefficients (added mass and hydrodynamic damping) and exciting forces were compared with the experimental data and other numerical calculations found in open literature. Furthermore, the effect of bulbous bow on the free surface elevation and motion responses were analysed by comparing the relative wave height generated by a Wigley hull catamaran with and without bulbs. It was observed that the size and fineness of the bulb were significant factors needed to reduce the relative wave height under the deck structure for the high speed catamarans or other multi-hulled vessels.

The principal justification for use of strip theory is that it gives estimates for seakeeping motions and structural loads in ships with satisfactory engineering accuracy. Recently, Milgram (2007) presented a modified form of strip theory formulation for underwater vehicles. The modifications are as follows: (a) the vehicle is submerged; (b) the water depth is finite; (c) forces on cross-sections are computed using Green's Theorem; (d) there are no transom stern corrections; (e) the forces and moments due to hydrodynamic lift forces on the vehicle fins are included; (f) there are no free surface hydrostatic effects. Furthermore, experiments were conducted in head and stern seas with a model underwater vehicle for a range of forward speeds, wavelengths and vehicle submergences. Force and moment magnitudes between the numerically implemented theory and experiments are, generally, in good agreement for most conditions.

Once the velocity potential on the hull has been calculated, the pressure can be found from Bernoulli's equation and forces and moments are obtained by integrating the pressure. Alternatively, a variant of Stoke's theorem can be used to obtain forces and moments directly from velocity potential. However, this theorem introduces some assumptions, and it was recommended by Zhang and Beck (2007a) to use the pressure integration method for the radiation problem. A challenge with the pressure integration method is the evaluation of the $\partial\phi/\partial x$ term. Bandyk and Beck (2008) use Radial Basis Functions (RBF) to evaluate this term. They report that this works well, except for isolated instances where these functions seem to give erroneous results. The difficulties with the $\partial\phi/\partial x$ term can be avoided by using higher order panels instead of the Constant Panel Method (CPM). Zhang *et al* (2008) report on the implementation of a Quadratic BEM (QBEM) into the 3D time domain LAMP code. The higher order panels also provide faster convergence with respect to panel size. Zhang *et al* (2008) report that results so far have not shown any significant difference between CPM and QBEM for the vertical motions and loads, and that this is probably partly due to the

fact that these problems are often dominated by inertia and nonlinear hydrostatics rather than the wave-body disturbance. They expect the difference between the two methods to be more pronounced for the horizontal modes of motion.

Gao and Zou (2008) developed a higher order Rankine panel method based on Non-Uniform Rational B-Splines (NURBS) to solve the 3D radiation and diffraction problems with forward speed. The velocity potential distribution on the body surface is described by B-splines, after the source density distribution on the body surface is determined. The method is firstly applied to the unbounded flow problem of a sphere and spheroids and is verified by comparing the numerical results with analytical ones. Furthermore, the radiation and diffraction problems of a submerged sphere and the diffraction problem of a submerged spheroid were investigated. The predictions were compared with the analytical results and experimental measurements found in open literature. From the comparisons, it is seen that the method is effective for the 3D radiation and diffraction problems with forward speed.

In general, the computational error of the panel method is mainly due to four reasons: (i) the geometrical approximation; (ii) the assumptions in the distribution of velocity potential or source strength on a panel; (iii) the evaluation of the singular terms in the integral equation; (iv) the evaluation of the free surface Green's function. Qiu and Peng (2007) introduced a panel-free method to remove the error due to the first three sources, and to compute the wave interaction with bodies at forward speed in the frequency domain. The desingularized integral equation in terms of source strength distribution was developed by removing the singularity due to the Rankine term in the forward speed Green's function. NURBS surface was adopted to describe the exact body geometry mathematically. The integral equations were discretized over the body surface by Gaussian quadrature. The accuracy of the method was demonstrated by its application to the radiation and diffraction problems of a submerged sphere and a Wigley hull at forward speed. The method was extended by Peng *et al* (2007) to compute the wave interaction with floating bodies of complex geometry. The hydrodynamic coefficients and motion responses were calculated for a LNG carrier in shallow water waves and a FPSO platform in deep water. The computed results agree well with experimental data and those obtained by panel methods.

2.2.3 Level 2: Froude-Krylov Nonlinear Methods

In the 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 IRFs. The time domain response will contain a convolution integral with the IRF to account for the memory effects.

Another common starting point is to solve the problem directly in the time domain using the 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, such as due to slamming and green water. One must be careful to avoid including terms that are already part of the linear solution. Vertical viscous forces are also sometimes included by semi-empirical methods, and the influence of these have been studied by Arribas and Fernandez (2006) for high speed mono-hulled vessels.

In the methods based on linear IRF it is implicitly assumed that the structure responds linearly to the loads; i.e. there is a nonlinear relationship between the wave amplitude and the load amplitude, but the relationship between load and response remains linear, as given by the IRF or RF. It is assumed that these functions are valid for the conditions that the ship encounters during the time domain simulation. If the roll angle becomes large or if large portions of the hull come out of water this latter assumption may not be valid.

The Level 2 time domain 3D formulation LAMP-2 is extended to handle multiple bodies and various cable and fender systems by Weems *et al* (2007). Calculations of ship motions are compared with model test results. The validation indicates that the key hydrodynamic motions and forces are well predicted by the method. Validation results for heave and pitch motions of catamarans were presented by Lin *et al* (2007). Quite good agreement for heave and pitch motions is shown, but the presented validation includes only a few sample time traces. They also evaluated a set of software tools for the hydrodynamic design and performance assessment of innovative high speed sealift hull form. Using a series of model tests, these tools (ComPASS, Das Boot, VERES, LAMP, FANS and SHAPE) were assessed for their ability to provide useful guidance to designers. Nonlinear potential flow codes such as Das Boot and LAMP showed the ability to capture motions of innovative hull forms. Furthermore, extending potential flow codes with additional models allowed a wide range of practical design problems to be tackled, including estimations of slamming pressures, modelling motions with active SES cushions, and investigating manoeuvring.

A two-step approach, similar to the one used in the Level 2 methods, is often used when seakeeping and manoeuvring calculations are coupled, e.g. for manoeuvring assessment in waves. A method applied to two side-by-side moored vessels at forward speed in waves was presented by Murthy Chitrapu *et al* (2007). They use a 3D zero speed Green's function method with speed correction for the linear frequency domain solution. After transformation to time domain, the manoeuvring forces are included. The method is validated using model tests for two ships. Sutulo and Guedes Soares (2006) developed a mathematical model, with six Degrees of Freedom (DoF), for seakeeping-manoeuving analysis of slender ships operating in regular waves. In still water it reduces to standard lumped-parameter manoeuvring models, whilst in straight path motion in regular waves it corresponds to existing nonlinear strip theory

seakeeping models. The Froude-Krylov and restoring forces are nonlinear whilst the radiation and diffraction forces are linear. Manoeuvring corrections are added based on considerations similar to the Munk method. Memory effects are dealt with by increasing the number of state variables. Some simulation of standard manoeuvres in regular waves is presented for the S-175 container ship.

Mikami and Shimada (2006) worked on a time domain strip method which includes body-nonlinear effects in hydrodynamic forces, as well as in hydrostatic and Froude-Krylov forces. Hydrodynamic forces are calculated as the sum of memory effects, which are impulse responses to relative velocities of the ship geometry and the wave at each time step. The memory functions are calculated beforehand for ship sections at different drafts. This approach may be regarded as an intermediate step between Level 2 and Level 3. Comparison with experiments were carried out for a Wigley hull and two container ships. Quite good agreement was obtained for heave, pitch and VBM in head seas. For the post-Panamax container ship sway, roll and horizontal bending moments (HBM) in oblique waves are also presented. The agreement with experimental data is quite good, but the HBM is more accurately predicted by a linear Rankine source method. The experimental data indicate that the HBM behaves in a more linear manner than does the VBM.

2.2.4 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 regriding and recalculation of the disturbance potential for every time step. The computational costs will therefore increase dramatically as compared to Level 2 methods.

Zhang and Beck (2006, 2007b) presented a 2D body-nonlinear method based on Rankine sources with constant strength over each panel, i.e. CPM. The method was further developed by Bandyk and Beck (2008), already mentioned in section 2.2.2. The body boundary conditions used in calculating the disturbance potentials assumes that the pitch and yaw motions are small. Hydrodynamic coefficients and RAOs agree quite well with experiments and linear prediction methods for the S-175 container ship. Results for nonlinear forced motions are also presented, but nonlinear seakeeping calculations are not presented. A 3D version of this method was developed by Zhang (2007) and results from this method are presented by Zhang and Beck (2007a). Results for the nonlinear seakeeping problem have not yet been presented. Only forced motion and wave resistance calculations were published for a sphere and a modified Wigley hull. These calculations show good agreement with experiments and results from a Green's function method. A comparison of the 2D and 3D methods was presented by Zhang *et al* (2007). The agreement was good, while the 2D method was an order of magnitude faster. The 2D method is also better for modelling arbitrary hull geometries.

Ogawa (2007) compared results from a nonlinear strip method by Ogawa *et al* (2006),

where the radiation and diffraction problems are solved at each time step, with experimental data for a post-Panamax container ship. RAOs for motions, accelerations and VBM are compared for different wave steepness, heading and forward speed values. VBM was measured at amidships and at the quarterlengths. Quite good agreement was obtained, except for the VBM at the fore quarterlength, which displayed a high sensitivity to wave height.

2.2.5 *Level 4: Body-exact Methods (Weak Scatterer)*

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. This problem can be circumvented by mapping the geometry into a computational domain where the incident wave surface becomes a flat plane (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. The weak scatterer hypothesis was introduced by Pawlowski and Bass (1991) for a 3D panel method. Recently, Peng *et al* (2006) extended this method from mono-hulls to multi-hulls; so that hydrodynamic interaction between the hulls is included. Calculated heave and pitch motions of a twin-hull SWATH/catamaran vessel in regular and irregular waves agree quite well with experimental data.

2.2.6 *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 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 (Bandyk and Beck 2008). Lin and Hoyt (2007) applied a 3D fully nonlinear method presented by Lin and Kuang (2006) to a fast amphibian vessel. The method is developed for six DoF calculations of arbitrary shaped hulls in finite water depth, but the paper does not present results for the nonlinear seakeeping problem.

Sun and Faltinsen (2007) presented a 2.5D theory with a fully nonlinear BEM method for the analysis of porpoising and dynamic behaviour of planing vessels in calm water. Whilst Zhao *et al* (1997) used a very high Froude number assumption so that hydrodynamic coefficients are independent of frequency and Froude number, the present work properly includes the effect of gravity. Linear stability theory was

applied to predict the inception of porpoising, and it was shown that the new methods compares better with experimental data than does the method which uses frequency independent hydrodynamic coefficients.

An interesting development is the work by Yan and Ma (2007) who extended the QALE-FEM (Quasi Arbitrary Lagrangian-Eulerian FEM) based on a fully nonlinear potential theory to deal with the fully nonlinear interaction between steep waves and 2D floating bodies. In this method, complex unstructured mesh is generated only once at the beginning of the calculation and is moved to conform to the motion of boundaries at other time steps, avoiding the necessity of high cost remeshing. Using the developed techniques and methods, various cases associated with the nonlinear interaction between waves and floating bodies were numerically simulated and compared favourably with experimental results.

2.2.7 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. For these types of problems, methods solving the RANS equations are often used. In these methods, the water/air volume is normally discretized, and a finite difference, finite volume or a finite element technique is used to establish the equation system. 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, the latter more suitable for violent flows.

Tahara *et al* (2006) presented an overview of CFD methods and employed two RANS equation solvers (CFDShip-Iowa version 4 and Flowpack version 2004e) for a container ship, in towed and self-propelled conditions. They also provided comparisons with available experimental fluid dynamics data. It was concluded that the accuracy of the methods would be acceptable in practical design, after performing extra case studies to verify the trends in the current solutions. On the other hand, Zwart *et al* (2007) described an algorithm for solving free surface flows around ship hulls. The solution algorithm implicitly couples velocity, pressure and volume fractions. The conservation equations were discretized using finite volume method. The algorithm was implemented in the ANSYS-CFX software package, and is validated by comparing with experimental data on a number of ship hull benchmark cases in both steady and transient conditions. The calculations were performed for a Wigley hull and a Navy surface combatant ship. The wave elevations and wave forces were calculated and compared with experimental measurements under steady and transient flow conditions.

Carrica *et al* (2006) studied the forward speed diffraction problem in head regular waves for the surface combatant DTMB 5512 using a RANS approach with a single phase Level Set method to compute the free surface. Predictions were compared with experiments for two cases. The first is at Froude number 0.28 in long waves, where the

response is linear. Validation was performed for resistance, heave forces, pitch moments, unsteady free surface elevation and unsteady nominal wake velocity profiles. In the second case, the Froude number is 0.41 in short waves, and the nonlinearities are more pronounced. Here, validation was performed for heave forces and pitch moments. Good agreement was obtained for the first case, while there were more discrepancies in the high speed nonlinear case.

Yang and Löhner (2006) presented a RANS solver with a Volume of Fluid (VOF) method for free surface computations. In their NWT, the heave and pitch motions of an LNG carrier in head waves were studied. Regular waves of different length and height were investigated. Slamming and water-on-deck events are also handled by the code. No validation is presented for this case. Another application of a RANS solver (FLUENT) with a VOF method is presented by Sasanapuri *et al* (2007). In their NWT, resistance, manoeuvring and heave/pitch motions in head regular waves of a generic catamaran were studied. Validation was not presented, but the calculated steady resistance is compared with results from a validated potential theory code, showing good agreement.

El Moctar *et al* (2006) applied the RANS solver COMET with a VOF method to a 100 m motor yacht travelling at 13.4 knots in head regular waves. Time series of measured and predicted pitch motion and vertical acceleration at FP show good agreement. They also compared the longitudinal distribution of vertical shear forces and vertical bending moments for two container ships predicted using their RANS method and a 3D BEM (GLPANEL). Since the RANS method includes slamming loads, it predicts larger load effects in the fore part of the ship, when compared to the BEM.

To analyse a ship advancing in head waves, one usually imposes an incident wave field at the inlet boundary. It is modelled as velocity and pressure perturbations, added to the uniform stream. The perturbations are usually derived from the linear potential flow solution for free surface waves. This approach requires large computational resources, because the grid must be very refined between the ship and the wave maker. Moreover, wave reflections will affect the incident waves, and it is difficult to apply the method to irregular or focused waves. To overcome these problems, Ferrant *et al* (2008a) used the so called SWENSE (Spectral Wave Explicit Navier-Stokes Equations) method to calculate the motions of a ship at forward speed in irregular waves. The approach uses a fully nonlinear potential flow description for the incident wave systems combined with a modified set of RANS equations, with free surface equations accounting for the interaction between the waves and the ship. A basic SWENSE calculation is performed in three steps: (a) determination of the undisturbed incident flow; (b) solution of the SWENSE equations giving the nonlinear viscous flow correction to the incident flow and (c) solution of the initial problem based on the previous two steps. Application to 6-DoF self-propelled ship manoeuvring in irregular waves was presented by Ferrant *et al* (2008a, b). Validation is not presented for this case; but the method has been previously validated two different applications; the first is for captive tests on a naval combatant model in head waves as reported by Luquet *et*

al (2005), the second for a Tension Leg Platform (TLP) in regular and irregular waves as reported by Luquet *et al* (2007). The SWENSE approach combined with an SPH solver was presented by Guilcher *et al* (2006), but only the diffraction problem for a fixed submerged cylinder was investigated

Hu and Kashiwagi (2006) presented a CIP-based method, which is validated for a Wigley hull at Froude number 0.15 in head regular waves. It is concluded that the method predicts heave and pitch motions and forces with sufficient accuracy. Kashiwagi *et al* (2007) improved the CIP method by implementing a new interface capturing scheme, proposed by Xiao *et al* (2005). Predictions were compared with Wigley hull measurements at Froude number 0.15 in head regular waves and a range of wavelengths. For heave, the agreement with experiments is reasonable for most wavelengths, but a 3D Rankine panel method and a strip method are shown to give better results. For the pitch RAO, the accuracy of the CIP method is closer to that of the potential methods, but the experimental data are more scattered for the longer waves.

2.3 *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 these 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. For example, Schellin (2007) examined the determination of safety levels under freak wave conditions. The reserve strength of a jack-up structure with respect to rule based design capability under freak wave condition was assessed using advanced CFD codes like COMET.

Clauss *et al* (2006) argue, based on analysis of collected data, that rogue waves are serious events and that a ship will encounter more than 3500 such waves in its lifetime of 25 years; hence, they should be considered in ship design. They generated variations of the New Year or Draupner wave (NYW) in a wave tank. These comprised (i) NYW with local elongated period and (ii) NYW with local elongated wave period and increased local wave height. Experimental tests with an FPSO model indicated that both variants resulted in larger maximum VBM than the original NYW, with variant (ii) producing the largest response which was slightly larger than the DNV (Det Norske Veritas) rules value. The authors concluded that local wave pattern is extremely important for maximum responses. They also emphasized the need to determine maximum responses using numerical methods in time, rather than the more conventional frequency domain. Guedes Soares *et al* (2006) compared measured and calculated responses for the aforementioned FPSO in a wave train containing a rogue wave, obtained from NYW. Their predictions are based on a strip theory, accounting for nonlinearities relating to hydrostatic restoring and incident wave excitation. The comparisons between numerical and experimental results for the amidships vertical bending moment show good agreement. They also varied the position, both

numerically and experimentally, that the large wave crest passes along the ship and concluded that it did not affect the maximum amidships bending moment magnitude. The maximum amidships VBM, measured or predicted, is 10% smaller than the DNV rules value.

Fonseca *et al* (2006) used the same 2D partly nonlinear methods to predict vertical bending moments on a container ship travelling in 20 different wave trains, containing rogue waves. These wave trains were based on data recorded from hurricane Camille, North Alwyn platform and NYW. They also carried out long-term distributions of the VBM for the container ship operating in the Northern North sea using 10-8 probability of exceedance, i.e. approximately 24 years life. The long-term bending moment values were larger than the maximum values predicted in the rogue wave trains, indicating non-rogue wave conditions capable of inducing larger bending moments than rogue waves.

Clauss and Schmittner (2007) investigated the deterministic analysis of wave-structure interaction in the sense of cause-reaction chains, and analyzing structural responses due to special wave sequences (e.g. three sisters phenomenon) for the precise generation of tailored wave sequences. Applying conventional wave generation methods, the creation of wave trains satisfying given local wave parameters, and the generation of wave groups with predefined characteristics is often difficult or impossible, if sufficient accuracy is required. In this paper an optimization approach for the experimental generation of wave sequences with defined characteristics is presented and applied to generate scenarios with a single high wave superimposed to irregular seas. The optimization process is carried out in a small wave tank. The resulting control signal is then transferred to a large wave tank in order to investigate wave-structure interaction at a large scale.

2.4 Hydroelasticity

2.4.1 Theoretical Methods

Remy *et al* (2006) presented a general method for hydroelasticity analysis, including definition of structural model, ship and cargo mass distributions and ship geometry. In the analysis, firstly, the dry dynamic properties, such as natural frequencies and mode shapes are calculated. Then, the fluid-structure interaction effects are determined in terms of modal hydrostatic stiffness, modal added mass and modal hydrodynamic stiffness, and modal wave loads are calculated. Finally, the wet natural frequencies and associated wet modes are obtained as well as the transfer functions (or RAOs) for determining ship structural response to wave excitation. The authors also conducted an experimental study for a very flexible barge in the BGO (First Basin, Toulon, France). The barge was constructed to be quite flexible in order to expose high level of hydroelastic phenomena. The model tests were performed in irregular waves generated by JONSWAP spectra. Senjanović *et al* (2008) investigated the hydroelastic response behavior of this flexible barge using the aforementioned methodology. They compared

the predicted RAOs with the aforementioned measurements, showing reasonably good agreement.

Riggs *et al* (2008) carried out a more detailed comparison of the results from a select group of models from a study for a pontoon (mat-like) Very Large Floating Structure (VLFS), initiated by Specialist Task Committee VI.2 (ISSC 2006b). They discussed the developments in computer codes for linear hydroelasticity in recent years, driven in part by the motivation to investigate the wave induced response of VLFS. The codes covered a mix of both fluid models (potential and linear Green-Naghdi) for the calculation of fluid-structure interaction forces, and structural models (3D grillages, 2D plate, 3D shell). Three different codes, namely HYDRAN, VODAC and LGN were used to obtain the dynamic responses for a rectangular pontoon structure, 500 m long and 100 m wide. In all programs, the fluid is assumed to be incompressible and inviscid and the flow is assumed to be irrotational. HYDRAN uses a traditional 3D constant panel Green's function formulation for the fluid and a 3D shell finite element model for structure. VODAC uses a traditional 3D constant panel Green's function formulation, together with the interaction theory, for the fluid and 3D grillage model for the structure. LGN uses the Green-Naghdi equations in the fluid domain and a linear Kirchhoff plate model for the structure. It was demonstrated that all three models can be used with confidence, especially for preliminary studies. LGN is the most computationally efficient, and HYDRAN is the most computationally demanding. On the other hand, it should be noted that LGN is limited to a structure that can be modeled as a uniform plate and for relatively shallow water.

Chen *et al* (2006a) reviewed existing hydroelasticity theories. They classified them into different types, namely: 2D linear theory, 2D nonlinear theory, 3D linear theory and 3D nonlinear theory. Based on the 3D nonlinear hydroelasticity theory by Wu *et al* (1997), the nonlinear equations of motion in frequency domain and in time domain are presented. It was noted that the second order forces may have a great effect on the responses of VLFS. It was also noted that 2D and 3D linear theories are relatively mature, but others, such as the 3D nonlinear theory and the hydroelasticity considering nonlinear structural behavior are still being developed. Furthermore, they concluded that the time domain methods are only suitable for fully nonlinear problems, and that the development of effective nonlinear hydroelasticity theories in the time domain should be the main focus in the near future. Recently, Temarel (2008) presented ongoing developments on hydroelasticity theory, with particular reference to nonlinear and viscous effects.

2.4.2 Ship Structures

Ergin *et al* (2007) applied a 3D linear hydroelasticity method, based on the work by Ergin and Temarel (2002), to the fluid-structure interaction of a 1900 TEU container ship. The wet resonance behavior (frequencies and mode shapes) was investigated for fully loaded and ballast conditions. The method is based on a boundary integral equation method, together with the method of images in order to impose appropriate

boundary condition on the fluid's free surface. The infinite frequency limit condition was imposed on the free surface, and this condition may be assumed acceptable for the high frequency vibration of fluid-structure systems. The calculated wet natural frequencies and mode shapes were compared with those obtained from FEM calculations (ABAQUS) showing very good agreement. The hull and the surrounding fluid domain were discretized using structural and fluid finite elements, respectively. Hirdaris *et al* (2006) reported on the influence of fluid-structure interaction modeling for a bulk carrier travelling in regular waves, considering both symmetric and antisymmetric motions and distortions. They employed strip theory for modeling 2D fluid-structure interaction, in conjunction with Timoshenko beam idealization of the ship's structure. They also used a 3D BEM, with a pulsating source distribution over the mean wetted surface to model 3D fluid-structure interaction, in conjunction with either beam or 3D FEM. In addition they examined different types of structural modeling for the deck with reference to modeling hatch openings. They reported differences between 2D and 3D fluid-structure interaction models for this bulk carrier, attributed to the shortcomings of the Timoshenko beam theory to model structural discontinuities and their influence on torsion and warping.

Mikami and Kashiwagi (2008) presented a nonlinear strip method capturing the geometric nonlinearities in the hydrostatic restoring and Froude-Krylov forces. The frequency dependence in the radiation and diffraction forces was accounted for using convolution integrals. The hull was modelled using Timoshenko beam theory. The dynamic response is analysed in time domain using modal decomposition. Numerical calculations were performed on a 716 TEU container ship, for which existing model tests results were available in terms of relative vertical motions at the bow and amidship VBM in head sea. The author's main interest was on green water influence on global loads. Shipping water height was computed and it was observed that this introduces a considerably large hogging moment amidships. Park and Temarel (2007) presented a 2D hydroelasticity method for symmetric dynamic behaviour of ships in waves including the influence of nonlinearities. They provided extensive comparisons with experimental measurements for the S-175 container ship travelling in regular head waves. They demonstrated that the nonlinear modifications of radiation force components due to added mass and fluid damping can be as important as flare slamming and nonlinear hydrostatic Froude-Krylov force for the response predictions. The nonlinear predictions were obtained using two different methods based on direct integration and convolution integration, respectively. Both methods predict results close to each other and are in agreement with experimental measurements of motions and VBM.

Tian and Wu (2006a, b) investigated the nonlinear hydroelastic responses of a SWATH travelling in irregular waves. The nonlinear fluid-structure interaction forces were due to large motions and the instantaneous wetted surface effects. They calculated the nonlinear hydrodynamic actions induced by the rigid body rotations and the variations of instantaneous wetted surface area. They confirmed that the latter has a relatively greater contribution than other nonlinear hydrodynamic actions. The first order wave

potentials and responses, which have major contributions to the second order hydrodynamic actions, were obtained using a translating-pulsating Green's function and the Kelvin steady wave flow solution based on the linear 3D hydroelasticity theory. The linear and nonlinear rigid body motions, structural distortions and stresses of a 150 tonnes SWATH travelling in regular and irregular head waves with forward speeds of 11 and 12 knots were numerically simulated. It was observed that the nonlinear predictions of the stresses and the deflections are larger than the linear predictions by up to 20~30%.

Wu and Moan (2006a, 2007) described a hybrid time domain nonlinear simulation and introduced the peak over threshold (POT) method as one of the stochastic analysis procedures to predict the short-term nonlinear wave-induced extreme hydroelastic responses. A SL-7 class container ship and a modern LNG carrier were chosen as example vessels to investigate the influences of hull flexibility and structural damping on the short-term prediction of extreme vertical load effects (vertical bending moment, shear force, etc.). Taghipour *et al* (2007) presented a time domain hydroelastic analysis for marine structures. The convolution terms in the mathematical model are replaced by their alternative state-space representations whose parameters were obtained using the realization theory, an alternative parameter estimation method. The mathematical model is validated by comparison to experimental results of the very flexible barge by Remy *et al* (2006). Taghipour *et al* (2007) also employed an alternative parameter estimation method, namely impulse response curve fitting and regression in the frequency domain. The realization theory and frequency domain regression were compared for a modern container ship. Two scenarios were simulated: (i) the dynamic responses due to regular wave-induced excitations; (ii) transient responses after release from a displaced condition. The authors observed that the realization theory and frequency domain regression simulate the vessel responses equally well.

The increasing size of new container ships reaching almost 400m in length raises concern about possible occurrence of springing. This implies that hydroelastic effects must be assessed by the designer. Malenica *et al* (2008) presented a global hydroelastic model, based on modal decomposition in time domain using convolution integral technique, which can be applied to study springing and whipping effects on container ships. On the other hand these type of ships are prone to torsional loads in oblique waves, requiring the coupling between torsional and horizontal bending modes. A simple beam model for coupled torsional and horizontal bending vibrations can still be used in the preliminary design phase as shown by Malenica *et al* (2006), through comparison between a beam model and a full 3D FEM model for a barge geometry. Kim and Kim (2008) studied the springing phenomenon, at zero forward speed in oblique waves, using a beam finite element model for the structural response and a 3D BEM method for the hydrodynamic forces. The main problem posed by such mixed BEM-FEM approaches is the fluid-structure coupling via the body boundary condition, namely the fluid pressure at one body panel depends on the deformation velocity of the panel and vice versa. A quasi-Newton method based on the numerical evaluation of the gradient was applied for the solution of the coupled nonlinear problem.

Verification of the proposed approach was carried out using the flexible barge measurements by Remy *et al* (2006), showing a good agreement for the RAOs of the vertical motion of the various model segments. It was also shown that flexible and rigid body pressure distributions for the barge configuration may differ significantly, due to the occurrence of flexible body resonance frequencies.

2.4.3 *Specialist Structures*

Fu *et al* (2007) described a method for predicting the response of a flexible, floating interconnected structure using a general 3D linear hydroelasticity theory. All the modules and connectors are considered to be flexible, with variable translational and rotational connector stiffness values. The method is validated by a special numerical case, where the hydroelastic response for very high connector stiffness values is shown to be equivalent to that of a continuous structure. A numerical example of a two-module structure is presented. This model is used to demonstrate the hydroelastic response characteristics of flexible, floating interconnected structures (displacements, bending moments, etc.) under various conditions and the effects of connector and module stiffnesses on the hydroelastic responses.

Uğurlu and Ergin (2006) extended the hydroelasticity method proposed by Ergin and Temarel (2002), taking into account the effect of axial fluid velocity in order to predict the elastic responses of pipe lines conveying fluid. The fluid-structure interaction forces were calculated in terms of the generalized added mass, generalized fluid damping coefficients (due to the Coriolis acceleration of fluid) and generalized fluid stiffness coefficients (due to the centrifugal effect of fluid). Uğurlu and Ergin (2008) further extended the method by employing higher order panel method for the calculation of fluid-structure interaction forces. The predictions based on the method compare very well with analytical calculations as well as experimental measurements, found in open literature. The higher order panel provides faster convergence as well as better results in comparison with the constant distribution panel method.

Takagi (2006) examined the concept of a large floating wind power plant, of semi-submersible type, that is with slender struts and lower hulls. Hydroelastic effects in waves play a major role in the design of such structure. A relatively simple method was developed to assess the hydroelastic behavior of the structure, already at the concept design stage. In particular the following assumptions were made: (a) the length of the structure is infinite and the hydrodynamic effect of the strut is neglected, thus the problem is periodic in the longitudinal direction; (b) static stability is estimated based on the static waterplane of the strut; (c) strut and transverse beams are assumed to be rigid. A 3-DoF hydroelastic model was formulated for sway (horizontal mode), heave (vertical mode) and roll (torsion mode) assuming a sinusoidal deformation of the structure.

Kyoung *et al* (2007a) presented a study on the dynamic wave loading of an elastic cylinder. A piston-type wavemaker is adopted to generate the waves in time domain.

A FEM is adopted to solve the fluid-structure interaction problem. The elastic cylinder is modeled as a simple beam fixed on the sea bottom. The response of the beam in time domain is solved by modal superposition method. As the present work was an extension of the study previously performed by Kyoung *et al* (2007b), numerical validation of the present scheme was made for the same computational conditions. Numerical comparisons were carried out assuming, respectively, quasi-static, decoupled and coupled hydroelastic response. In the quasi-static analysis the cylinder elastically bends under the action of the wave exciting forces; the wave diffraction force is obtained using a rigid body assumption. In the decoupled analysis the equations of motion of the cylinder under the action of the wave exciting forces are solved. In the coupled analysis fluid-structure coupling is implemented via the body boundary condition.

An efficient Arbitrary Lagrangian-Eulerian FEM (ALE-FEM) approach was developed by Wang (2007) to treat the incompressible viscous flows with rigid / flexible moving boundaries. The constitutive relations for both fluid and flexible body are unified, with the flexible body being treated as a special fluid governed by equations formally identical to the Navier-Stokes equations for fluid flow. The fluid-structure coupling is implemented by the ALE formulation and the computational domain is discretized by FEM. The vibration of a flexible stick located behind a fixed rigid circular cylinder under an incoming uniform flow, is one of the examples used to demonstrate this method. Hence, this approach is, in principle, suitable to model the hydroelastic behaviour of control surfaces appended to ships.

3. SHIP STRUCTURES – SPECIALIST TOPICS

3.1 *Model Tests*

Luo *et al* (2007) reported on experiments with a segmented model of a ship, known to suffer at sea from whipping vibrations induced by stern slamming. Although the ship type is not mentioned (the full-scale length is 120 m and $C_B=0.6$), the results are applicable to ships with wide flat stern, such as cruise and container ships. The model comprised two segments flexibly connected at amidships, in order to correctly scale the first flexural mode. Both head and following regular and irregular waves were tested at zero and 5 knots ship speeds. The measured total vertical bending moment amidship was found to follow Weibull distribution. Following sea at zero speed was identified as the most critical for stern slamming loads and whipping response. The total amidships VBM in irregular following sea increased up to about 34% with respect to the wave component. Remy *et al* (2006) reported on measurements with a flexible backbone barge, already discussed in section 2.4.

Storhaug and Moan (2007) reported on measurements of wave-induced vibrations on large ocean-going ships. A ship model with and without bulb or flare was used. The model was cut into six segments, with the bow segment at 10% of model length. The

bow and stern segments were rigid. The flexible joints, at the aft and fore quarter lengths and amidships, were adjusted in order to realistically scale the vertical 2-node vibration mode. Vertical bending moment and shear force were measured at these joints. The model was tested in several sea states. The linear and second order springing resonance was investigated as a function of speed. Numerical values of wave frequency (WF) and high frequency (HF) fatigue damage were calculated. Lavroff *et al* (2007) investigated the parameters effecting whipping vibratory response of a high speed catamaran subject to slamming, based on testing a flexible segmented model in calm water. Wet and dry vibration tests showed a significant influence of variations in stiffness and mass on flexural bending frequency, but no influence on zero speed damping ratio.

Oka *et al* (2007) reported on a series of tests conducted on a backbone elastic model of a high speed vessel in various sea states, including whipping. The time traces of the encounter wave height and amidships VBM were analysed. The wave component was separated from the total by application of a low-pass filter. The statical distribution of the filtered data is well approximated by conventional Rayleigh distribution; however, the maxima predicted by Rayleigh's distribution may be severely underestimated due to whipping. To correct the statistical predictions, accounting for whipping, a two-parameter Weibull distribution can be fitted to the data. The method was also applied to full-scale VBM time traces, obtained in BF 7-8 conditions, showing significant occurrence of whipping. It was found that the full-scale maximum expected value, as predicted by the Weibull fit, is larger than the corresponding prediction from model test. For example, the 1/1000 expected maximum value was 7.3 and 8.0 times the standard deviation for the model and real ship, respectively.

3.2 *Full-scale Measurements and Structural Monitoring*

Storhaug and Moe (2007) reported on the results of a research project aiming at the experimental assessment of the importance of wave-induced vibrations by testing the same ship both at model and full scale. The ship is a 4400 TEU container vessel. The full-scale vessel was instrumented with a hull monitoring system and preliminary results were reported for a round trip between Europe and Canada. The monitoring system was comprised a WAVEX wave radar, 8 fiberoptic strain gauges suitably positioned along the girder of the midship section, 1 bow accelerometer and 1 MRU. In addition the following signals were taken from bridge: RPM, rudder angle, GPS, anemometer and solcometer. A structural study was performed, in order to derive the stress concentration factors and to combine the straining gauges' signals in order to separate the four global stress components (axial force, vertical bending, horizontal bending and warping). The measured time series of the stresses were processed in order to separate the WF and HF contributions. The corresponding fatigue damage was evaluated. The results collected so far showed that the HF damage increases the total damage by about 23%, somewhat less than can be expected. This can be explained partly by the fact that the vessel encountered heavy astern seas, thus reducing the whipping excitation, and partly by the finding that the damping ratio appears to be

higher (about 2%) than expected for this ship topology. Rosén *et al* (2007) discussed full-scale trials performed to evaluate the structural design of the Visby Class corvette, with particular emphasis on the determination of the applied design loads. The method involves pressure measurements, reconstruction of the spatial pressure distributions from discrete point values, calculation of panel loads by integrating the spatial pressure distribution, and derivation of statistical extreme values. Application of the method is demonstrated on full-scale trial data for the Visby Class corvette, a sandwich skin composite vessel built with carbon fibre-reinforced plastic.

It is undisputable that ship designers, ship builders, classification societies and ship operators are all interested not only in assessing the actual levels of structural safety of the ship under effective service conditions, but to further improve them and, thus, enhance operational efficiency. Enhanced use of structural monitoring confirms this view. All OOCL (Orient Overseas Container Lines) 8063 TEU container ships were equipped with a Hull Stress Monitoring System (HSMS), following ABS guidelines. Yu *et al* (2006) reported on the preliminary results of a full-scale measurement campaign carried out during the maiden voyage of the MV OOCL Europe from Busan to Port Suez. In addition to the HSMS the ship was equipped with an onboard wave measurement system, called WaveFinder, specifically developed to monitor sea conditions using the X-band navigational radar on the bow. The main purpose of this campaign was to validate the HSMS and WaveFinder against numerical results and available weather data and to investigate long-term statistics of sea loads. By and large HSMS use Long Base Strain Gauges (LBSG) at a section near amidships to monitor hull girder stresses related to VBM. On the other hand for container ships having a U-type cargo hold structure, the torsional moment may be an even more important design load than VBM. To this end Kenichiro *et al* (2006) developed an approach to derive the global moments from the LBSG measurements at amidships based on correlation parameters derived from FEM. For the present application a different method was adopted, based on the LBSG measurement from two adjacent sections around amidships, believed to yield more accurate results for the torsional component. In fact, having only the strain measurements at one amidships section one cannot evaluate the warping contribution to the torsional moment. The different levels of complexity of hull monitoring systems are illustrated through practical application cases by Sebastiani *et al* (2008). In particular the prototype active guidance system, developed by the authors, called SNS (Safe Navigation System), uses wave radar measurements of sea conditions and has an in-built hydroelastic model of the ship onboard. This provides predictions of slamming loads likely to result in the actual operational and environmental conditions, as well as estimates of resultant whipping loads and their combination with the wave component to produce the total VBM experienced by the ship.

Kivimaa and Rantanen (2007) described a comprehensive system that was developed to monitor hull girder loadings on the fast mono-hull SuperSeaCat4 (SSC4) operating in the Gulf of Finland, Baltic Sea. Strain sensors measured the bending moment, shear force, and torsion moment. Accelerations were measured at the bow, the after body

and at the center of gravity. Ship motions were measured in three degrees of freedom, and a wave radar system was used to monitor the encountered waves while the ship's operational parameters were monitored by a digital GPS unit.

3.3 *Ice Loads*

Increasing demands for hydrocarbons and promises of huge deposits in the remote regions of Arctic and subarctic mean new attractive opportunities for ocean technology companies. These resources need to be transported to trade centres by safe marine transport systems operating in inhospitable and pollution sensitive waters (Mahmood and Revenga 2006). The Arctic is a tough, fragile and dynamic environment that requires experience, planning and ingenuity to operate in. Environmental changes, harsher winters in the area of Baltic Sea and climate changes in other Arctic and Subarctic zones create new opportunities and new challenges for further exploration of Northern Regions. Numerous studies (e.g. Kubat *et al* 2007) suggest that perennial ice cover is declining and patterns of first-year ice melting are changing, allowing for more multi-year and pack ice shifting south into the traditional shipping routes and creating more challenging and hazardous conditions. Increasing needs for oil and natural gas from Canadian and Russian Arctic and waters of Alaska (Arctic and Subarctic zones) demands more and environmentally safer ice-strengthened vessels.

Choi and Lee (2006) reviewed changes in main particulars of ice going ships, in service and under construction, over the last 40 years. They divided the ships into four categories, namely conventional icebreakers, icebreaking tug/support/research vessels, icebreaking passenger/car ferries and ice-strengthened cargo ships. Findings indicate steady increase in demand and size for new ice-strengthened cargo ships. This change reflects increase in shipping activities in ice infested waters of Arctic and Subarctic regions. Demands for new generations of larger and faster designs of structurally sound and environmentally safe vessels operating in ice are on increase. Updates to existing ice class rules are necessary, as well as research to determine appropriate levels and patterns of ice loads. For example, with reference to LNG carriers, existing regulations are in most case developed for relatively small ships and not adequate for presently demanded larger ice going vessels. Wang *et al* (2008a) presented a procedure for evaluation of structural integrity of LNG carriers using FEM. The approach discussed the estimation of design ice loads based on two different loading scenarios. One is glancing in the bow and/or shoulder areas, and the other glancing impact in the midbody area. Suh *et al* (2008) described an approach to designing a 208K Arctic LNG carrier. In this case the design loads were obtained applying direct calculation of ice loads and wave loads. The design process includes several ice impact situations that can be categorized into design ice loads and accidental ice load scenarios. The design load conditions include tangent impact, tangent impact with hummock and finishing breaking. The accidental load circumstances consider tangent impact with thick ice in high speed, ramming and entrapment.

Daley (2007) discussed pressure-area models to determine local and global loads on

ship structures. Two distinctive models were examined, namely the “process” model, that describes how the average pressure relates to the total contact area and is used to calculate the collision force, and the “spatial” model, which illustrates how local peak pressures relate to areas within the total contact area and are used to determine design loads on local structures, such as plating and framing. The author re-examined the existing measurements (Polar Sea) and correlated his finding to existing design trends. He concluded that the pressure-area relationships should not be viewed as a single phenomenon but should be separated into spatial and process pressure-area relationship. The process pressure-area curve follows a rising trend in certain cases, that is opposite to the spatial curve, which is inversely related to the area. Based on these observations the author suggests that the present design standards may underestimate ice forces for large collisions and, consequently, underestimate local maximum pressures. Masterson *et al* (2007) presented updated pressure vs area curve for determining local ice pressure for offshore structures and ship hulls. The original curves were developed based on medium scale impact test in multi-year ice, ship ramming tests and ice load panels on the Molikpaq structure. Over the years it was thought that the original curve was too conservative and that the ship ramming data too high for local pressure calculations. Modification to the existing data and addition of new experiments allowed for updates to this curve. More temperature zones where thick multi-year ice is not present have justified the lower pressure curve. The formula has been successfully applied to the design of existing offshore structures.

Daley and Kendrick (2008) discussed methods for direct calculation of ice loads for designs of large fast ships operating in ice-covered waters. They focused on the midbody ice loads and identified four load scenarios: (a) ship trapped in closing pack ice, (b) vessel being deflected off a track edge and struck at the midbody on the opposite side, (c) vessel is struck on the midbody by large drifting ice floe and (d) strike on the midbody during turning manoeuvre. The authors identified benefits of direct tools in improving safety of operations through optimization of design and providing guidelines for operators. They concluded that the approach needs and can be improved by detailed data from field measurements of ice conditions, as well as loads and vessel motions from sea trials.

Kujala *et al* (2007) developed a semi empirical approach to estimate long-term ice loads on bow sections of ice-strengthened ships navigating in the Baltic Sea. The formula accounts also for effects of ridges. The procedure was developed based on full-scale measurements and analysis of the ice edge failure process. In addition damage statistics were collected and analysed to verify the proposed approach. Choi and Jeong (2008) used data from six publicly available icebreaking vessels (model scale tests and sea trials) to develop global ice load prediction formula for large ships at ramming mode. The formula is based on ice load limits obtained from MV Arctic sea trials and is valid for speed less than 4 m/s. Leira and Børsheim (2008) presented an estimate of ice loads acting on the hull of a small vessel based on measured strains and FEM of the ship’s bow structure. The authors investigated the influence of ice thickness and vessel speed on measured strains. The study found that the maximum

peak loads are strongly related to the ice thickness, whilst the mean load is related to the vessel speed. Statistical analyses of the time between the load peaks indicated that Poisson process is a suitable representation.

Valkonen *et al* (2007) carried out model experiments in ice to measure contact pressure and to investigate ice load distributions along the ship's hull during various operational manoeuvres. Models of a conventional tanker and large general cargo carrier were used. The contact pressure between the hull and the ice was measured using I-Scan tactile sensor sheets placed in four locations along the hull, namely bow, bow shoulder, amidships and aft shoulder, all on the same side. Straight ahead in channel, breaking out of channel and operation in curved channel manoeuvres were performed. The authors observed that the crushing of ice channel edges was the dominant mode of failure. The observed overall aft shoulder loads were higher than bow loads and were operational mode dependent. Izumiyama *et al* (2007) discussed model experiments carried out in level ice to measure local loads in the bow region. The ice loads were measured using a tactile sensor system. The authors noted that the loads followed the broken line-like pattern where short load patches were lined up along a horizontal line. The analysis further showed that load level is inversely proportional to load patch length. This observation confirms findings from full-scale trials.

Frederking and Kubat (2007) analysed ice local loads from full-scale measurements on five different icebreakers and ice going commercial vessels. The measurements were carried out in the Arctic Ocean (multi-year ice), and in the Baltic and Bearing Seas (first-year ice). The experienced maximum local pressure in multi-year ice was 8MPa on 0.7m² area and 1.7MPa over 0.6m² in first year ice. At a probability of exceedance 10⁻³ the estimate of local pressure was 4.5MPa and 1.25MPa, respectively. Comparable line loads were 4.5 MN/m for multi-year and 1.4MN/m for first year ice. Other observations indicate that average local pressure decreases with the inverse square root of the area and that the landing craft bow experiences line loads 25% lower than a conventional icebreaking bow. Frederking and Johnston (2008) presented comparison of full-scale local pressure data, from bergy bit impacts, collected on the CCGS Terry Fox off the east coast of Newfoundland, during the USCGC Polar Sea arctic trials in the Beaufort Sea and field tests at Grappling Island. The data was standardized to common basis and compared, taking into account contact area and probability of exceedance. Takimoto and Wako (2007) presented ice load data from sea trials conducted in the ice covered water of Sea of Okhotsk. The ice pack was a dominant form of ice in this region during the tests. The effects of ice concentration and ice thickness on ice loads were investigated. Ice loads at the forward part of the vessel and ice thickness, including the snow cover, was measured. The authors showed that ice thickness is the most important parameter affecting ice loads. They also compared experimental results with the Finish Swedish Ice Class Rules (FSICR), finding that the measured ice loads were lower than the loads recommended by FSICR. Variation in loads was attributed to differences in salinity between the Baltic and Okhotsk Seas.

To improve protection of life, property and environment for commercial ships navigating in ice-infested polar waters the International Association of Classification Societies (IACS) developed set of rules (IACS 2007b). The purpose of this document is to enhance and harmonize requirements for construction of steel vessels among the IACS member organizations. The development of the UR Polar Class rules were developed over a period of several years, was finalized in 2007 and recommended for implementation by all members in 2008. The UR Polar Class design ice loads are based on a glancing impact to the bow region with an ice floe scenario and are dependent on hull form, vessel speed and ice thickness. The ice loads are transformed to the average pressure by projection of the apparent contact area into a reduced rectangular load patch.

3.4 Global Structural Analysis

Design experience suggests that as a result of the imposed loading a ship will throughout its normal life bend as a non-uniform elastic beam in three distinct frequency regimes namely: (a) the ultra low frequency (b) the low frequency and (c) the high frequency. Ultra low frequency bending, often regarded as static, occurs in still water primarily due to the differential distribution between weight and buoyancy forces. Other effects which are independent of sea state may also result in bending at very low frequency. These, for example, may arise from diurnal temperature changes, effects of ship generated waves and variation in the loading condition during voyages. Low frequency bending occurs at frequencies associated with the natural heaving and pitching periods when the ship is in waves. This bending is primarily influenced by the time dependant differential distribution of wave, buoyancy and hydrodynamic effects. High frequency bending is in fact vibration oriented and occurs most strongly if any of the natural modes of vibration are excited either continuously by high energy waves of similar frequencies or by wave impacts. In the majority of ships, low frequency bending is the most important effect in both absolute terms and in accounting for the majority of stress reversals during a ships' life with still water bending moment coming next in absolute terms. High frequency bending will invariably produce the lowest stress magnitudes of the three types, but can have a profound effect on the number of stress reversals encountered.

The aim from a design standardization perspective has always been to devise practical rules and design procedures that take proper account of all still water and wave effects. Consequently, the rules of Classification Societies have been formulated on the basis of theory and experience. The rules are based on empirical formulae used for the determination of scantlings of structural members and the suitable arrangement of principal structure. The rule development process, wherever applicable, accounts for the effects of full-scale measurements and in-service experience. Over the last decade, continuous change in ships in terms of scale, type, speed and structure, in parallel with the increasing demands for safety, cost effectiveness, reliability and availability, lead to changes in standardization. As a consequence, the rules of the Classification Societies are being augmented and replaced by dimensioning based on rational stress analysis.

Typical examples are the development of standards and design procedures (e.g. IACS rules and direct analysis) for the ultimate strength assessment of the hull girder and the prevention of fatigue failure in primary hull strength members due to lifetime stress cycles. Despite the fact that the effects of high frequency bending are still not explicitly incorporated in standard design codes and direct calculation procedures, as technical developments occur various methodologies are incorporated in structural standards.

The global structural analysis assesses the entire hull girder structure and main supporting members. In brief, the design assessment standards currently available are as follows:

- Prescriptive: Minimum IACS Unified Requirements and Classification Society rules (IACS 2007a)
- First principles : Design procedures and simulation based design, i.e. direct calculation approach (LR 2006, ABS 2006);
- Combined prescriptive and First principles: IACS common structural rules for bulk carriers and tankers (IACS 2006a, b).

3.4.1 Global Structural Analysis by Classification Societies

In the process of the global structural analysis, the selection of design waves and evaluation of wave loads are very important. The global structural analyses by Classification Societies are different in the procedure of the design wave selection and evaluation of wave loads, as can be seen in Table 1. Whereas in the case of design wave selection some classification societies use the stochastic analysis to decide the design wave loads, others use their own rules.

Table 1
Design wave selection and wave load evaluation

Classification Society	Selection of design wave		Wave Load Evaluation	
	Rule	Stochastic analysis	Rule	Ship motion program
ABS		X		X
BV		X		X
DNV		X		X
GL	X			X
KR		X		X
LR	X		X	

The overall procedures of ABS (American Bureau of Shipping), BV (Bureau Veritas), DNV and KR (Korean Register of Shipping) are similar (ABS 2006, BV 2006, DNV 2003, KR 2008). LR (Lloyd's register) applies equivalent static loads on the structural model. The equivalent static loads are obtained from the design wave loads of the rule formulae, in which the combined dynamic effects of wave and ship motion are

reflected. Structural safety thereafter is assessed (LR 2006). GL (Germanischer Lloyd) selects design waves satisfying the rule design wave loads. Subsequently GL uses seakeeping analysis for the evaluation of ship motions and wave loads. GL also employs an artificial static heeling for the additional torsional moment in the forward region of the ship (GL 2007).

The ocean wave system is a random process; hence, there is a strong argument in favour of a statistical approach for evaluating wave loads and corresponding structural responses. Standard wave spectra and directional spreading factors are used to describe the seaway mathematically. Extreme lifetime loads are estimated from the seaway distributions. Thereafter, the structural analysis is performed for the extreme lifetime loads and the global strength is assessed, as outlined in the typical procedure shown in Figure 2.

3.4.2 Design Waves and Design Loads

The design waves are selected as the regular wave that gives the equivalent design wave loads obtained from the long-term analysis or the rules of Classification Societies. The dynamic loads including inertia forces, the hydrodynamic pressures and, where applicable, internal pressures of liquid cargo induced by ship motions, are transferred to the structural model. The pressure distribution over the hydrodynamic model may be too coarse to be used for the structural analysis. In such cases, it may be necessary to interpolate the pressure over the finer structural mesh. Hydrodynamic pressure may be linearly interpolated to obtain the pressures at each node of the structural model. The unbalanced forces resulting from the difference between the hydrodynamic model and the structural model should be minimized. The accelerations at the centres of elements, solid cargoes and liquid cargoes are calculated by the combination of motions in six DoF. The inertia force and internal pressures induced by the acceleration are calculated and distributed on the structural model.

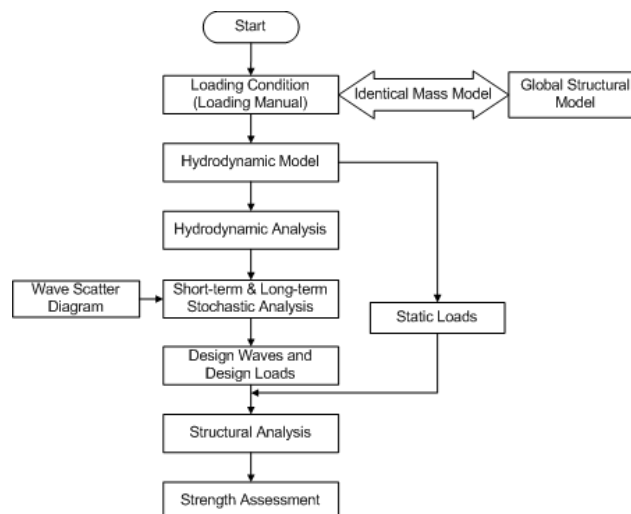


Figure 2: Flow chart for the global structural analysis procedure

3.4.3 *Structural and Hydrodynamic Models*

The loading conditions are determined based on the loading manual. Each loading condition needs to be carefully considered based on still water bending moment. The most severe cases, which can result in large deviations of VBM, are selected for the global analysis. The finite element models used are coarse mesh models of discrete elements and follow the arrangement of primary structure like decks, stringers, bulkheads webs and girders. The global structural model is required to have sufficient mesh density to represent the entire hull girder structure and main supporting members. Stiffeners are then simplified as line elements and lumped to the nearest element boundary. To have a better description of stress response, in a subsequent detailed assessment, primary supporting members and areas of interest are evaluated by a separate fine mesh of two- or three-dimensional form. The boundary displacements of these finer mesh models are referred back to the results of the corresponding 3D coarse mesh analysis. Strength response is verified against strength criteria of yielding, buckling, ultimate strength and fatigue strength. Since these criteria are the same in all cases and are applied to all structural components there is a unified safety level of structure all over the ship.

The hydrodynamic model comprises the hull form and weight distribution. The weight of the ship structure can be calculated from the global structural FE model using appropriate structural density. The structural density sometimes needs to be tuned to achieve the total weight of the ship structure taking account of local members, such as brackets, which are not contained in the global structural model. The heavy members such as main engine, shaft and outfits etc. are distributed properly over the global structural model to adjust to the lightship weight. Severe unbalanced force may result if the hydrodynamic model differs from the global structural model.

3.4.4 *Structural Analysis and Strength Assessment*

The structural strength of the hull is assessed by finite element analysis using the global structural model. The fundamental building block, upon which the rules are based, is the loading to be applied. The loads to be applied set up the two other fundamental building blocks, which consist of the engineering strength application formulations and the acceptance criteria. The loads are broken down into two major categories comprising of static and dynamic components. The static or still water components typically represent the loads associated with vessel operation loading conditions such as lightship weight, cargo, ballast, external buoyancy conditions. The dynamic or wave-induced components represent the loads associated with the vessel motions and accelerations imposed from the vessel reacting to the seaway. Wherever applicable, the rules specify the loading conditions and tank loading patterns to use and then impose corresponding dynamic loads to be applied. The dynamic loads are based on the fundamental vessel parameters in order to first calculate characteristic vessel motions and accelerations and then obtain the dynamic components of external pressure loads,

hull girder bending and shear, and internal tank pressure. Dynamic loads associated with sloshing, local impact at the bottom forward, forward bow and green water on deck are also specified.

The motions of the vessel and hydrodynamic forces are calculated by hydrodynamic analysis using a suitable wave load calculation program. The transfer functions are obtained through hydrodynamic analysis. The transfer functions are used for stochastic analysis to find the maximum wave loads occurring during vessel's lifetime. The short-term analyses are performed for each irregular wave condition, namely modal period, significant wave height. For overall strength evaluations, i.e. long-term analysis, the wave loads are imposed using waves a vessel may encounter based on a probability of exceedance of 10^{-8} . These loads represent the extreme loads based on exposure to the north Atlantic environment defined in accordance with IACS Recommendation 34, over a 25 year design life (IACS 2001). The dynamic loads are represented by a series of Load Combination Factors (LCF) which represent the superposition of the various dynamic load components at a given point in time when the major dynamic load component is being maximized. For fatigue evaluations, representative characteristic loads are used to represent the large number of modest fatigue-inducing fluctuating load ranges, which are based on a probability of exceedance of 10^{-4} . Since fatigue calculation results are very sensitive to load and corresponding stress range applications, the most representative characteristic loads are applied which strive to eliminate any large conservative assumptions. It should be noted that the follow-on fatigue calculation methods impose safety margins later in the applied method and acceptance criteria itself; hence, imposing additional conservatism at the load determination stage is not necessary.

3.4.5 *Recent Research and Developments*

MOERI (Maritime and Ocean Engineering Research Institute) and major Classification Societies investigated wave loads and motion response experimentally and numerically (Hong *et al* 2008). MOERI carried out a series of systematic model tests for a large container ship. Classification societies performed numerical analyses using their own seakeeping codes. Model tests and numerical results agreed very well for various responses of ship, such as motions in six DoF, bending moments and torsional moments. Unlike vertical wave bending moment, measured torsional moments did not reveal significant nonlinear effects in bow- and stern-quartering waves. Speed effects on torsional moment in stern-quartering waves were sensitive to locations, but higher speed did not induce higher torsional moment. Fang *et al* (2007) employed the design wave method to predict the wave loads for a ship encountering the worst sea state with respect to the critical dynamic loading parameter. Two different hydrodynamic numerical models, i.e. 3D pulsating source technique and 3D translating-pulsating source technique, were applied to calculate the corresponding RAO of the ship moving in waves. Incorporating the RAO of relevant physical properties, their extreme values can be calculated. With the time and period of occurrence of the corresponding extreme value, the time history of the wave load in this period can be simulated, the so

called equivalent irregular wave approach. Using the equivalent irregular wave approach can offer the effective and practical base for the ship structural analysis.

Recent developments in emerging and conceptual load prediction methodologies are briefly explained, as they are of interest to this report.

Limit State Analysis (LSA) and LRFD (Load and Resistance Factor Design) are relatively recent developments within the context of ship structural design although they have been employed in some standards for a few decades. LSA design looks beyond the intact behaviour of the structure to establish the limits, both from a safety and operational perspective, so that the design point(s) reflect the boundary of unacceptable behaviour. There are ship structural rules that have employed LSA design, e.g. the new IACS Unified Requirements for Polar Ships (IACS 2007b). In certain areas, notably related to buildings, bridges and offshore structures, it is common to use LRFD. The approach attempts to achieve a consistent risk level for all comparable structures by employing calibrated partial safety factors. The approach does not attempt to model complex (nonlinear) paths to failure, including feedback and interdependence, gross errors or any but the simplest of human errors. LRFD has not been implemented in ship structural design, at least partly due to concerns about its suitability. LRFD is often implemented along with concepts from LSA. When combined, LRFD and LSA design can properly balance risk and reflect, to all concerned, the actual capability limits of the structure. Together, this is intended to clarify and communicate the realistic structural risks

Formal Safety Assessment (FSA) is a recent development in the area of structural standards. It is more of a standards development approach than a design standard. The International Maritime Organization (IMO) has led the development of this concept. It is described as “a rational and systematic process for assessing the risks associated with shipping activity and for evaluating the costs and benefits of IMO's options for reducing these risks”. The IMO, and others, are evaluating FSA as a method to comparatively evaluate the components in proposed new regulations or to compare standards. The complexity of risk assessment technology itself is probably the major obstacle standing in the way of wider use of the FSA approach.

In recent years, there has been a strong trend towards what is generally referred to as performance-based standards (PBS). These standards describe a context and safety targets that they expect the design to meet, and then leave it to the proponent to achieve the targets in any manner they wish. In PBS, there are no specific loads or strength levels prescribed. The designers are expected to demonstrate the achievement of a target level of safety by an analysis of loads and strength. This approach is very popular in certain industries, especially the offshore oil and gas industry. CSA S471 (CSA 2004) is an example of this approach.

On the other hand, the notion of Goal-Based ship construction Standards (GBS) is relatively recent (Hoppe 2005). Conceptually, these standards suggest that future ship

design rules, including load predictions in waves, should be based on a five tier system bringing together codes of design practice and performance/operations based design. Tier I (goals) and Tier II (functional requirements) have already been agreed in principle. The plan for the pilot project on trial application, using the IACS Common Structural Rules (CSR), of the Tier III (verification process) has been agreed.

3.5 *Sloshing - ship motions coupling*

Kim *et al* (2007) considered the coupling effects of liquid sloshing on ship motions. The ship motion is solved linearly using the IRF method, while the nonlinear sloshing flow is simulated using a finite-difference method. Their method focuses on the simulation of the global motion of sloshing flow, ignoring some local phenomena. The sloshing-induced forces and moments are added to wave-excitation forces and moments, and then the corresponding body motion is obtained. In addition a soft-spring concept and linear roll damping are implemented to predict more realistic motions of surge, sway, yaw and roll. The developed schemes are applied to two problems, namely the sway motion of a box-type barge with rectangular tanks and the roll motion of a modified S175 hull with rectangular anti-rolling tank. Motion RAOs are compared with existing experimental results, showing fair agreement. It was found that due to the nonlinearity of the sloshing flow, ship motions show a strong sensitivity to wave slope.

Lee *et al* (2007) investigated the coupling, as well as the interactions, between ship motion and liquid sloshing by a time-domain simulation scheme. They use an IRF scheme to solve the ship motion. The liquid sloshing in a tank is simulated in time domain by a Navier-Stokes solver. A finite difference method with SURF scheme is applied for the direct simulation of liquid sloshing. The computed sloshing force and moment are then applied as external excitations to the ship motion. The calculated ship motion is in turn input as the excitation for liquid sloshing, and the process is repeated for the ensuing time steps. They also developed a coupled system based on 3D potential flow, both for ship motion and liquid sloshing. Both methods were applied to a barge-type FPSO hull equipped with two partially filled tanks. The time domain simulation results show similar trend when compared with experimental results. The most pronounced coupling effects are the shift or split of peak motion frequencies. It was also noted that the coupling effects between vessel motion and liquid sloshing changed appreciably with filling level. The frequency domain coupled analysis also showed the observed phenomena.

4. OFFSHORE STRUCTURES – SPECIALIST TOPICS

4.1 *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. At the same

time, it is 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. Specific examples are the touchdown of the cable with the ocean floor, the drag damping induced by the mooring system on the floating structure and the snap-and-slack-loading impacts.

Low and Langley (2006) presented time and frequency domain coupled analysis for deep water floating production systems. A linearized frequency domain approach was developed and validated against time domain analysis results of the coupled vessel-riser-mooring system, accounting of both first and second order motions. It was concluded that the frequency domain approach yields very good predictions of the system response, since the linearization scheme employed for the quadratic drag forces on the risers and mooring lines yields a very good estimate of the resulting contribution to slow drift damping. For intermediate water depths, Low and Langley (2007) made systematic comparisons between numerical results obtained by two alternative methods of analysis. A frequency domain approach and a hybrid approach in which the low frequency motion was solved in the time domain, whilst its high frequency counterpart in the frequency domain. The two analyses were coupled, taking into account that the low frequency motion affects the mooring line geometry for the high frequency motion, while the high frequency motion affects the drag forces which damp the low frequency motion. Le Cunff *et al* (2008) conducted a frequency domain analysis of a moored vessel, including low frequency effects. Comparisons were carried out with time domain simulations, to show the robustness of the frequency domain analysis. Some calculations were performed with either only low frequency terms or only wave frequency terms, in order to examine the effect of modeling low and wave frequency terms. An interesting conclusion is that the low frequency motion is reduced by the wave frequency motion, whilst the wave frequency motion is not affected by the low frequency motion. Kannah and Natarajan (2006) carried out an experimental study on a typical external turret-moored FPSO, through a vertical anchor leg mooring (VALM) arrangement, in order to investigate the effect of parameters influencing the mooring and hawser line forces and motion response for different loading conditions with different hawser lengths. A 1:100 scale model was tested, in head regular waves, for three loading conditions with three hawser lengths.

Chen *et al* (2006b) investigated the coupled dynamic analysis of a mini TLP using a Morison type loading formulation and accounting for the dynamic interactions between the hull and its risers and tendons, which may be a critical design issue in the frequency ranges outside the wave frequencies of significant energy content. Comparative evaluations between coupled dynamic numerical predictions, quasi-static approaches and experimental measurements were made, confirming that the coupled analysis represents a reliable computing tool. Nogueira *et al* (2006) implemented a fully coupled nonlinear modal analysis scheme in time domain for the case of floating offshore systems. This scheme accounts for the nonlinear timely variations of the stiffness and added mass of the system in evaluating the interaction effects between the hull and the mooring lines, and risers attached to it. Based on the results obtained, the

importance of calculating the system's natural periods in different positions was emphasized. Due to the nonlinear behavior of the mooring lines and risers, the system's natural periods in the neutral design position can show considerable variations from their counterparts in an equilibrium position under current action. The coupled semi-submersible / free-hanging drilling riser dynamics during re-entry operation in ultra deep waters were investigated by Yamamoto *et al* (2007) in time domain. The system's dynamical model accounts for the nonlinear platform dynamics together with the dynamics of the free-hanging drilling riser and the action of a Dynamic Positioning System (DPS) of the semi-submersible. Chatjigeorgiou *et al* (2006), presented a quasi-static motion response analysis of a Gas Import Floating Terminal, moored through a turret mooring system, subjected to operating and survival environmental conditions. The results compared well with experimental data from physical model tests. Zeng *et al* (2007) carried out a large amplitude motion response analysis, including nonlinearities induced by large displacements of TLP. Predictions were compared with those from a small displacement model, for a range of wave periods and headings, showing notable differences between the two models. The coupled motion response analysis of a triangular TLP, for different angles of wave incidence, were investigated by Chandrasekaran *et al* (2007a). Hydrodynamic loading was modeled using Stokes fifth order nonlinear wave theory along with additional nonlinearities arising from tether tension and change in buoyancy caused by the set down effect.

In addition to the aforementioned investigations, dealing with the coupled floater-mooring and riser system dynamic analysis, studies were carried out on the nonlinear dynamic behavior of marine risers and mooring systems. In this context, Larsen and Passano (2006) presented a new approach for capturing the dynamic behavior of a catenary riser at its touchdown area. The method was based on combined use of an empirical linear frequency domain model for VIV to calculate the hydrodynamic forces, and a nonlinear structural model for time domain analysis. The benefit from using the nonlinear model is that stresses in the touchdown area are described more accurately. Chatjigeorgiou (2006) presented a perturbation approach and an associated boundary layer problem solution methodology to calculate natural frequencies and corresponding bending vibration modes of vertical slender structures. Asymptotic approximations to the shape of the vibrating riser-type structure were obtained. Passano and Larsen (2007) investigated the extreme bending response of catenary riser in the region immediately above the touchdown area, in the case of large heave motions at the riser's upper end. The clear trends found between the prescribed axial velocity at the riser's top and response quantities in the touchdown area were used to estimate individual response values and complete samples of response minima and maxima. Vidic-Perunovic *et al* (2007) examined the influence of nonlinear second order springing deflection of a production vessel's hull on flexible riser response. Vertical motions, including the second order high frequency contribution due to the springing deflection, are assigned to the flexible riser at its attachment point to the vessel. Several environmental conditions were examined in order to consolidate the trend in riser behaviour. The significance of the high frequency quadratic terms in the loads along the flexible riser was also discussed. Chang and Fisher (2007) performed parametric

studies to develop a modelling scheme for a load-sharing marine drilling riser. The results were compared to those of the composite model. Significantly different tension patterns between the two models were observed.

4.2 *Vortex-induced Vibrations (VIV)*

An increased worldwide demand for energy and the resulting upsurge in offshore oil drilling and production activity has spawned a corresponding surge of research into several different aspects of VIV, a highly nonlinear dynamic phenomenon. Investigations include full-scale measurements, model-scale experiments and numerical simulation, with the objective of understanding the conditions causing VIV, assessing its effects and methods for suppressing it. Iranpour and Taheri (2006) presented a state of the art review of methods available for estimating fatigue life of marine risers used by the offshore industry, concluding that available approaches focus more on the VIV portion of the task, and less on the actual fatigue life analysis. Recommendations for the course of future research on VIV-induced fatigue damage are proposed.

From an operator's perspective, it is far more desirable to eliminate, or at least reduce, VIV than it is to simply quantify its effects. Taggart and Tognarelli (2008) reported on research on the hydrodynamic performance (VIV suppression and drag reduction) of various commercially available devices including a dual-fin splitter and an airfoil-shaped fairing. In addition, a relatively new inflatable suppression device was evaluated, and found particularly promising for VIV mitigation during drilling operations in areas of high current.

4.2.1 *Full-scale Measurements*

Trarieux *et al* (2006) reported on a detailed analysis of 22,000 records of data (each representing about seven minutes duration) obtained from the Foinaven Umbilical Monitoring System (FUMS). Results of spectral analysis are shown for several conditions of wave height, current speed and direction, along with a comparison to theoretical predictions. A fatigue damage analysis is also presented, including a comparison between the widely used rain-flow counting method and an alternative method based on a simply calculated bandwidth parameter. Srivilairit and Manuel (2007) analyzed full-scale field measurements of riser acceleration and current velocity profiles obtained from a drilling riser located in a 1,000,m depth site. Their analysis used an efficient numerical technique known as Proper Orthogonal Decomposition (POD) to identify energetic current profiles. They also used POD to derive the energetic spatial vibration modes associated with the VIV response of the riser for in-line and cross-flow motions.

Vandiver *et al* (2006) presented results from two field experiments designed to investigate VIV at higher than tenth mode in uniform and sheared flows. Both experiments showed significant energy at the expected Strouhal frequency, and also at two to three times the Strouhal frequency. In some cases, the highest stress and

greatest fatigue damage were found at higher harmonics; total fatigue damage including the third harmonic was found to be up to forty times more than the damage rate due to vibration at the fundamental (Strouhal) frequency alone. Jhingran and Vandiver (2007) cited preliminary results from another set of experiments that confirm the importance of higher harmonics in estimating fatigue damage due to VIV, noting that current methods only account for vibrations at the Strouhal frequency, while in certain regions of the pipe higher harmonics accounted for more than half the measured strain and increased fatigue damage by a factor of more than twenty. Swithenbank and Vandiver (2007) reported on a series of experiments conducted in Lake Seneca with long flexible cylinders at high mode number, using an unusually high density of sensors to capture the high vibration modes. One objective was to identify the power-in region, a region of the pipe that is the source of vibration for a given current profile. Other regions of the pipe serve to damp the structural vibrations. Four factors effecting the location of the power-in region were identified, namely the angle of the pipe relative to the vertical, the current profile, the current direction gradient and the end effects at high mode number. A dimensionless parameter was presented which helps in prediction of VIV for a given current profile.

Jaiswal and Vandiver (2007) described the VIV response of long cylinders fitted with strakes and presented damping measurements obtained from experiments conducted in the Gulf Stream, during October 2006. The strakes were a triple helix design. The pipe was towed in a variety of current profiles, varying from nearly uniform to highly sheared. Measured responses were compared with results modelled using mode superposition and Green's function.

Tognarelli *et al* (2008) presented results from an extensive in-situ monitoring project on several mobile offshore drilling units and offshore production platforms worldwide. The measured data shed light on some of the physical details of full-scale riser response, omitted from predictive riser design tools. The data were compared to calculations made with commonly used VIV analysis software. A means of adjusting the parameters to reduce typical over-conservatism in the analysis was then proposed. The data were also used to establish performance indicators for some of the VIV suppression devices presently in use. Beynet *et al* (2008) discussed results from an impromptu full-scale riser test, conducted when BP had to retrieve a drilling riser in the Gulf of Mexico due to excessive loop currents. A drill pipe was instrumented and deployed under the drilling vessel to a depth of 1,000 feet, and the drilling vessel drift relative to the loop current was varied to produce a wide range of surface current speeds and current profiles. Results include cross-flow and in-line VIV, as well as additional response at higher frequencies not currently predicted by VIV analysis tools.

4.2.2 *Model-scale Experiments*

Masuda *et al* (2006) described a series of forced oscillation tests with rigid circular cylinders suspended by a flat spring in still water. It was found that power spectra of VIV can be classified into four patterns, according to the number of spectral peaks.

Power spectra obtained from experiments were compared with 2D CFD computations. Ikoma *et al* (2007) reported on a subsequent series of similar experiments demonstrating that the drag coefficient increased and that the inertia coefficient decreased when larger VIV response occurred under forced oscillation. Fajarra *et al* (2007) presented experimental results of vortex-induced oscillations on an inclined cylinder that is free to oscillate only in the cross-flow direction. Results for the vertical cylinder are in agreement with other measurements reported in the literature. For the inclined model the results for amplitude, drag and lift are compatible with decomposition of the flow into the direction normal to the axis of the cylinder.

Lee *et al* (2006) presented VIV test results for two faired flexible cylinders in tandem at three lateral spacing intervals, subject to uniform flow. The VIV responses and motions of both cylinders are presented, along with conclusions as to the effectiveness of the fairing. Xu *et al* (2008) presented measurements of the wake field behind three riser models, obtained using Digital Particle Image Velocimetry (DPIV). The models included a bare circular cylinder, a faired cylinder, and a cylinder fitted with strakes. The strength of the vibratory response of the cylinders was found to be directly related to the wake mode; strong, regular vortices produce large amplitude vibration, while weak, scattered vortices produce little or no vibration. Braaten *et al* (2008) carried out an investigation of the higher order modal response of riser fairings. Tests showed that the rotational DoF of the fairing introduces the possibility of coupling between cross-flow translation and rotation, potentially resulting in instability at higher modes.

Korkischko *et al* (2007) performed an extensive series of experiments to investigate the flow around circular cylinders with and without strakes. Lift, drag, amplitude and wake pattern of plane and helically-straked cylinders were investigated. Reynolds number ranged from 2,000 to 10,000. Bernitsas *et al* (2008) presented two studies related to an investigation of using surface roughness as a means of reducing or enhancing VIV amplitude and synchronization. Sandpaper strips were used to control flow characteristics by varying strip width, grit size and location.

Uneven seabed conditions may cause multiple free spans in pipelines, allowing VIV responses in several modes to occur. Iltstad *et al* (2006) performed a series of scaled model tests to study multi-mode behaviour. It was found that for single mode response, the maximum cross flow amplitude may be 1.3 times the pipeline diameter, but for multi-mode interactions the amplitude is less than 0.8 times the diameter. Use of a frequency parameter, instead of a mode evaluation procedure, for use in fatigue analysis, was demonstrated.

4.2.3 Numerical Simulation

Constantinides and Oakley (2006) investigated rigid circular sections, using finite element CFD methods accurate to second order, for both bare sections and those fitted with strakes. Two turbulence models were used, namely Spalart-Allmaras and Detached Eddy Simulation (DES). Simulations for fixed and moving cylinders at high

Reynolds numbers showed good correlation with laboratory experiments. Flow visualizations illustrate how strakes mitigate VIV. Esperança *et al* (2006) discussed the implementation of a 3D finite difference model using the Large Eddy Simulation (LES) technique and Message Passage Interface (MPI) that can be run on a cluster with an arbitrary number of computers. The method achieved good agreement with experimental data and other published numerical results. Lucor and Triantafyllou (2006) presented a method to identify VIV modes of a riser, based on results of CFD simulations coupled with a model of a long beam under tension and placed in cross-flow. Uniform and exponential shear velocity profiles were evaluated. The response modes were found to represent nonlinear equilibria between flow-induced excitation forces and structural dynamics of the riser.

Pontaza and Chen (2006) presented a series of 3D VIV simulations for circular cylinders operating at high Reynolds number and low structural damping, allowing for two-DoF motion. The numerical implementation scheme uses overset grids and multiple processors working in parallel. The 3D grids around the cylinder are free to undergo arbitrary motion with respect to fixed background grids, achieving more efficient processing by eliminating the need for grid regeneration at every time step. Pinto *et al* (2006) applied an unsteady RANS code to simulate a typical riser VIV problem and compute the 3D riser-fluid interaction. The analysis was calibrated with published test data for a 2D flow past a bare riser and a riser with helical strakes. Spectral analysis of the frequency response patterns was then performed to identify the critical carrier frequencies. Results illustrate good comparison between numerical and experimental results. Holmes *et al* (2006) reported on fully 3D CFD simulations combined with a structural model of a tensioned riser to predict riser vortex induced motion, thereby overcoming the shortcomings of combining a series of 2D simulations to calculate fluid forces on a riser. The FEM used is tolerant of sparse meshes and high element aspect ratios, permitting economic solutions for large fluid domains. Thus, long risers can be treated with readily available computers, as demonstrated by simulations of a riser with L/D over 1400, giving favourable comparisons with previously published data.

In an attempt to identify the numerical scheme most suitable for simulation and analysis of VIV, Wanderley *et al* (2006) evaluated a range of CFD algorithms, examining grid generation, boundary condition implementation and the coupling between fluid flow and body motion equations. Their findings show that the most successful algorithm applies the Beam and Warming implicit scheme to solve the 2D slightly compressible Navier-Stokes equations and the $k-\epsilon$ turbulence model to simulate turbulent flow in the wake of the cylinder. Constantinides and Oakley (2008) reported on a comparison between VIV predictions obtained from a 3D CFD model and data from field experiments on a riser with L/D ratio in excess of 4,000. Results showed good agreement and confirm the ability of the CFD simulation to predict the observed harmonic content, thereby offering a method for design validation in regions of higher harmonics outside the range of existing empirical methods. Bearman *et al* (2006) compared laboratory measurements for a vertical tension riser with predictions from

five CFD-based riser codes. The predictions covered a wide range of approaches, namely (a) vorticity-stream function with a finite volume scheme, (b) FEM on a triangular grid, (c) pressure correction method in a finite volume scheme with unstructured grids, (d) discrete vortex formulation and (e) a velocity-vorticity method using a hybrid Eulerian-Lagrangian vortex-in-cell method. Both cross-flow responses and in-line deflections showed a wide range of scatter (i.e. 23% to 169%), by comparison to measured data.

In contrast to continuum based numerical models, where only space and time are discrete, Frandsen (2006) examined an approach based on a single phase Lattice Boltzmann model, which also treats particle velocity as a discrete variable. The goal is to reduce the need for applying empirical turbulence models. This study is limited to laminar flow simulations and continuous free surface, but the long term objective is to simulate bluff body flows at high Reynolds number and breaking waves.

Sidarta *et al* (2006) presented a method for estimating VIV fatigue damage, using any of a number of available cross-flow codes with shear flow capability. The method seeks to reduce the current conservatism, by accounting for the power-in region, the power-out region, competing modal excitation, and the possibility of multiple constraints. Underscoring the difficulty in predicting riser and tendon fatigue damage due to VIV, Yang *et al* (2008) reported on a comparison between predictions made with the Shear7 V4.5 code and data from an extensively instrumented scaled model riser test. The study indicates reasonable predictions for bare risers. However, more work needs to be done to achieve acceptable accuracy for risers with strakes.

Halkyard *et al* (2006) reported on the Vortex Induced Motions (VIM) of spar-type floating production systems, which impact mooring and riser design. This paper offers a discussion of best practices for use of CFD for this class of problems, and presents comparisons of CFD with model test results. The interaction between the structure of a truss-type spar platform and a riser array is extremely complicated. Constantinides *et al* (2006) applied CFD to the analysis of a full scale truss spar with multiple risers and reported good agreement between predictions and experimental data. Wang *et al* (2008b) discussed 2D and 3D CFD models of the new cell-truss spar configuration, using the FLUENT code. In 2D simulations, turbulence was modelled using the Shear Stress Transport (SST) $k-\omega$ method, while the 3D simulations used the DES turbulence model. A conventional truss spar was also modelled, for comparison, and results were found to be in general agreement with other published predictions and experimental results.

To estimate loads and responses of linear dynamic structures based on measured data, Mainçon *et al* (2008) presented an inverse FEM to process measurements obtained from VIV experiments on a reduced scale riser model in a shear current. The technique permits visualization of the distribution and history of hydrodynamic excitation forces and damping zones. Huera Huarte *et al* (2006) used an indirect method of determining instantaneous in-line and transverse force distribution along a marine riser using

displacements measured at a large number of points in laboratory tests. The riser was idealised as an Euler-Bernoulli beam with low flexural stiffness and the solution is linked to FEM, with two DoF per node. The linear model deals with cross-flow and in-line motions independently. The authors conclude that the proposed method can be used for validating flow-induced forces predicted by CFD coupled with structural codes.

As an alternative to fitting strakes to suppress VIV in marine risers, field experience suggests that buoyancy modules can be used to similar effect. Normally used only to manage riser top tension, the modules can be staggered along the length of a riser, alternately exposing bare riser segments. Holmes *et al* (2008) used a series of CFD simulations to gain some insight into the efficacy of this tactic. While they observed some reduction in VIV, they concluded the benefits were small. Another means of VIV suppression is through the use of fairings fitted to the riser. Pontaza and Menon (2008) presented results from numerical simulations of a series of plain and aspirated fairings at high Reynolds number with three DoF. Several designs were considered, each assessed in terms of mean drag reduction and VIV suppression.

4.3 Moonpools

The complex hydrodynamic behaviour of moonpools is dominated by potential flow methods, e.g. Pesce *et al* (2006). The use of complete CFD solutions is beginning to emerge (e.g. Sadiq and Yao 2008a).

Yeung and Seah (2007) investigated the Helmholtz and other symmetric modes of resonance of a moonpool between two heaving rectangular floating cylinders. The hydrodynamic behaviour around these resonant modes was examined together with the associated mode shapes in the moonpool region. It was observed that the damping coefficient can vanish near each of the resonance frequencies. The Helmholtz mode is characterized by a region of modest variation of added mass value, from negative to positive near the Helmholtz frequency. The peaks are, however, bounded with the cross-over point in sign corresponding to a bounded spike in damping. The higher order resonant modes are characterized by the presence of standing waves in the moonpool, leading to large spikes near the resonance frequencies. As the moonpool gap decreases, the resonant motion is more extreme or narrow-banded. The intensity of the moonpool motion is closely related to a spiky damping coefficient and a concurrent sign change in the heave added mass. As expected, a smaller moonpool width leads to a more piston-type behaviour of the wave elevation. Pesce *et al* (2006) developed an alternative Lagrangian formulation of the equation of motion in the moonpool. The usual Lagrange equations of motion cannot be directly applied, with mass varying explicitly with position. In this particular context, a naive application, without any special consideration on non-conservative generalized forces, leads to equations of motions which lack (or exceed) terms of the form $\frac{1}{2}[\partial m/\partial q (\dot{d}q)^2]$, where q is a generalized coordinate. This paper discusses the issue a little further by treating some applications in offshore engineering, such as trapped modes in the presence of freely

floating structures. Porter and Evans (2008) discuss trapping waves from the moonpool problem point of view. A freely floating motion trapping structure can be defined as one or more rigid bodies floating on the surface of a fluid, which extends to infinity in at least one direction, whose free motion under its natural hydrostatic restoring force is coupled to that of the surrounding fluid in such a way that no waves are radiated to infinity. The resulting local time harmonic oscillation of the structure and the surrounding fluid is called a motion trapped mode. Such a structure would, if displaced slightly from its equilibrium position and released, ultimately oscillate indefinitely at the trapped mode frequency. Previous examples of motion trapping structures were devised using an inverse approach in which the shape of pairs of such structures are determined implicitly by sketching certain streamlines. In this paper an alternative direct approach to the construction of motion trapping structures in the form of a pair of identical floating cylinders of rectangular cross-section in two dimensions is presented. It is also shown that a thick-walled axisymmetric heaving circular cylinder can act as a motion trapping structure.

Faltinsen *et al* (2007) presented combined theoretical and experimental studies of the 2D piston-like steady state motions of a fluid in a moonpool formed by two rectangular hulls (e.g. a dual pontoon or catamaran). Vertical harmonic excitation of the partly submerged structure in calm water was assumed. A high precision potential flow method, which captures the singular behaviour of the velocity potential at the corner points of the rectangular structure, was developed. The linear steady state results were compared with new experimental data and show generally satisfactory agreement. The influence of vortex shedding was evaluated, using the local discrete vortex method, and was shown to be small. Thus, the discrepancy between the theory and experiment may be related to the free surface nonlinearity. This is a seminal paper with respect to moon pool oscillation modelling.

Sadiq and Yao (2008b) presented a towing tank experimental set-up and procedures to acquire combined acoustic and hydrodynamic data for a moonpool experiment. The experimental technique is capable of monitoring pressure fluctuations, acoustics, free surface wave height inside the moonpool and structural vibration of a moonpool model, at the same time, with a better estimation and accuracy. The results were compared with numerical modelling predictions and empirical relations. A detailed comparison was carried out on collected data using the Empirical Mode Decomposition (EMD) method. Data collected from sensors are shown to be within engineering practice limits, verifying the importance and authenticity of the data acquisition procedure used. Only the piston mode oscillations were observed for F_n 0.1 to 0.2, both for square and circular moonpools shapes. Borges Malta *et al* (2006), in addition to their potential flow analyses, used model tests for the estimation of the damping of the water column motions in the moonpool.

Gupta *et al* (2008) studied the effect of a moonpool (or centrewell) in a spar. A unique aspect of the moonpool in spars is the presence of partial closure (or guide) plates at the bottom, allowing passage of seawater. Depending on the design of a spar (e.g. the

number of risers), the typical period of moonpool vertical oscillation can be close to the peak of extreme sea state spectra. The spar's heave motion is, thus, coupled with the moonpool water oscillation and presents itself as a two-oscillator problem. This complex interaction is largely ignored in current practice, but it is addressed by this paper. The results of the new model highlight the importance of moonpool hydrodynamics in predicting the heave motions of spars. It was concluded that motions of the moonpool water are not affected significantly by the spar, indicating weak coupling from spar to moonpool. Phasing of the moonpool motions with respect to the incident waves plays an important role; hence the Spar's motions are significantly affected by the moonpool water motions, indicating strong coupling from the moonpool to the spar.

Son *et al* (2008) examined recess type moonpools. These are vertical wells with step, frequently found in drill-ships. The recess moonpool originally came about in order to move the drilling equipment without hull interferences. It was also shown that the recess type moonpool contributed to the reduction of relative motion inside the moonpool during zero speed operation. However, once the ship is under way, the moonpool results in large drag due to the oscillation of the water inside. A drag reduction method was investigated in this research by analyzing the flow behaviour inside the moonpool in a model basin. The moonpool was modified, based on the results of numerical and experimental studies, obtaining more than 10% drag reduction, compared to normal rectangular moonpools. The work by Morris-Thomas *et al* (2007) on an Oscillating Water Column device (OWC), used for wave energy conversion via wave interaction with a semi-submerged chamber coupled to a turbine, is also of interest. In this work a shore-based OWC is studied experimentally to examine energy efficiencies. The wave environment considered comprises plane progressive waves of various steepness and water depth values. The key focus of this experimental campaign is the influence of front wall geometry (e.g. draught, thickness and aperture shape) on the OWC's performance. The results showed a broad-banded efficiency centred about the natural frequency of the OWC. The magnitude and shape of the efficiency curves are influenced by the geometry of the front wall.

4.4 VLFS, TLP and Semi-submersibles

A rigorous formulation for slowly varying drifting force on VLFS was derived by Kida and Utsunomiya (2006) using the near-field approach. The method was applied to a pontoon-type 300m long VLFS. They compared the results with those of Newman (1974), Shimada and Maruyama (2001) and Namba *et al* (1999). They concluded that Newman's method overestimates the slowly varying component and is no more applicable to VLFS, Namba's method has good accuracy when applied to pontoon-type VLFS and Shimada's method is useful and convenient for pontoon-type VLFS when it can be assumed that all the energy is reflected by the floating structure. The method was also applied to a semi-submersible type VLFS. It was shown that other approaches may overestimate to a large extent, and that their approach may be best suited for the estimation of the slowly varying drifting force on semi-submersible VLFS.

Tabeshpour *et al* (2006) presented an approach to calculate second order perturbation added mass fluctuation on vertical vibration of TLPs. Total motion in waves can be considered as a superposition of the motion of the body in still water and the forces on the restrained body. First and second order perturbations were used to solve the free and forced vibrations, respectively. Their work is likely to be important in fatigue life studies of mooring lines. Chandrasekaran *et al* (2007b) examined the response of a triangular TLP under impact loading. Hydrodynamic forces on these TLPs are, normally, evaluated using the modified Morison equation, based on water particle kinematics arrived at using Stokes' fifth order wave theory. The numerical studies showed that impulsive loading acting on the corner of the TLP column significantly affects its motion response. On the other hand, impulsive loading acting on the pontoons does not affect the TLP's behaviour.

Srinivasan *et al* (2006) applied the concepts of both hydrodynamic added mass and separated flow damping to the design of a large deepwater floating vessel, based on the column-stabilized principle. The platform is designed to face resonance due to extreme waves and utilizes the damping to control its motion. The design is justified and verified with the results of a scaled model study in a large wave tank. Murray *et al* (2007) presented a hydrodynamics analysis of a conceptual dry tree semi-submersible for drilling and production platforms. Computational analysis showed that the hull form can be optimized to control the cancellation period, magnitude of the heave RAO below the cancellation period and the heave natural period. The relative areas of the column and pontoon are varied to demonstrate the global effects on the hydrodynamic forces acting in these structural components, whilst the area of the heave plate is kept constant. Results showed that by keeping the displaced volume of the hull constant the relative areas of the column and pontoon can be varied to affect the magnitude of the hydrodynamic forces on the columns and pontoon and, thus, the shape of the heave RAO.

5. UNCERTAINTIES

The International Towing Tank Conference (ITTC) in 2008 has recommended an alternative approach to experimental uncertainty, namely the ISO-GUM (International Organization for Standardization, Guide to the Expression of Uncertainty in Measurements; ISO 1995) procedure (ITTC 2008a). Until now ITTC was endorsing the approach by the American Institute for Aeronautics and Astronautics (AIAA 1999, 2003), developed for wind tunnel testing. However, the international community of ITTC believes that the ISO-GUM method better addresses its needs. Therefore, the ISO method, nomenclature and symbols for the uncertainty analysis are recommended for adoption in ITTC standards and procedures.

The GUM concept of uncertainty in a measurement distinguishes between two types of uncertainty components. They are grouped according to the way their numerical values

are estimated: (a) Type A components are estimated by statistical approach based on repeated observations. They are characterized by the experimental variance s_i^2 or standard deviation s_i of the mean value and number of degrees of freedom ν_i . The resultant standard deviation of the mean is called type A standard uncertainty; (b) Type B components are evaluated by means other than repeated observations. They are characterized by the quantity u_j^2 that can be thought of as the variance or standard deviation u_j obtained based on a pool of reliable information from past experience and educated judgment. The estimated value is called type B standard uncertainty. Uncertainty types A and B are not substitutes for random and systematic uncertainties used in the AIAA (1999, 2003) approach. Both types are evaluated based on probability distributions and are quantified by values of variance or standard deviations. The standard uncertainties are the fundamental means for presenting an uncertainty in a measurement.

When a final experimental outcome is obtained from results of few individual quantities, the ultimate uncertainty is called combined standard uncertainty $u_c(y)$. The uncertainty of the measured result can be then evaluated using relevant variance values and applying the law of propagation of uncertainty, namely

$$u_c^2(y) = \sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i)$$

In addition, if there is a correlation between individual input quantities the combined standard uncertainty needs to be corrected by an expression correlating these quantities, namely

$$u_c^2(y) = \sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j)$$

When an interval about the result of a measurement to express an overall uncertainty, and associated variability and specific level of confidence in the final results is required the expanded uncertainty U has to be used. This is obtained by multiplying the combined standard uncertainty by coverage factor k , i.e.

$$U = k u_c(y)$$

The value of k is selected based on required level of confidence. Normally in engineering applications 95% or 99% confidence level is acceptable. The relevant k values for normal distribution are 2 and 3 respectively.

5.1 *Experimental Uncertainty Analysis*

Most published experimental data are supplemented by uncertainty analysis. Typically numerical values are presented, albeit with limited explanations on the approach used

and its underlying assumptions. The majority of experiments is conducted for verification and validation of numerical codes. As contributions to the subject of experimental uncertainty in recent publication has been limited, no sample of publications is presented in this report.

5.2 Numerical Uncertainty Analysis

Uncertainty analyses of computational codes are regularly presented as part of the verification and validation process. Examples of such analyses are presented for investigations involving modelling the flow around ships, though not necessarily involving evaluation of loads. Wu and Moan (2006a), in their time domain nonlinear hydroelasticity investigations, carried out statistical analysis to study the sensitivity of the predicted extremes (e.g. VBM) to the changes in the threshold of the POT method, as well as the statistical uncertainty in the prediction due to the limited duration of the nonlinear simulation. It was recommended that 90% to 95% quantile should be used as the threshold in the POT method and more than 100 hours of time domain simulation should be carried out in order to obtain satisfactory predictions of the short-term extreme nonlinear load effects.

Marcer *et al* (2007) presented a qualitative validation of RANS-based EOLE code for simulation of nonlinear effects, such as ship roll damping, due to viscosity and wave radiation. The validation was conducted by comparing hydrodynamic and hydrostatic moments obtained from calculations and forced oscillation model tests. The CFD code uses k- ϵ turbulence model and a VOF method to simulate free surface effects. Experiments were conducted using 1:24 scale bare and appended hull model. For the experiments the model was fixed to the carriage through a 3D motion generator and dynamometer. Comparison of calculated and measured hydrodynamic and hydrostatic moments for zero speed show good agreement in periods and some discrepancies in amplitudes of moments. Vestbøstad *et al* (2007) carried out validation and verification of a 2D CIP method. This is a high order upwind scheme for solving the Navier-Stokes equations. The aim of the code is to compute forces on offshore structure due to extreme waves. The authors identified benchmark tests for examining different effects. The benchmark data included numerical and experimental results. For example, they used a case of moderate sloshing to check the mass and energy conservation properties and wave generation in a NWT, and made comparisons with model test data. The temporal convergence was checked by running simulations with different constant time steps and with adaptive time step. The adaptive time step resulted in more efficient and stable simulation. For longer time steps they experienced problems with convergence. For spatial convergence the authors used three sizes of grid. The code verification was conducted by qualitative comparison of CIP simulations against their own benchmark data.

For verification of complex numerical codes the Method of Manufactured Solution (MMS) is often applied. The principles of the MMS method are outlined by Roache (2002). Verification of a code can be done by systematic discretization convergence

tests using a known benchmark solution. The best benchmark solutions are exact analytical solutions sufficiently complex that all elements of the governing equations, boundary and initial conditions can be assessed. Exact solutions are not easily available, but as code verification is a purely mathematical exercise these do not have to be physically realistic. Roache (2002) proposed MMS to generate exact solutions for code accuracy verification. The MMS is an exact solution to the governing equations that can be obtained by solving the problem in reversed order. In the approach one first picks a continuum solution by defining unknowns using suitable mathematical functions. The solution is then passed through the governing partial differential equations to obtain an appropriate source term. This source term is subsequently used to modify the original governing equations so that the manufactured solution is an exact solution to the modified equations. The method is also suitable for grid convergence studies to confirm or establish the order of accuracy, the rate at which error tends to zero as spatial and time discretizations decrease. The author also indicates the importance of distinguishing between verification of a code and verification of a calculation. In general, verification of a code needs to be performed only once, unless the code is modified. Verification of a calculation, however, might be case sensitive and good practice requires that users perform their own systematic discretization convergence study before each new application. Eça and Hoekstra (2007) presented verification of a Navier-Stokes solver for 2D unsteady flow of an incompressible fluid using MMS. They developed two manufactured solutions, namely a periodic and a steady state solution. The developed manufactured solutions were computed on six equally spaced Cartesian grids and for six time steps. The grid refinement ratio for spatial and time discretization was 1, 1.2, 1.5, 2, 3, and 6. The authors used the Root Mean Square (RMS) error measure for comparison between the computed and exact (MMS) results. RMS errors for two velocity components and a pressure coefficient were presented. The periodic solution was used for the iterative error by applying three convergence criteria. This allowed identifying a criterion independent solution, which was then applied to the steady state solution calculations for six different time steps and grid refinements. The criterion guaranteed solutions independent of machine round off and iterative errors, so the discretization errors and observed orders of accuracy could be established. In concluding, the authors indicate that the MMS is an excellent tool for verification of codes.

Étienne and Pelletier (2005) presented an approach to sensitivity and uncertainty analysis conducted on a problem modelling the interaction between a viscous incompressible flow and an elastic structure undergoing large displacements. The problem is usually solved through coupling of dedicated computational fluid dynamics and computational structural dynamics codes. The authors used the stationary Navier-Stokes equations to describe the fluid behaviour and a Lagrangian frame together with large displacement large strain theory to describe the solid. The solution is obtained by a Newton-Raphson adaptive FEM. To resolve the deformation problem of boundaries and fluid mesh a pseudo-solid approach was used, formulated at the continuity level. This approach allowed them to use the sensitivity equation method for velocities and pressures in the fluid and displacements of the structure. The verification process also

included code verification exercise using the MMS and verification of calculation and sensitivity analysis for an elastic cylinder immersed in uniform flow. Applications of sensitivity analysis to obtain uncertainty bands, in order to determine key parameters and/or perform “what if” studies for the parameters controlling the system are also presented.

5.3 *Benchmark Data*

The ITTC Seakeeping Committee (ITTC 2008b) proposed an updated definition of experimental benchmark data and a list of minimum requirements for an experimental data set to be recognized as a complete ITTC benchmark. The basic requirements are such that the provided information is sufficient for the repeatability of the test, either experimentally or numerically. The benchmark data is intended to facilitate validation of numerical codes. A number of papers have been identified as a potential source of benchmark data. For example, Leguen and Fréchet (2007) presented seakeeping experiments performed with a 25m model (1:5 scale) of a frigate. The structure of the model hull was similar to the structure of the full-scale ship, i.e. built to maintain elastic similarity and proper scaling relation between modes of resonance of the model and the ship. Experiments were conducted in regular waves and speeds up to 4 m/s. The model was instrumented to obtain model motions and global deformation of the body in waves. Roll damping at various speeds was measured and whipping and slamming phenomena were observed. The paramount purpose of this unusual experiment was to collect data for validation of design tools, including predictions of hull motions and structural responses.

Olivieri *et al* (2008) presented parametric roll model experiments, focused on repeatability with respect to initiation and roll amplitude. The tests were performed in a towing tank with the model free to roll, pitch and heave in regular head waves, with surge, sway and yaw being restrained. The experiments were carried out for three metacentric height (GM) values and a range of speeds and wave steepness values. Roll decay tests were conducted before each test to obtain accurate values of roll natural period and damping. The aim of this project was to create reliable and complete benchmark data. The results indicated that parametric roll initiation depends on oscillation of the righting arm due to incoming waves and ship’s vertical motions. It was also noted that roll amplitude depends on the amplitude of the incoming waves and encounter frequency. Uncertainty analyses were part of this project and show uncertainty in the roll amplitude between 1% and 4%, depending on speed and value of GM.

6. **PROBABILISTIC METHODS**

6.1 *Probabilistic Methods for Ships*

It is important to predict the probabilistic characteristics of loads and load effects of

ships during their life against buckling, yielding and fatigue strengths in order to design rational ship structures. In the case of nonlinearities, of loads and their effects, there is no established effective methods for their prediction. The most general and precise approach is to use nonlinear simulations for all short-term irregular sea states and conditions encountered by a ship.

6.1.1 Long-term Distribution

Wu and Moan (2006b) predicted the long-term load effects considering structural vibrations due to flexible deformations. The shipmaster's judgment was accounted for, assuming that heavy weather is avoided through selection of a slightly longer and more benign route. The authors employed a nonlinear strip method to predict the extreme load effects on a pentamaran. The averages of the scatter diagrams for areas 15 and 16, along the summer route, and 24 and 25, along the winter route (Hogben *et al* 1986), were used as the design scatter diagram for the long-term predictions. They found that the extreme VBM is comparable to the design loads when the ship's flexibility is neglected. However, the structural dynamic effects, mainly due to whipping, increase the extreme values by 30% to 50%. The downside of this approach is that it is time prohibitive in terms of number of calculations.

Collette *et al* (2007) proposed a distributed computational system for semi-automatic calculation of long-term nonlinear motions and loads for novel vessels. The system combines the nonlinear time domain motion simulations with a data management and post-processing server. The cluster has 1024 independent computer nodes. They used the system to predict the statistical distributions of loads on a SWATH. It was shown that the system is capable of running hundreds of, full-scale, hours of simulation in a short time, an indication of its potential capability for extensive application to the prediction of extreme ship response. Essentially, there are two options for reducing calculation time. One is to reduce the number of short-term sea states by selecting the short-term sea states amongst all combinations (e.g. Kawabe and Moan 2007). The other is based on a concept of specifying the time instance, in irregular seas, where the response becomes maximum, as discussed in section 6.1.2.

The former approach was applied by, for example, Baarholm and Moan (2000) who identified the most important sea states that significantly contribute to the extreme value. Kawabe and Moan (2007) broke down the long-term distribution into a couple of factors such as, the significant wave height, the average wave period and heading angle. It was shown that the maximum wave-induced load with a probability exceedance around 10^{-8} in the long-term distribution is decided mostly by the most severe short-term wave conditions which have the largest significant wave height with a governing mean wave period. They further applied this approach to investigate the effect of ships' operational intervention on the maximum wave-induced load, showing that it provides very accurate estimates for a VLCC, a bulk carrier and a container ship. Kurata *et al* (2008) pointed out that the approach by Kawabe and Moan (2007) does not result in correct predictions for the variance or the probability distribution function

of the maximum responses, because it is intended to efficiently estimate the most probable maximum value, taking nonlinearity of loads into consideration. Derbanne *et al* (2008) introduced a smoothing method to determine Weibull coefficients of responses over the entire scatter diagram through calculations in limited number of short-term sea states, assuming that the short-term characteristics are well described by the Weibull distribution. Consequently, the statistical parameters in every short-term sea state are obtained in comparatively short time. Subsequently, long-term predictions of nonlinear bending moment can be carried out, as the authors have done for 14 ships of various types.

The effect of operational intervention on long-term prediction has attracted attention. Shu and Moan (2006) evaluated the effects of heavy weather avoidance by assuming two strategies; one is based on the operability criterion and the other on wave climate forecast. Without consideration of heavy weather avoidance, long-term predictions of VBM in conventional ships, obtained using the 3D code WASIM, agree well with Classification Society rule value. They showed that the operational intervention effect depends on the strategy chosen for heavy weather avoidance. A reduction of the extreme values of VBM of 30, 20 and 10% for limit significant wave heights of 8, 10 and 12m, respectively, is reported. Naito *et al* (2006) noted a similar trend, from onboard data, namely that the extreme response does not increase proportionally with increasing significant wave height and that the increase rate becomes less. This trends are explained by operational intervention, such as voluntary change of the encounter period and wave direction based on the shipmaster's judgment. They investigated such operational effects on the long-term probability distribution of VBM, and proposed a long-term prediction method with operational criteria. They showed that the results obtained using the proposed method correlate well to onboard data, whereas those predicted by the conventional method, not accounting for the human elements, are likely to be overestimates.

6.1.2 Short-term Distribution

The concept of specifying the time instance, in irregular seas, at which the response becomes maximum, or a series of conditioned wave methods is not new. For example, the Most Likely Extreme Response (MLER) was proposed by Adegeest *et al* (1998), the Most Likely Response Wave (MLRW) and the Conditional Random Response Wave (CRRW) were proposed by Dietz *et al* (2004). CRRW accounts for transient vibrations such as whipping. These techniques commonly use linear transfer functions to specify the aforementioned time instance. The fundamental assumption of wave conditioning techniques is that the nonlinear response is a correction of the linear response. ISSC recommended that the response conditioning methods be verified with further numerical simulations and experiments before they can become established tools (ISSC 2006a).

Drummen (2007) presented the results of an experimental investigation into the applicability of the conditioned waves. Rigid and flexible hull models were employed.

The MLRW and CRRW methods were compared with crude results (from crude Monte Carlo type experiment under random wave generation) in random irregular waves. It was shown that MLRW agrees very well with the crude results in random irregular waves for the rigid hull case. However, the agreement becomes much worse for the flexible body case. The original CRRW method works well even for the flexible body case, however, it requires larger CPU as 100 runs are performed for each response level. As a compromise, the author recommended the use of CRRW with 10 runs in conjunction with a correction factor, since with 10 runs the extreme value is underestimated by comparison to the crude results. The author also performed numerical analyses and showed that CRRW with 26 runs underestimates the extreme value by about 15-25%. The response conditioning techniques appear to be more established; nevertheless, there is the issue regarding CPU time, particularly for non-Gaussian type problems. Another disadvantage of the response conditioning techniques is that different responses require different simulations (Adegeest *et al* 1998). Fukasawa *et al* (2007) proposed the Design Irregular Wave (DIW) method, which is similar to MLRW in terms of phase matching based on linear response functions. The authors proposed that the wave is conditioned on the particular load response functions, such as VBM, instead of the respective response functions, such as local stress, removing the necessity for many different simulations.. It was shown that this method, in combination with the most severe short-term wave conditions, deterministically provides a practical and swift estimation of the extreme structural response under nonlinear loads corresponding to probability levels of exceedance between 10⁻⁶ and 10⁻⁸.

While the conditioning methods are based on linear response functions, another efficient approach using FORM (First Order Reliability Method) has been proposed for extreme response predictions. In this approach, irregular seas are represented by a set of uncorrelated normal standard distributed random variables. The mean out-crossing rate is expressed analytically by the design point in terms of the random variables, and the reliability index. Assuming a Poisson distributed process of peaks, the probability of exceedance is calculated from the mean out-crossing rate. Once the design point and reliability index are determined by FORM, a critical wave episode together with a probability of occurrence is easily determined. Due to the efficient optimisation procedures implemented, FORM can efficiently specify the time instance when a response has a maximum, even when the system has strong nonlinear characteristics. Juncher Jensen (2007a) applied this method to a few problems, i.e. a jacket response including the second order stochastic waves, parametric roll where a bifurcation type of response is included and large sway motion of a TLP. The required time for nonlinear simulation to find the extreme value is reported to be 60s to 300s in real scale to cover memory effects in the response. This is considered to be a significant amount of reduction in calculation time. On the other hand, Kogiso and Murotsu (2007) noted a difficulty of this method, related to a drawback of FORM. They performed a time domain analysis implementing FORM, to predict the probability of capsizing of a large passenger ship, and also conducted a Monte Carlo simulation for comparison. The result by the Monte Carlo simulation was found to be 30 times larger than that by

FORM. They concluded that there are multiple design points and that the limit state function can be represented by multiple linear functions.

Load effect in abnormal or freak waves has also drawn attention. Fonseca *et al* (2006), already mentioned in section 2.3, investigated the long-term distribution of structural loads using numerical modelling. Comparing the response in the abnormal waves with the long-term value at an exceedance probability of 10^{-8} , it was shown that abnormal waves do not necessarily induce the largest ship responses.

6.2 Probabilistic Methods for Offshore Structures

This section of the report offers a brief overview of developments in two areas of investigation, namely reliability analysis and estimation of extreme values, and methods for characterizing extreme sea conditions, illustrated with a few examples.

Khan and Ahmad (2007) discuss dynamic response and fatigue reliability of marine risers under random loading, using a response surface method in conjunction with FORM. The limit state function is established for cumulative fatigue damage using S-N curve and fracture mechanics approaches. Results were compared with those obtained from Monte Carlo simulation methods, and highlight the effects of uncertainties in various random variables on riser fatigue reliability. Wang *et al* (2007b) presented a method for quantifying the probability of failure for platforms that are subjected to hurricane events. The platform failure limit state is defined in terms of platform capacity and environmental load. Annual probability of failure is estimated using FORM, and the reserve strength ratio is investigated. Results may be used to evaluate the level of risk associated with hurricane exposure, and may be incorporated into risk-based underwater inspection programs as part of the Structural Integrity Management (SIM) process. Juncher Jensen (2007b), mentioned in the previous section, advocates the use of FORM for prediction of extreme values of wave-induced loads. Various nonlinearities can be included, insofar as the procedure makes use of short duration time domain simulations. To illustrate the procedure, a jack-up rig subjected to second order stochastic waves was analyzed to determine probability of overturning as a function of sea state and operational time. Moarefzadeh and Melcher (2006) investigated the reliability analysis of offshore structures under wave and wind actions using second order random wave theory. To represent the non-Gaussian properties of the resulting wave kinematics and load processes, the Hermite moment transformation was used together with an extension of the, so called, sample-specific linearization method. Using the proposed procedure, simple structures were analyzed in one- and multi-dimensional cases and the results for structural probability of failure were compared with those obtained using simple linear wave theory. Outcomes showed that the use of nonlinear wave theory may affect the results considerably.

Naess *et al* (2007) presented a study of extreme response statistics, applying the Mean Number of Upcrossings (MENU) method, for drag dominated offshore structures based on the mean up-crossing rate function, which can be easily extracted from simulated

stationary response time histories. Present practice requires that a large number of lengthy time domain analyses be performed for several extreme sea states, but the proposed method provides estimates of reasonable accuracy based on a smaller number of shorter duration simulations. Results were presented for a jacket structure operating on the Norwegian continental shelf.

Culla *et al* (2007) presented two techniques to predict the statistical moments of the horizontal motion of a floating moored dock in random sea. The dock is represented by a lumped mass, the mooring cables by equivalent nonlinear springs and the hydrodynamic forces are modelled by a modified Morison equation. The model of the floating dock leads to a nonlinear ordinary differential equation. An alternative solution, in this paper, is based on the development of two more efficient techniques to predict the relevant statistical moments of the dock's response, namely Conventional Perturbation–Statistical Perturbation (CPSP) and Statistical Linearization–Statistical Perturbation (SLSP). The results, compared with those obtained by Monte Carlo simulations, show, a satisfactory agreement. Arena and Nava (2008) discuss in-line loading on slender marine structures. This can be computed by means of Morison's equation, which includes the inertia term and the drag term. In random waves the Morison's equation needs a linearization in the drag term, in order to obtain the force spectrum. In this work, the quasi-determinism theory is applied for the calculation of the drag force given by high 3D wave groups. It is shown that when a crest-to-trough wave of given height occurs on a vertical pile, the quotient between maxima of sectional drag force, according to Morison's equation, and the force obtained by linearization (both calculated at a fixed depth) is proportional to the ratio of the wave height to significant wave height. Then, it is shown that the Borgman linearization is not conservative for the calculation of extreme drag forces. The results are finally validated using Monte Carlo simulations in random seas.

Tromans *et al* (2007) determined the statistics of extreme wave crest elevation and wave height for realistic, directionally spread sea and swell. The nonlinearity of steep waves was modelled to second order and a response surface method was used to deduce the crest elevation or the wave height corresponding to a given probability of exceedance. As would be expected, nonlinearity effects make extreme crests higher than corresponding linear ones, but nonlinear effects on wave height are relatively small. Stefanakos (2007) predicted expected return periods for values of significant wave height in the Gulf of Mexico based on a new method for non-stationary extreme value calculation, as obtained from nonlinear wind or wave time series analyzed and a new definition of return period based on MENU. The procedure was applied to long term measurements of wave height in the Gulf of Mexico, based on buoy and satellite altimeter data. Results were shown to give more realistic estimates than would be obtained from more traditional methods.

7. FATIGUE LOADS

7.1 *Fatigue Analysis of Ships*

Structures are often subjected to low and high frequency load components, e.g. still water loads and wave loads, mooring tension force due to wave loads and slowly drifting, and whipping loads due to slamming. Efforts are focussed towards incorporating the combination effects of the low and high frequency load components for fatigue strength analysis (see also section 3.4). Huang and Moan (2006) proposed a formula for estimating the fatigue damage that accounts for the combination effects of the low and high frequency load components assuming firstly each component is Gaussian and then non-Gaussian. Winterstein's transformation was employed for correcting the combination factor obtained by assuming Gaussian distribution, in terms of kurtosis of the response process. It was shown that the fatigue damage predicted by their method is very close to the rain-flow count prediction for many cases, obtained by varying the ratio of the magnitudes between the two load components and the ratio of the centre frequencies. Baxevani *et al* (2007) presented a method for calculating wave load induced fatigue damage accumulated by a vessel sailing along the north Atlantic route. This method is based on the Palmgren–Miner additive rule and the rain-flow count. For simplicity, the load the vessel is experiencing is assumed to be proportional to the encountered significant wave height. The asymptotically normal character of the nominal damage is shown and used to derive the probability distribution of fatigue life prediction. It was concluded that the proposed method improved on already existing ones by making use of the information contained in the variance of the fatigue damage accumulated during the voyages.

For crack propagation analysis, it is necessary to generate rational stress time history because the order of the load is influential on the results. For this purpose, the “storm model” was proposed Kawabe *et al* (2004). The model was further developed, with considerations for sea areas and seasons, by Osawa *et al* (2006). The new model was applied to the crack propagation in a bulk carrier. The authors found that the shorter life could be predicted by the new model, depending on the assumed sea areas and seasons. In the original storm model, it was assumed that the duration of the storm is constant, 84 hours based on the observations. Arena and Fedele (2002) proposed an Equivalent Triangle Storm (ETS), in which the duration of the storm is expressed as an exponential function, with an argument of the storm strength. Kawabe (2006) reanalyzed the wave data for the north Pacific ocean provided by NOAA, and performed the wave hindcasts. Then, he proposed a relationship between the storm duration and the storm's significant wave height, finding that the results better fit the ETS model.

A concern has been raised with reference to vibratory effects, such as springing and whipping, which may increase fatigue damage significantly. Onboard measurement results, including the effects of wave induced vibrations on the fatigue damage, were reported by Storhaug *et al* (2006) and Okada *et al* (2006). Storhaug and Moan (2007) conducted a model experiment on an iron ore carrier in 19 short-term head sea states, in ballast and loaded conditions. The sea states were selected so that they include those

with dominant contributions to fatigue damage. They compared the additional fatigue damage due to vibrations, with the wave frequency damage. The additional fatigue damage was determined as the difference between the total fatigue damage and the wave frequency fatigue damage. It was shown that the fatigue damage due to the vibrations accounts for 43% of the total damage in ballast condition, when involuntary speed reduction was considered. It was also shown that the operations may have a significant effect on fatigue damage. The results show a fair agreement with the full-scale measurements. Okada *et al* (2006) analyzed full scale measurement data on a post-Panamax container ship for three years, to investigate the additional fatigue damage due to vibrations. They showed that the fatigue damage due to all frequencies is 0.105 and that of wave frequencies is 0.050. Hence, the fatigue damage increases approximately twice due to the whipping stress.

Oka *et al* (2008) conducted an experiment with the model of a large container ship, considering the effects of flexibility in comparatively large waves. They showed that wave-induced vibrations contribute five times more to fatigue damage compared to the wave frequency load in the selected short-term irregular sea states, with significant wave height of 5m and mean wave period of 12s. Further numerical, experimental and full-scale investigations are necessary in order to clarify the effects of vibrations on fatigue damage and structural design. Operational effects such as loading, voluntary/involuntary speed reduction and routing, structural damping, and the warping stress under torsional vibration are of concern in particular.

7.2 *Fatigue Analysis of Offshore Structures*

Van der Cammen (2008) investigated the fatigue life of structural members on the side shell, deck and bottom of a FPSO. The model is developed in the time domain and validated against available model test data and full-scale measurements. It was demonstrated that the individual sea states can be represented by short time series, making it possible to consider many sea states, as required in a fatigue assessment, and making it feasible to use time domain computations. The sensitivity of fatigue life predicted by this model was investigated. It was found that the accuracy of the environmental and loading condition data input to the model are equally important as the model itself. Vessels are designed based on historical environmental data, but a particular vessel is likely to encounter different environmental conditions during its life. Furthermore, the vessel will most likely be operated differently than assumed in the fatigue calculations. Both factors have a significant impact on fatigue life. Therefore, for offshore inspection, maintenance and repair and for lifetime extension work at a yard, it is important to record loads that the vessel encountered.

Gao and Moan (2007) studied fatigue damage induced by non-Gaussian bimodal wave loading in mooring lines. Catenary mooring lines are typically subjected to bi-modal loads, comprising of wave frequency (WF) component due to the first order wave forces and a low frequency (LF) component induced by the second order wave forces. A fatigue combination rule was extended to cover the non-Gaussian case. Both WF

and LF mooring line tensions due to wave loading were simulated in the time domain for different sea states and the combined fatigue damage was estimated using rain-flow count. The accuracy of the frequency domain method for estimating the bi-modal non-Gaussian fatigue damage of mooring lines was verified by the time domain simulations and is considered to be acceptable. Zeng *et al* (2007) studied the fatigue damage of the tether of a TLP in finite displacements and adverse operational conditions. The stress time histories of the tether in random waves were calculated and rain-flow count employed to obtain the fatigue load spectrum. Miner's linear cumulative law model was used to obtain the fatigue damage of the tether. The short-term analysis of fatigue damage of the TLP in certain sea states was also performed. Gong *et al* (2007) developed a code to evaluate cumulative damage and fatigue life of jacket structures. Rayleigh's distribution model was adopted to discretize wave and mooring forces, and linear Airy wave theory was employed to predict the fluid loading. S-N curves and Miner's rule were used for the fatigue damage assessment and prediction of fatigue life. The results showed that fatigue damage induced by a single wave loading was very minor, compared to the combination approach. It was noted that the linear addition of fatigue damages, respectively, arising from wave, high frequency and low frequency mooring loads was not rational and resulted in overestimating the fatigue life of jacket structures.

Chen *et al* (2007b) investigated fatigue strength of tubular joints. A 3D FE model of the truss spar platform was introduced in the HydroD code to look for the most serious sea state resulting in maximum structural response. Then FE analysis was carried out to obtain the boundary conditions for use with a detailed model of the tubular joint and identify hot spot stresses. Finally, using S-N curves, the life of tubular joints can be predicted after refining the previous hot spot stress. Spanos *et al* (2006) presented a method for estimating the fatigue life of fluid-conveying pipelines. The pipeline was subjected to a random support motion that simulates the effect of the FPSO heaving. The equation of motion of the pipeline was derived assuming small amplitude displacements, modeling the empty pipeline as a Bernoulli-Euler beam, and adopting the, so called, plug-flow approximation for the fluid. The power spectrum of the acceleration at deck level was determined using the RAO of the FPSO. The computed stress spectrum was used to estimate the pipeline fatigue life employing an appropriate S-N curve.

Yue *et al* (2008) carried out failure mode analysis of ice-resistant compliant structures based on monitoring oil platforms in Bohai Gu. The results showed that ice-induced vibration of jacket platforms is significant. The ice-induced vibration not only causes significant cyclical stress of tube nodes, but also large acceleration response, which can endanger the pipeline systems on the platform and discomfort crew members.

8. CONCLUSIONS

8.1 Wave- and Current-induced Loads on Offshore Structures

Evaluation of wave loads on large offshore structures is, usually, dealt with through potential flow analysis, with viscous effects only considered for specific problems, such as slow drift motion. Analytical solutions, using first order radiation/diffraction, are only available for simple body geometries. The first order asymptotic expansion method has been extended to second order for bodies with simple geometry. Simulations in shallow water zones and the solution of the low frequency loads are tackled using quadratic transfer functions and an extension of the middle-field formulation. Fully nonlinear methods are also under development, but require further verification against experimental measurements.

The influence shallow and confined (e.g. harbours) waters on the fluid loading is becoming important, as a consequence of increasing shallow water operations. Classical diffraction theory, together with techniques for eliminating wave reflection from boundaries, forms the basis of current prediction methods dealing with variable bathymetry. This is an area that requires experimental data for validation.

The influence of current on the body-wave system is handled using potential flow and, mainly, focusing on second order wave drift damping. Investigations centre on relatively simple geometries.

Side-by-side configurations, used in offloading operations, are at the centre of multi-body interactions. The lid approach provides the basis of current predictions. However, work is beginning to emerge on second order wave amplification in the gap region. In addition, research is ongoing on interactions involving multiple cylinders and arrays of porous cylinders, focusing on predictions of wave run-up and free surface in the bodies' vicinity. A related problem is the complex hydrodynamic behaviour of moonpools. Theoretical studies are, by and large, carried out using potential flow methods, although use of CFD methods is beginning to emerge. Important issues relate to resonant modes, motion trapping and the coupling/interaction between the motion of the moonpool water and the body. There are only a few experimental studies involving moonpools.

The majority of publications on cables, risers and mooring systems during the past few years tackle, in the main, the subject of the coupled floater-mooring global response. Nevertheless, issues relating to the nonlinear dynamic behaviour of mooring lines and the slow drift motion of moored floaters continue to attract interest. Particular examples are the dynamics of cables and risers, the touchdown area with the ocean floor, the mooring line induced damping on the floating structure and the snap- and slack-loading impacts.

The importance attached by academia and the energy production industry to the consequences of VIV is corroborated by the quantity and range of investigations addressing this issue. Numerical simulations are, in general, carried out through a range of CFD methods using various turbulence models. Most simulations make use of 3D modelling requiring computational efficiency, achieved, for example, using

multiple-processors and avoiding regriding. Full- and model-scale measurements are available. This type of investigation should continue as it is vital in providing validation data for the numerical simulation studies, both in modelling VIV and its suppression. The influence of higher harmonics and multi-mode interaction are highlighted in many studies. More research should focus on VIV-induced fatigue damage.

8.2 *Wave-induced Loads on Ships*

The vast majority of codes and applications for ships at forward speed make use of potential flow analysis. Within this group there is a large variety of methods ranging from linear theories to fully nonlinear methods, where the complete nonlinear potential flow problem is solved with as few assumptions as possible. Between these two extremes there are many partially nonlinear, or blended, methods, aimed at including the most important nonlinear effects. However, since the importance of the different nonlinear effects will vary from case to case and from response to response, it is difficult to arrive at a single method, which is appropriate for a wide variety of cases. Nevertheless, current computer codes used for practical calculations all lie somewhere in this regime of partially nonlinear methods. Fully nonlinear potential theory codes and RANS solvers are still not sufficiently mature for practical calculations of motions and loads for ships with forward speed. An interesting development with RANS methods is their application to simulate the manoeuvring problem, though the issue of unifying seakeeping and manoeuvring has not been tackled yet, as in the case of potential flow analysis.

Two- and three-dimensional linear hydroelasticity theories in frequency domain have reached a degree of maturity. However, three-dimensional nonlinear theory, as well as, hydroelasticity considering nonlinear structural behaviour are still under development. Development of an efficient fully nonlinear hydroelasticity analysis should be the main focus in the near future. More experimental studies and numerical investigations are needed in order to further understand the nonlinear mechanisms and validate nonlinear hydroelasticity. Use of RANS solvers, within the context of fluid-flexible structure interactions, should be investigated.

There is a substantial body of work, both numerical and experimental focusing on the generation of abnormal or rogue waves. These investigations are important for the evaluation of consequent loads on ships. Evaluation of rogue wave induced loads continues to be dealt using partly nonlinear methods and comparing predictions with a small number of available model tests, with favourable agreement. It will be interesting to apply fully nonlinear methods, including RANS approaches, to this type of wave loading.

As ships change, in terms of scale, type and operational/economic/environmental requirements, the use of first principles approach in global structural analysis, either on its own or in combination with prescriptive rules, is becoming more prevalent. Various

Classification Societies have a similar approach for the global structural analysis, but different ways for design wave selection and wave load evaluation method. Developments, such as Goal-Based ship construction Standards, present a challenge in bringing together codes of design practice and performance/operation based-design.

8.3 *Ice Loads on Ships*

Good understanding of ice mechanics is required to improve understanding of parameters influencing process pressure-area curves and their relationship with spatial curves. Sound knowledge of physical properties of ice is crucial for predictions and development of robust empirical expressions. More full-scale trials are needed to provide better evidence of large force impacts and to gain better understanding of the contact process and provide data for validation of numerical codes.

8.4 *Measurements on Ships*

Tests with elastic backbone segmented models, properly calibrated in order to scale the first vertical (i.e. two-node) mode of the full-scale ship, still represent the major source of information on springing and whipping responses. Where only longitudinal strength is concerned a simple two-segment model with a cut amidships can be used, but only the first vertical mode can be correctly scaled. To investigate springing and whipping vibration, models with five to six segments should be used and scaling should, at least, be extended to the second vertical mode.

The expansion of the installation of hull stress monitoring systems onboard ships, undoubtedly represents an important development. However, in the case of large and complex ship structures, such as the recent mega-size container ships and multi-deck super cruisers, it may be not sufficient to measure the stresses at a few critical spots in order to take a decision on the ship's structural safety status. Even with the availability of detailed 3D global FE models, the transition process from an accurate measurement of local deformations to a reliable estimate of a dominant global load parameter, such as the vertical bending moment of a cruiser or the torsional moment of a container ship, is not at all straightforward and without many uncertainties. Furthermore conventional hull monitoring systems, in spite of their accuracy and complexity, have in common a passive attitude towards structural safety. That is to say they may raise the alarm of a possible risk but are not capable of advising the ship's master on the effects of a change in ship speed and/or course, given the actual environmental and operational loading conditions. Systems are being developed which actively support operational decisions, thus increasing safety. For a monitoring system be active it is necessary to feed the system with an accurate and reliable knowledge of the ship's structural response to hydrodynamic loads induced by the waves, including impulsive loads such as slamming, actually encountered during its operations.

8.5 *Uncertainty Analysis*

The committee is not in a position to recommend application of either GUM or AIAA method. Advantages of one method over the other have not been documented or presented systematically in the open literature. Conducting uncertainty analysis on experimental data is of paramount importance, using either method, and should be accompanied by information on method used and as many details as practically possible on the test. Experimentalists are encouraged to adopt this process.

It is recognized that both model experiments and sea trials are providing the most reliable data for validation of numerical codes and empirical expressions. Publication of complete set of results is of the highest value for those involved in numerical simulations. Even though the information is often classified or proprietary, the committee can only hope that more data will be publicly available.

Publications on verification and validation are, by and large, developed by and targeted to numerical code developers. It is very important to make a distinction between verification of a code and verification of a calculation. Verification of a code must be conducted by its developer and should include limited validation for a selected type of applications. A user, particularly for a new or unusual code application, must conduct his/her own calculation-related verification and validation. Guidelines need to be provided for users, particularly inexperienced ones, to improve credibility of outputs.

8.6 *Probabilistic Methods*

Response conditioning techniques, such as MLER and CRRW, for efficiently estimating the entire nonlinear extreme response value distribution for a selected operational profile, have become established where ships are concerned. However, it has also been shown that these techniques are time consuming, especially when transient loads, such as whipping after slamming impacts, are involved. Modifications to these techniques have to be developed in order to obtain more efficient predictions. Another method, based on FORM was applied to several problems and shown to be effective when compared with Monte Carlo simulations. This method, nevertheless, needs to be verified for its effectiveness with further numerical simulations.

Reliability analysis, using methods such as FORM, appears to be widely used in offshore structures, e.g. risers and jack-up rigs. Inclusion of nonlinearities in fluid loading is considered very important. Estimation of extreme sea conditions and extreme responses has been focused on, due to the longer lifetime of offshore structures.

8.7 *Fatigue Loads*

Efforts were focused on including nonlinear effects in fatigue predictions for ships. Important properties are non-Gaussianity, broad band width of the nonlinear response and the sequence of loads. Hydroelastic vibrations, such as springing and whipping, are shown to be predominant for fatigue damage in particular cases. Further investigations are necessary in order to clarify in which case and to what extent these

need to be considered in fatigue analysis and structural design of ships.

The issues in fatigue analysis of offshore structures are, by and large, similar to those for ships. The range of structures concerned, e.g. FPSOs, mooring lines, jackets and pipelines, require the use of a suitable method to evaluate fluid loading. The environment, and its non-Gaussian nature, appears to be the dominant factor. Evaluation of cumulative damage is another important issue.

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