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COMMITTEE I.2

LOADS

COMMITTEE MANDATE

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

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KEYWORDS

Wave induced loads, Hydroelasticity, Slamming, Whipping, Sloshing, Green water, Loads due to collision and grounding, Vortex induced vibrations, Vortex induced motions, Mooring system, Lifting operation, Floating offshore wind turbines, Probabilistic method, Design waves, Cables/risers, Fatigue, Uncertainty analysis.

CONTENTS

1. INTRODUCTION

The content of this committee's report is composed in accordance with its mandate by the expertise of its membership. Its structure and content follow along similar lines to those adopted in previous ISSC reports, that is ISSC2012, ISSC2015 and so forth. Wave-induced loads on ships are reviewed in two different sections, namely 2 and 3. Section 2 focuses on two-dimensional(2D) and three-dimensional(3D) methods, dealing with linear and nonlinear methods and including applications of the so called CFD (Computational Fluid Dynamics) methods. Section 3 reviews specialist topics such as slamming, whipping, sloshing and green water loads as well as loads due to damage following collision and grounding. Wave-induced loads on offshore structures are reviewed in section 2 and 4, the former dealing with single and multi-body interactions, including a note on the effects of current and bathymetry. On the other hand, section 4 focuses on specialist topics, such as vortex-induced vibrations (VIV), vortex-induced motions (VIM), cables and risers, offshore lifting, offshore installation, submersibles and floating offshore wind turbines. Continuing from previous reports, in section 6 and 7, current state of progress in probabilistic approach of loads on ship including short-term 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 in section 7.

2. COMPUTATION OF WAVE-INDUCED LOADS

In recent years, the trend for further development and enhancement of numerical methods for the computation of wave loads continued, with new technological challenges of the marine industry setting the focus areas. Developments included the computation of wave loads acting on floating structures and vessels advancing in sea way as well as methods to account for hydroelastic phenomena and violent hydrodynamic loads.

For stationary floating bodies, progress was made regarding loads from steep non-linear waves, the impact of wave-current interaction and various multi body interaction problems, as encountered during offloading operations between FPSO and shuttle tanker or crane operations with heavy cargo in seaway, for instance.

Safety concerns regarding manoeuvrability triggered research on the wave loads acting on low powered vessels operating in severe sea states, but also the loads on vessels advancing at design speed through waves remained of great interest in recent years. Several benchmark studies on sea keeping calculation codes have been carried out, illustrating the need to identify the most suitable code for the given ship form and operation speed profile. In this context strip theories have been extended for more accurate predictions of wave sagging moments, including 2D+T approaches for higher ship speeds. The enhancement of 3D potential theory methods continued to be of great interest too, being true for Green function based approaches and Rankine methods.

RANS methods become increasingly popular, however due to excessive computational cost in comparison with strip and panel methods they are still reserved for niche applications, e.g. nonlinear excitation of springing vibration or green water phenomena.

Although not directly related to wave loads, work on added resistance in waves is discussed in this section too, since such work provides improved understanding of involuntary speed reduction and hence, more realistic assumptions regarding ship speeds in adverse weather conditions.

Also the investigation of hydroelastic effects continued to be of great interest in recent years and thus new publications on the hydroelastic response of ships and Very Large Floating Structures (VLFS) in waves are discussed in this section too.

2.1 Zero-Speed Case

2.1.1 Body-wave interactions

A time-domain 3D Rankine panel method based on a simplified variant of the mixed Eulerian–Lagrangian (MEL) scheme is developed by T. Shivaji and D. Sen (2015) for studying steep nonlinear waves interacting with ship shape body and offshore configurations at zero speed. One of the important numerical problems of an MEL-type time-domain solution scheme for the full nonlinear floating body problem is associated with the coupling between hydrodynamic forces and rigid body motions which tend to cause numerical instability inhibiting long-duration time-domain simulation. Improved numerical schemes such as the acceleration potential method of Tanizawa (1995, 1996), the implicit coupled scheme of Dombre et al. (2015) have been devised to handle this coupling. In the work presented by T. Shivaji and D. Sen (2015) a method similar to acceleration potential with the linearization of diffraction and radiation potentials is devised. This makes the implementation different and simpler compared to original method of Tanizawa (1995, 1996). This method enables to produce very long-duration simulation results. In this work (1) a fully linear formulation where all external forces are computed on the mean wetted surface, and (2) an approximate nonlinear computation where the hydrodynamic interaction forces (diffraction and radiation forces) are determined on the mean surface and the forces arising from the incident steep waves and hydrostatic restoring forces are determined based upon the exact wetted surface under the nonlinear incident wave. Numerical computations for three realistic marine structures, the barge, the S175 hull, and the semisubmersible are presented. The linear computations for which very long duration simulations are achievable from the presented method are validated against results from other available methods. It is found that the nonlinearities of the forces and motions are strongly dependent on the above water hull geometry. Compared to a small water-plane area hull (the semisubmersible), or a wall-sided hull (the barge), a flared hull (S175) results in pronounced nonlinear features in the forces and motion time-histories. The method is developed for stationary floating bodies undergoing oscillation about their mean location, thus not suitable for freely drifting body.

When the ship operates in adverse weather conditions, drift forces play major role with respect to the manoeuvrability of the vessel. As such to address the minimum power requirement of IMO, extensive experimental and numerical investigations were carried out in the EU SHOPERA project (Potthoff, R and Moctar, B, 2016). Post Panamax 14000 TEU container ship DTC used for benchmarking of drift forces in SHOPERA was used by Cong Liu et al (2017) for numerical computations of drift loads. These computations are based on volume of fluid (VOF) and overset mesh methods, discretized by finite volume method (FVM). Problem is treated as a zero forward speed case. NAOE-FOAM-SJTU solver, developed under the framework of the open source OpenFOAM was utilized for this study. An open source library waves2Foam is imposed in this solver to handle the wave problem. Seven wave conditions with a wide range of incident angle are considered. The wavelength is in the range of short waves. The prediction of wave drift forces agrees well with the measurements. The maximum value of longitudinal drift forces is captured at the heading angle of 60° in numerical computations which is in-line with the EFD. The peak value of transverse drift computed is for the case of 90° which is also in accordance with the EFD. However, the under prediction of this value is attributed towards the geometry simplification (absence of bilge keel in numerical model) and strong nonlinear effects (wave breaking) when wave crest hits port (or starboard) side. The time history curves of drift forces illustrate that nonlinear behaviour is more notable when the incident wave is from the bow. The FFT results of drift forces explain that the natural frequency of roll plays a significant role in these time history curves. All these curves fluctuating within the frequency of waves and the FFT results show that only the wave frequency dominates these motions. Basic ability to deal with the maneuverability in waves is achieved through this work.

Arbitrary Lagrangian Eulerian (ALE) formulation is used for tracing markers on free surface as well as wave-body intersections. The feature of ALE is that complex mesh is generated only once at the beginning and fluid marker is moved along prescribed path at all other time steps. Since the prescribed path for each marker is equidistantly arranged, at any instant, the relative positions of adjacent markers are well maintained, and thus good mesh quality can be ensured throughout the computation. In order to trace the exact wave-body intersections i.e. waterline, the marker (intersection) is enforced to move along cross section line of body surface, which can take into account complex body geometry above still waterline.

Zhang and Kashiwagi (2017) studied interactions between water waves and non-wall-sided surface using fully nonlinear potential theory based on ALE formulation. In this computation, HOBEM and 4th-order Runge-Kutta method are adopted as initial boundary value problem (IBVP) solver. For improving computational efficiency, the total velocity potential is split into incident wave component and disturbed one. Diffraction of nonlinear waves by non-wall-sided surface is studied and validated with the example of a circular cylinder. Because the prescribed path is well organized in space, good mesh quality is ensured even though the body has complex geometry. To prove capacity of this scheme, nonlinear wave diffraction by ship geometry is also studied and results show good agreement with experimental results.

2.1.2 Body-wave-current interactions

Station keeping analysis is an important activity in the design of any vessel/DP system that eventually determines the machinery and thruster configuration and thruster size selection. In order to obtain reliable results, it is crucial to apply engineering tools that realistically represent the flow physics and resulting hydrodynamic forces. Present computer tools are based on the assumption that wave drift and current forces can be superimposed. However, there are also mutual interaction effects between waves, current and hulls that should be accounted for in the evaluation of the wave drift forces.

In MULDIF, a 3D diffraction/radiation panel code developed by SINTEF Ocean (Sprenger et al 2017) within the framework of a JIP, wave-current-body interaction is taken into consideration by a new potential flow numerical model. A case study with offshore vessels and general cargo ships of different main dimensions has been performed to assess the capabilities of MULDIF for station keeping purposes in wave and current environments. The first-order vessel motions as well as mean second-order drift forces for zero forward speed without current have been calculated. Through an interface to SINTEF Ocean's vessel response code VERES, viscous roll damping due to hull-water friction, flow separation at bilge keels, lift effects as well as normal forces acting on bilge keels and hull pressure created by the presence of bilge keels is included. Thus, realistic roll response is obtained. Roll reduction tank effects are considered through the external damping matrix. Model tests for the selected vessels have been performed in SINTEF's Ocean Basin in a soft-mooring arrangement in different irregular sea states and headings in deep water. The models were equipped with two two-component force transducers, measuring the x- and y- components of the forces. The yaw moments have been calculated from the y-force measurements. In order to measure the vessel motions in six degrees of freedom, an optoelectronic position measuring system has been used.

The verification and validation of the wave-current interaction effects on first order motions and mean second order drift forces using MULDIF has been published earlier by Stansberg et al (2013) and Hermundstad et al (2016) for various types of bodies. Based on the results of the case study performed for the two offshore vessel hulls (Sprenger et al, 2017), it is concluded that it is important to consider the effect of wave-current interaction in the early design phase. First order motions are influenced by the presence of currents, this effect is increasing with increasing current velocity and decreasing vessel size. A stronger impact of wave-current interaction is observed for mean second order wave drift forces and yaw moments. With increasing current velocities, wave-current interaction effects lead to higher loads, especially in sea states with lower peak periods. For higher current velocities above 1.5 m/s, the loads calculated with interaction effects are dropping again below the values that are calculated without wave-current interaction. The total forces without wave-current interaction are not conservative but lower compared to the results with interaction effects over a wide range of peak periods. Total mean longitudinal forces without wave current interaction are up to 35% lower for some sea states.

More research is necessary in this area to get insight of wave-current interaction. The most relevant task is to extend the validation of the wave-current interaction effects on first order motions and mean second order wave loads on ship type floating bodies. Such an experimental and numerical study should cover a variety of combinations of current angles and wave headings. To establish a more realistic numerical model, the actual current coefficients for the hulls should be determined, e.g. by CFD, and applied in the validation study instead of generic coefficients.

2.1.3 Multibody interactions

Multiple floating structures are widely used in different areas of marine operations. During offshore installation and underway replenishment, two vessels are side by side positioned in close proximity. When two vessels are moored side-by-side with a narrow gap between them, intense free surface motions may be excited in the gap as a result of complex hydrodynamic interactions. These influence motions of the vessels and forces in mooring lines. Higher wave elevations in between two floating vessels stand as a hindrance in operations like offloading. A configuration with minimum wave elevation is recommended for these reasons.

The computational scheme of 3D MEL developed by T. Shivaji and D. Sen (2015) based on a numerical tank approach for interaction of large-amplitude waves with a single floating body is extended to the problem of wave-interaction with multiple floating bodies (Shivaji Ganesan and D. Sen, 2016). The coupled system of two side-by-side fixed and/or floating bodies interacting with a large amplitude nonlinear wave is studied using a direct time domain solution method. The numerical scheme is implemented over a time-invariant boundary surface to solve the boundary value problem for the unknown velocity potentials. A 4th order Adams–Bashforth–Moulton scheme is used for time marching of rigid-body motion histories of the individual bodies and evolution of the free-surface including the gap region in which large resonant fluid motions occur. A systematic study has been carried out to evaluate the performance of the developed time domain method in simulating the forces and motions as well as the fluid motion in the gap region between the two body system in various arrangements and in different wave-headings. At first, the computed numerical results have been validated and verified with computational and experimental results available in literature for standard geometries such as vertical truncated cylinders and rectangular boxes. Secondly, effectiveness of the damping lid model which is introduced to suppress wave resonance in the gap region is investigated including its influence on maximum sway forces on fixed and floating rectangular barges in side-by side configurations. Thirdly, comparative studies on absolute and relative motion response for two cases (two rectangular barges, and a FLNG-FPSO + shuttle tanker) in side-by-side arrangement are detailed to bring out the importance of nonlinearities arising due to steep nonlinear incident waves. Finally, coupled motions of the two-body system of an FPSO and a shuttle tanker floating in side-by-side configuration in a steep nonlinear wave field are studied in which the two bodies are connected through hawsers and the FPSO is moored to the ground. Additionally, there is a fender between the two bodies. Developed numerical scheme is suitable for multiple (more than two) body interaction. The effectiveness of damping lid method is highlighted. Importance of nonlinear FK formulation in such problems is revealed.

Seung-Ho Ham et al (2015) have derived a Discrete Euler–Lagrange (DEL) equation to represent the motion of a multi- body system, in which many bodies are connected physically by joints or wire ropes. By discretizing and re-formulating the traditional Euler–Lagrange equation, authors obtained a discrete time integrator. The integration scheme mixes the Stömer–Verlet method for dynamic equations with the linearly implicit Euler method for constraint equations. The stability and performance issues are dealt with the new formulation. Equations of motions are automatically derived which was the major constraint of similar previous works. It is achieved by defining the equations of joint constraints and their derivatives. In addition, the stretching of the wire rope is mathematically modelled as constraints for stability. Linearized hydrostatic and hydrodynamic forces are used similar with previous works. Authors applied the DEL equation to a mass–spring system with the large spring coefficient. A spring pendulum modelled by a constraint-based wire rope was tested. Despite the large spring coefficient, the DEL equation with the constraint-based wire rope shows relatively stable motion. The automatic formulation was also tested by three-dimensional multiple pendulums. Finally, a floating crane and a heavy load connected by constraint-based wire rope, based on set of regular waves with different wave heights, directions and periods was simulated.

Hyewon Lee et al (2015) dynamically simulated a wireline riser tensioner (WRT) system to analyze the dynamic response of the riser string in a mobile offshore drilling unit (MODU) such as a drilling rig or a drillship. The main function of the WRT system is to sustain the tension to avoid buckling, regardless of the MODU motion. The WRT system consists of a tensioner ring, a wireline, pneumatic cylinders, and air pressure vessels (APVs). It reduces the vertical (heave) motion of the top of the riser string caused by the MODU motion. In this study, the equations of motion of the drilling rig and the WRT system were formulated based on multibody system dynamics. The discrete Euler–Lagrange equation was used to formulate the equations of motion. For the external forces, both the hydrostatic and hydrodynamic forces were considered. Several simulations were performed with various sea states to analyze the motion of the riser string and the efficiency of the WRT system. Furthermore, the gas volume inside the APVs was changed to investigate its impact on the efficiency and performance of the WRT system.

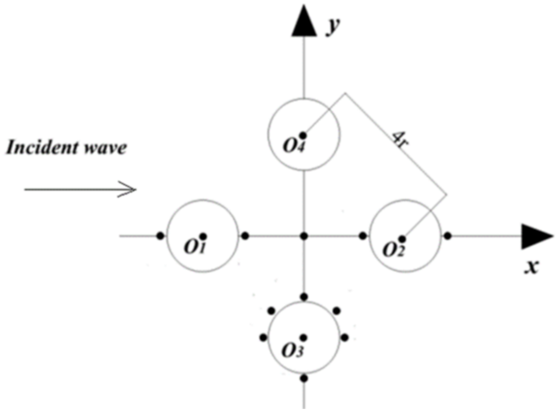

Figure 1: Top view of the arrangement of the four cylinders model, Z. Wang et al (2017). (This figure is originally reproduced in this report)

Zhengke Wang et al (2017) investigated the problem of hydrodynamic interactions among multiple floating bodies located in proximity in waves with the help of four cylinders as shown in Fig. 1. In this figure, dots represent the locations where free surface elevations are measured. Commercial software FLUENT is used to study the interaction phenomenon of an adjacent four-cylinder body in water waves. A time domain simulation on the problem of a four-cylinder body in regular waves is carried out based on viscous flow theory. The continuity equation and Navier-Stokes equations are taken as the governing equations, and a volume of fluid (VOF) method is used for free-surface capturing. The wave run-ups on the surface of each cylinder are then systematically investigated, and its corresponding wave forces are also discussed and analysed. By comparing with a single cylinder in the same wave condition, the influence mechanism of interaction among multiple floating bodies on wave forces is investigated. Highest wave elevation at the centre of the array is observed. Also, the wave elevations at the inner side of each cylinder are larger than the outside.

Chen and Zhu (2017) employed three-dimensional time domain Rankine source method with HOBEM to solve hydrodynamic interactions of side by side vessels with and without forward speed. Radiation and diffraction problems are solved with linearity theorem. For forward speed problem, both double body (DB) flow and uniform stream (US) linearized computations are carried out. Added mass, damping coefficients, hydrodynamic forces and motions responses of side by side vessels are computed and hydrodynamic interactions are investigated. Zero speed case is investigated with an example of side by side arranged modified Wigley hull and a rectangular barge. Further, numerical investigation is carried out for a Supply ship and a Frigate advancing in waves parallel in close proximity. Ship motions of DB linearization computation are generally better agreement with experiments than of US linearization method. It suggests steady flow has significant effects on side by side ships unsteady motions and a more exact basis flow model would improve computation accuracy. Results of motions response of smaller Frigate in condition of two ships on parallel course are quite different with that of single ship condition due to the existence of bigger Supply ship. In addition, results show two ships with forward speed would be subject to attracting lateral force, which shall increase with speed and the reduction of lateral distance. If the principal dimensions of two close ships have much difference, influences of hydrodynamic interactions on the smaller ship would be greater.

A multi objective optimisation programme (using MATLAB) has been developed by Shashikala and Shankar (2017) for optimising the gap between ship and tugboat for minimum wave elevation. Ship and tug boat are modelled using ANSYS AQWA for different spacing between the two. Response of ship and tug boat along the wave elevation at different points on the floating bodies are calculated under regular and random waves. Optimisation coding simultaneously optimise wave elevation at tug boat, ship and the centre of the gap. The range of optimum spacing has been obtained from the code. Difference in the optimum spacing for different approach headings (900 and 00) is observed. For lower frequencies (less than 1 rad/s) wave elevation in the gap does not change much. Drastic changes in the wave elevation in the gap are noted for higher frequencies.

2.2 Forward-Speed Case

The forward-speed case is both an important and challenging topic in the field of computational hydrodynamics. One recent demonstration of the challenge is the statistical analysis of Kim and Kim (2016) on the performance of 17 seakeeping analysis codes. To study the effect of forward speed, heave, pitch and, vertical bending moment were studied at Froude numbers 0.05 and 0.12. The analysis shows that the numerical results become more scattered at the higher Froude number, which indicates that the increasing forward speed is a difficulty for the computational methods. One well-known issue for the forward-speed case is the balancing between the run time of a solver and the level of detail of modelling flow. Determining e.g. which nonlinear effects should be modelled is not necessarily self-evident. Recently, Hirdaris et al. (2016) studied the influence of nonlinearities on the symmetric hydrodynamic response of a 10,000 TEU containership by comparing the results of four different numerical methods and model experiments. As an example of their findings, the differences between predicted and measured vertical bending moments vary depending on both position and heading and further investigations are recommended especially for locations away from amidships. In a third recent benchmark study on forward-speed case, Gourlay et al. (2015) reports that the results of four modern commercially available numerical codes on ship motions in shallow water show good agreement with model test results without a special trend of over- or under-prediction. Next, the studies with the main focuses on the application of one or two methods on structural loads and ship motions are described. Finally, some studies addressing mainly added resistance of a ship advancing in waves are mentioned shortly.

Recent studies on strip theories have addressed the prediction of sagging moment. Vásque et al. (2016) address the prediction of sagging moment in extreme waves by comparing numerical and experimental results of vertical bending moments for a bulk carrier and a roll-on/roll-off ship. The results demonstrate that a partially nonlinear time domain strip theory assuming linear radiation and diffraction (Fonseca and Guares Soares 1998a,b) overestimates the sagging bending moment in extreme waves, even though the same method has shown good agreement with model tests data in moderate amplitude waves. Rajendran et al. (2015a, b) offer improvements to the prediction of sagging moments by extending the method. Rajendran et al. (2015a) extend the method by including the surge mode in head seas. The numerical and experimental results for the S175 container ship and a chemical tanker indicate that the surge reduces the vertical bending moment at deck level while its effect on the vertical motion is negligible or small. Rajendran et al. (2015b) extend the method by including the body nonlinear radiation and diffraction forces. The results of the new and the original code are compared with experiments for a modern cruise ship. The effect of body nonlinear hydrodynamic forces on sagging moment is observed through comparisons.

Recent studies on strip theories address also 2D+T methods. Bandyk and Hazen (2015) improve the prediction of forward-speed effect of a body-exact theory based on a time-domain Rankine source method by a 2D+T strip theory variation. Meng and Qiu (2015) present an application of a body exact 2D+T strip theory for the prediction of the motions of a high-speed displacement ship.

In the field of 3D potential theory based methods using a Green function, several recent studies address the development of methods.

Guha and Falzarano (2015a) developed a three-dimensional panel method for the calculation of hydrodynamic force coefficients for ships with moderate forward speed in the frequency domain. The code uses the zero-speed infinite depth Green function and considers the effect of forward speed using encounter frequency. The frequency independent part of the Green function is evaluated analytically. The method is validated for ship motions and forces.

Kalske and Manderbacka (2017) extend a three-dimensional panel method to conduct computationally efficient forward-speed computations in frequency domain. The applied extension uses the zero-speed Green's function with correct frequency of encounter and speed correction terms corresponding to the terms in the Modified Strip Theory. The method is vali-dated for ship motions.

Yao and Dong (2016) study local steady flow effects on hydrodynamic interaction between two parallel ships advancing in waves. They have developed frequency domain methods with and without incorporation of local steady flow through m-terms in the boundary conditions. The numerical results are compared against experiments for wave loads and free motions of two parallel ships with an identical speed in regular head waves. The method predicting the local steady effects gives more accurate results, especially around the resonant frequencies.

Sengupta et al. (2016) present a simplified approach based on the 3D time-domain panel method using a transient free surface Green’s function for the prediction of nonlinear ship loads and motions. A modified form of the body-kinematic condition is proposed to approximately incorporate partial nonlinearities in the diffraction potential. The results on forces, motions and vertical bending moments are presented for a Wigley hull and S175 hull.

Kukkanen and Matusiak (2014) present a nonlinear time domain method that uses the transient tree-dimensional Green function. The program includes both the exact and linear body boundary conditions. The capability of method to predict nonlinearities in the ship motions and hull girder loads is demonstrated by comparing the numerical and original experimental results for a ro-ro passenger ship with a bulbous bow and a flat bottom stern.

Qiu et al. (2017) developed further a panel-free method using the forward-speed Green function by an algorithm to re-arrange the control points for Non-Uniform Rational B-Splines (NURBS) surfaces. Improved ship motions and load predictions are demonstrated thanks to reliable and accurate m-term computations.

Gonzalez et al. (2017) extend an existing time domain panel method for the computation of the non-linear free water surface by implementing the mixed Eulerian-Lagrangian approach. The validation of the code is presented regarding the wave resistance of a submerged spheroid and Wigley hull, and non-linear wave forces on a standing cylinder. Simulation of a catamaran model in head waves is demonstrated.

Chen and Liang (2016) present a new multi-domain method, which uses an analytical control surface surrounding bodies. In the analytical domain external to the control surface, the linear boundary condition on the free surface is satisfied using a Green function method. In the domain internal to the control surface containing the bodies, different methods capable of e.g. modelling viscous effects and non-linearities can be applied.

Mohammadi et al. (2015) applies the panel method MAESTRO-Wave and the strip method VERES to study static still water and dynamic wave-induced loads on a trimaran ship in intact and damage conditions.

Some recent studies have addressed three-dimensional Rankine panel methods.

Riesner et al. (2016) developed a non-linear time-domain boundary element method to predict ship motions and loads in waves. The predictions of radiation forces using either damping or added masses based approach are compared. The damping coefficient based approach performs better at zero speed, while, in some cases, the added masses based approach can give better results with increasing forward speed.

Chen and Zhu (2017c) present a three-dimensional time domain Rankine Source method with high order boundary element method (HOBEM) to solve hydrodynamic interaction of vessels side by side with and without forward speed. The results indicate good accuracy of the method in general and suggest that the accuracy of predicting steady flow has significant effects on the accuracy of predicting unsteady motions of ships side by side.

Von Graefe et al. (2014) compare the three-dimensional Rankine Panel method GL Rankine and a zero-speed free-surface Green function method for the prediction of sectional loads of a 6500 TEU container ship. GL Rankine solves the linear seakeeping problem in the frequency domain and takes directly into account the forward speed effect, while the Green function method uses an encounter-frequency correction for the forward speed effect. GL Rankine gives better results in general and especially at a larger forward speed.

In the field of RANS, recent studies address validation of methods and analysis of flow.

Motions and slamming of high-speed planing hulls is one recent topic. Fu et al. (2014) compares the results of RANS-solvers CFDShip-Iowa and NFA (Numerical Flow Analysis software) against experimental results for USNA planing geometry at Froude number 1.8-2.1. Mousaviraad et al. (2015) focus on the validation and analysis of Fridsma prismatic planing hull at Froude number 1.19 in regular and irregular waves using CFDShip-Iowa V4.5.

Mousaviraad et al. (2016) study the capability of the RANS-solver CFDShip-Iowa V4.5 to predict the ship-ship interactions in calm water and waves. In the case of replenishment condition, the results show average error values comparable to single-ship results and smaller error than that of previously applied potential flow methods. In the overtaking condition, a close agreement between computed and measured time histories is obtained.

Hänninen et al. (2016) analyse further previously validated RANS results to define flow features that cause the development of vertical second harmonic wave loads, which can excite springing of a large cruise ship in short and steep head waves. The results underline that the careful prediction of three-dimensional and impact-type behaviour of the flow is relevant for the modelling of excitation of second-order resonant springing.

He et al. (2017) present numerical simulations on the green water of a Wigley hull conducted with the CFD software FINE/Marine. The focus is on the analysis of dynamic pressure on deck and superstructure.

Recently, several studies have addressed the computation of added resistance of a ship advancing in waves. Guha and Falzarano (2015b) improve the near field formulation of added resistance by including the effect of hull flare angle at the mean water surface in the context of a 3D Green function frequency domain solver. Hong et al. (2015a) applies three dimensional frequency domain forward-speed Green function and suggest that the prediction of added resistance using Maruo's far-field formulation can be improved by adding an appropriate value of added depth to the actual vertical coordinate in the three-dimensional Kochin functions. In a further study, Hong et al. (2017) improve the stability of results by evaluating the Green function using the adaptive Gauss-Legendre quadrature. Qian et al. (2015) studies the motions and resistance of a small-waterplane-area-twin-hull with inclined struts using a strip theory, RANS and model tests. Kim et al. (2016a) apply URANS for the prediction of added resistance and motions of KCS in regular head waves. Park et al. (2016) compares the capability of a frequency domain strip method and a time domain Rankine panel method to predict ship motions and added resistance at different drafts against experimental results. Kim et al. (2017a) study the added resistance of KVLCC2 in short and long waves and Kim et al. (2017b) for various speeds and wave steepnesses in head waves using the 3-D linear potential method PRECAL and the RANS-method STAR-CCM+. Kim et al. (2017c) study the added resistance of an LNG carrier in waves using the RANS-method Star-CC+, a Rankine panel method WISH and model tests. Lyu and el Moctar (2017) demonstrate that a for-ward speed Rankine source boundary element method and a RANS solver coupled with the nonlinear rigid body equations of motion are reliable methods for the prediction of wave-induced second order hydrodynamic loads of different ships. Seo et al. (2017) study added resistance and vertical motions of a 3600 KRISO containership (KCS) for various head waves using Open FOAM.

2.3 Hydroelasticity Methods

2.3.1 Hydroelasticity methods of ships

In the past few years 2D hydroelasticity method was utilized to resolve specific problems. Bennett et al. (2015a) studied the global wave-induced loads and whipping responses of a ship encountering an abnormal wave sequences. The influence of heading angle on the vertical responses of a 13,000TEU containership was investigated by Zhu & Moan (2015) by using 2D strip method and 2.5D strip theory in time domain. Heo et al. (2016) developed a numerical method to predict ship springing response of a ship based on 2D quadratic strip theory. Using a body nonlinear time domain method based on strip theory, Rajendran et al. (2016a, 2016b) predicted the spring and whipping response of containerships in waves. Lin et al. (2017) analyzed the springing responses of a 350,000DWT VLCC by combining 2-D strip method and 3-D Finite Element Method (FEM) in the frequency domain.

Several 3D linear hydroelasticity methods were proposed and developed both in frequency domain and time domain. Kashiwagi et al. (2015) proposed two practical methods for ship hydroelasticity problems with forward speed, of which one was the 3D time-domain Green-function method and the other was the frequency domain Rankine panel method. Kara (2015) and Sengupta et al. (2017) developed 3D time domain hydroelasticity methods to predict the hydroelasticity of floating bodies based on the boundary-integral equation method with three-dimensional transient free surface Green function, satisfactory agreement was achieved between their numerical results. Yang et al. (2015a) presented two methods based on the time domain Green's function and the inner and outer regions matching technique respectively to predict hydroelastic responses of ship advancing in waves in time domain. Based on the above method, the time domain hydroelastic responses of CSSRC 20,000 TEU ultra large containership with zero speed was investigated by Wang et al. (2017). Kang & Kim (2017) investigated hydroelastic interactions of a deformable floating body with random waves in time domain. They proposed an efficient way of obtaining distributive loads for the hydrodynamic integral terms including convolution integral by using Fubini theory. Using a simplified coupling model with non-deformable local tank, Malenica et al. (2015) studied the global hydroelastic response of the ships coupling with the sloshing effect.

The three-dimensional nonlinear hydroelasticity methods developed continuously by considering the nonlinear factors such as the instantaneous position variation of body surface, the incident wave force, the restoring force and the slamming force, etc. Kim et al. (2015b) proposed several high-fidelity procedures for numerical analysis of ship hydroelasticity and a fully coupled model was introduced containing the 3D Rankine panel method, the 2D generalized Wagner model, the 1D/3D FEM. Considering the nonlinear restoring force and slamming force, Chen (2015, 2017a) developed a kind of 3D nonlinear time domain hydroelastic method, in which a proportional, integral and derivative (PID) autopilot model is applied to solve the divergence problem of motion equations and load responses of a 13,000TEU container ship in oblique regular waves. Park et el. (2017) used a fully coupled fluid–structure interaction model to compute the mean drift force on a flexible barge. Both the near-field method and the far-field method were employed in the computation of drift force. Ren et al (2016) investigated the longitudinal wave loads of a trimaran by using a 3D time-domain nonlinear hydroelasticity theory considering the influence of nonlinear factors such as slamming. It was found that the computed value under ultimate working conditions was significantly larger than the LR Trimaran rule value.

A Joint Industry Project of Wave-Induced Loads on Ships III (WILS JIP III) was conducted by Korea Research Institute of Ships and Ocean Engineering (KRISO). Drop tests of 2D sections as well as seakeeping tests of a 10,000-TEU containership and many comparisons between numerical method and experiment were carried out in the project. The parametric study of slamming and whipping of the containership was analyzed by Kim & Kim (2015a) based on a fully numerical model consisting of a 3D Rankine panel model, a 3D finite element model and a 2D GWM. Meantime, Kim (2015c) carried out numerical simulation of springing and whipping response of the containership by using 3D nonlinear time-domain method which considers nonlinear hydrostatic restoring and Froude-Krylov forces. Lauzon et al. (2015) focused on the comparison between the experimental results and numerical results computed by the hydro-structure software developed by Bureau Veritas. On the basis of Fluid Structure Interaction (FSI) model, the wave induced global loads and whipping responses of the containership were also investigated by Lee et al. (2015b).

To predict strong nonlinear loads reasonably and consider the viscous effect, CFD tools are utilized to investigate the hydroelastic response of large ships. Lakshmynarayanana et al. (2015) studied the fluid-structure interaction of flexible floating bodies in waves by coupling CFD software (Star-CCM+) and FEA software (Abaqus). The whipping response of a Joint High Speed Sealift model moving in a large seaway was studied in time domain by using open source CFD codes OpenFoam and higher-order boundary element method in Craig et al. (2015)'s study. Robert et al. (2015) proposed a numerical approach which combined a viscous flow solver and a beam model to investigate the hydroelastic response of a flexible barge in time domain. Computational methods which couples the Reynolds-averaged Navier-Stokes (RANS) equations and nonlinear motion equations was presented by Moctar et el. (2017) to assess slamming-induced hull whipping.

2.3.2 Hydroelasticity methods of VLFS

Very Large Floating Structures (VLFSs) have drawn attention from many researchers worldwide. For the hydroelasticity issue of the VLFSs deployed in open and deep sea are concerned, Mirafzali et el. (2015) employed a meshless numerical method to solve the interaction of fully nonlinear water waves with the floating elastic plate. A semi Lagrangian method and a leap frog time marching scheme were used to calculate the displacement and the velocity potential on the free and plate surfaces. Cheng et al. (2016) investigated the hydroelastic responses of a mat-like, rectangular VLFS edged with dual horizontal/inclined perforated plates using Eigen function expansion-matching method (EEMM), FEM-BEM hybrid method and compared the results with experimental data. Using the Euler-beam model, Wang et el.(2016a) investigated the hydroelastic responses of a horizontal plate impacting with the water at both forward and downward speeds theoretically and numerically.

If a floating body is deployed near seashores in complicated geographical environment, the wave conditions, wave loads and the hydroelastic responses of the floating structure will be quite different from those in open and deep sea. Recently China Ship Scientific Research Center (CSSRC) have proposed several numerical approaches for the analysis of a VLFS near islands and reefs. Yang et al.(2015b) and Li et al. (2016) treated the uneven seabed as a fixed body boundary condition to account for its influence on the diffraction and radiation of floating structures. Ding et al. (2016) and Wu et al. (2016a) analysed the effect of inhomogeneous wave distribution on the VLFS by considering different wave conditions on each sub-module of the VLFS. Bu unifying the Boussinesq equation and the Rankine source method, Wu et al. (2017a, 2017b) and Ding et el. (2017) established a direct coupled method to analyse the hydroelastic response of floating bodies in the inhomogeneous waves induced by the complicated geographic environment when the floating body is deployed near islands and reefs. Considering the constant and variable seabed, Karperaki et el.(2016) analyzed the transient hydroelastic response of floating elastic plates based on the Euler-Bernoulli strip and the linearized shallow water equations. Cheng et al. (2017) employed a 2D fully nonlinear numerical wave tank to investigate the interaction between a monochromatic wave and a floating elastic plate over the variable seabed. By treating the flexible floating structure as "elastic beam connected rigid sub modules", a practical numerical hydroelastic analysis method has been investigated by Lu et al. (2016). Based on the above method in frequency and time domain, Wei et al. (2017, 2018) and Fu et al. (2017) applied different incident wave condition onto different modules to analyze the effect of inhomogeneous wave distribution on the hydroelastic response of the floating plate and the floating bridge respectively.

3. SHIP STRUCTURES - SPECIALIST TOPICS

3.1 Slamming and Whipping

Sea surface impact on ship hull, known has slamming is a one of the loads the structure has to withstands, especially in rough seas. In top of the local structure load directly induced by slamming events, the consequence vibratory response, called "whipping" is of primary importance. This section focuses on the slamming loads themselves, and much less on the whipping issue. Indeed, strictly speaking, the whipping should not be considered as a load but as a response. Besides, more relevantly, this whipping issue will be thoroughly covered by next section "I.3 Hydro-elastic response". Here it is just noted that the whipping issue is of high practical relevance, which makes the accurate assessment of the slamming phenomena a crucial step. It is also noted that the practical global response model (that compute the ship motions, including the effect of slamming loads) are, nowadays, generally made of a potential, time-domain code (often weakly non-linear) coupled to 2D potential model for slamming (most of the time Generalized Wagner Model). These kinds of model are described in (Malenica & Derbanne, 2014) or (Tuitman, 2010). Applications and assessments of these models with regards to model test were conducted in several projects (WILS II and III), and quite a few papers, see for instance (Kim, Kim, Yuck, & Lee, 2015) and (de Lauzon, Benhamou, Malenica, & others, 2015). Full CFD on irregular waves including slamming is not common practice, but can nevertheless be found (Oberhagemann, Shigunov, Radon, Mumm, & Won, 2015) and is very probably something that will develop in the future.

The difficulty to incorporate 3D model into practical, engineering sea-keeping calculation is probably one of the reason why most of the research on slamming loads is quite concentrated on 2D approaches. That said, some of the below described papers do report possible limits of the 2D strip approximation. To begin with, the papers investigating 2D impact are thus reviewed. Some of them improved the numeric of quite widespread model, some others focus on more complex phenomena, that are not, today, included in practical design tools.

To begin with the 1st category, i.e. numerical improvements, (de Lauzon, Grgi, Derbanne, & Malenica, 2015a) present new approach to improve the Generalized Wagner Model is introduced. It uses BEM and Kelvin's Green function. The key new feature is to separate the singular part from the regular one. The singular part is integrated semi-analytically. The model has been successfully validated through comparison with analytical results as well as experiments. Compared to existing, model, the key advantage is the robustness, and the ability to deal with a very wide range of shape and arbitrary velocities.

Another improvement to numerical is also presented in (Wang & Faltinsen, 2017). This work allows solving for the Dobrovol'skaya's boundary integral equations for quite small deadrise angle, down to 1°, while previously used method encounter difficulties below 4°. Results were successfully compared to standard BEM calculation for higher deadrise angle. For small angle, the results are consistent with asymptotical model.

Bao, Wu, & Xu (2017) studied that the free fall of finite wedge is investigated with potential, non-linear model. Compared to classic infinite wedge impact at imposed velocity, two difficulties are to be tackled: the finite width makes important the flow detachment, and the motion equation has to be solved in a coupled fashion. Results are compared to SPH computation and to experimental results, yielding a very decent agreement. It is also shown that, in the simulated case, a flow computed ignoring detachment would lead to slightly different motion. Also, as expected and documented in previous study, the coupling between the body motion and the slamming model yield decreased loads (due to the deceleration when the wedge hits the water).

Alaoui, Nême, & Scolan (2015) focus on an experimental set up capable to accurately measure the slamming and pressure at constant velocity. The accuracy of the constant was checked, and repetition test were made, successfully: the results are repeatable. Also, it has been observed that the pressure and impact were almost not dependent on velocity: Cs and Cp are approximately constant. Furthermore, the values of those coefficients are in accordance with some analytical and numerical analysis.

Sun, Sun, & Wu (2015) focus on two specific features, firstly, the entry is in waves, and not in calm water as most of the academic cases. Several conditions are tested (relative wave length, phasing…). Secondly, the gravity, neglected in most of the simplified model is included. The paper reaches conclusions about the relevance of gravity: negligible when the impact time is much less than the ratio of entry speed to the acceleration due to the gravity, and then it affects significantly the pressure distribution when the impact time progress. The wave characteristics, as well as its phasing with regards to the wedge, have of course significant effects. Those effects are found difficult to sketch. Also, it is noted that the discontinuity at the wedge tip, which would require a proper Kutta condition, is not handled at this moment.

Above described paper are based on potential theory, which is currently the bases for practical, engineering, purpose. However, the approximated description of the physics (no flow detachment, incompressible flow) together with the improving CPU power call for more sophisticated models. Quite some research is currently undertaken on CFD (in a broad sense, including SPH), and part of it is quite relevant to slamming. A lot of effort has been performed to demonstrate the ability of CFD to assess slamming events and to improve the confidence in this tool. The different contributions definitively demonstrate the added value of CFD to slamming assessment. They also point to the increasing relevance of code and hardware related issue. The algorithm and equation are important, but the computational aspects (scalability, CPU/GPU) are crucial to make the method competitive. Then, CFD is now used to investigate some special phenomena that would be quite challenging to tackle with potential flow tools (compressibility is the main example)

As a start on CFD validation, we can cite many studies (Hong, Kim, Hwang, & others (2017), Southall, et al. (2015) and Charles Monroy, et al. (2017)) which undertake a quite comprehensive benchmark of various code to assess slamming loads and pressure. Two geometries are investigated: a wedge, and a ship section. Model tests results were provided by WILS III JIP. While comparison between the various codes and the model tests is decent, some scatter can be observed. Generally; the CFD codes match better with the experiment, especially on the ship section, where the potential theory is not able to deal with the flow separation at the bulb. Of course, CFD calculations times of magnitudes slower: reported calculation times were in seconds for potential codes, hours for CFD). Interestingly, the papers shows that the scatter among CFD codes is wider that among potential codes. With very similar software (if not identical), results are can vary, highlighting mesh sensitivity, but also the additional expertise required to handle CFD codes compared to potential ones.

Wen & Qiu (2015) used a Constraint Interpolation Profile approach (CIP) to solve the Navier-Stokes equation. The calculation is done in multiphase, for 3D geometry. Emphasis is put on the parallelization of the code, which results in more acceptable calculation time. Computation on a falling edge and a ship section is performed and comparison with experiment, BEM and VOF CFD is made, showing a quite good agreement.

Buruchenko & Canelas (2017) validated a SPH code through comparison with experimental results as well as other CFD code (VOF and CIP). The results of SPH-dual-physics are very comparable to other results from VOF and CIP, and agree quite well with the experiment. Unfortunately, the computational cost of the various method used is not reported/compared

Kamath, Bihs, & A. Arnsten (2016) used the open source code REEF3D to compute the free-fall of wedge (incompressible). Reef3D uses finite difference on cartesian grid, and free-surface is here capture with level-set. Computed wedge velocity is compared to experiment, showing a very good agreement.

While a lot of papers are focused on improving the CFD tool and checking its results with model test, CFD is now mature enough to be used as a tool to investigate some phenomena.

In (Elhimer, Jacques, Alaoui, & Gabillet, 2017), the effect of aeration on slamming forces is investigated, both numerically and experimentally. First, impact forces of a cone entering into aerated water are calculated, using the finite elements software ABAQUS. Different aeration rate are tested (from 0% to 10%), for a range of impact velocity. Results show significant effect of aeration on impact forces, which can be reduced up to 70% compared to the pure water/incompressible case. The force (and pressure) decrease is dependent on the velocity. Then experiment is performed, using a hydraulic shock machine, void fraction was measured with optical probes. Numerical results confirm the trends observed numerically (i.e. decrease of the impact force with aeration rate), however, the numerical model seems to significantly overestimate the loads for aerated case (while this overestimation is very slight in case of pure water).

Ma, et al. (2015) studied the compressibility effect on flat plate, where this effect is expected to be very significant. On the numerical side, the model used is a compressible two phases model, on the experimental side, forces and pressure were recorded thanks to an S-type cell and five miniature pressure transducers. The numerical model was able to quite accurately match the experiment, and correctly reproduced the pulsatile slamming loads.

While, that the focus is generally on monohull (containership) bow, slamming can also be a relevant issue on other places. For instance, (Swidan, et al., 2016) experimentally investigate wetdeck slamming loads on a catamaran. Documented drop tests with catamaran hull are quite scarce, especially in 3D, and this work fills this gap. To ensure the accuracy of the tests, uncertainty analysis has been undertaken, and tests have shown a good repeatability. Results showed a classic evolution of the impact loads with V^2. Also, in top of the flow analysis undertaken, the paper provides a good dataset for benchmarking numerical codes.

Stern slamming has been investigated in (Wang & Soares, 2016), on chemical tanker, both numerically and experimentally. The test conditions are irregular head waves. Numerically, the 3D sea-keeping has been performed to compute the ship motion, and slamming forces has been evaluated in second steps, in decoupled way. Two different slamming models has been used MLM (Modified Longvinovich Model), and ALE (LS-dyna implementation). Compared to experiment, both models largely over-predict the slamming forces. The first explanation given is the difference between the calculated motion and the experimental ones. The second is the importance of the 3D effects. The 2D numerical results were reported as highly sensitive to slight motions changes.

While, most of the drop test are performed with 2D section, (Wang, Wu, & Guedes Soares, 2016) investigate the slamming loads on a 3D bow. The geometry investigated is the bow of sea-river link ship, instrumented with pressure sensor. On the numerical side, the impact is model with finite element (3D) with ALE. The numerical impacts were made a constant speed, while the experiments were free fall. Several drop heights and pitching angle have been investigated. Overall, the agreement between model tests and experimental results are decent but not perfect. Compressibility effect in the model tests were reported at 0° pitch angle. Unfortunately, no comparison to the widely used 2D strip approach is made.

3.2 Sloshing

3.2.1 Introduction

Sloshing is the oscillatory motion of the free liquid surface inside partially filled containers that may possess strong nonlinear character depending on the level of excitation. It may result large impact forces on container walls and have significant coupling effects with ship motions, thus has practical importance regarding the performance and safety of marine transportation systems. During the reporting period, main theoretical and experimental interest was on the interaction between sloshing and global ship motions and sloshing suppression using baffles.

3.2.2 Experimental Investigations

In recent years, model testing has been mostly used to observe the physics of the sloshing-coupled ship motion problems, to investigate the efficiency of sloshing suppression, and to obtain validation data for the numerical tools.

Zhao *et al*. (2014) conducted 2-D model tests for a Floating Liquefied Natural Gas (FLNG) section excited in sway, heave, and roll, with the main interest of identifying the mutual effects between the ship motions and internal free surface. They observed strong coupling for sway and roll motions compared to the heave motion, and also concluded that for the same wave excitation, the sloshing oscillations tend to be severer for lower filling ratios. The interaction of sloshing fluid and roll response of LNG carriers was examined by Zhao *et al*.

(2016a) through a barge-like vessel having two spherical tanks. Here, the objective was quantifying the magnitude of the interaction for different sea and loading conditions. Zhao and McPhail (2017) conducted a similar set of experiments with spherical tanks filled with liquid cargo and equivalent frozen-cargo having the same dynamic characteristics, to observe the effect of liquid cargo motions on the global roll response of a barge-like vessel at an intermediate load condition. Xu *et al*. (2017) examined the effect of sloshing on the hydrodynamic responses of an FLNG-LNGC (LNG Carrier) system during side-by-side operation by ballasting the vessels with both solid and liquid cargo. They found that sloshing may have beneficial effect on FLNG motion for certain loading combinations and that the relative motions between the vessels are composed of wave-frequency and low-frequency components.

Nayak and Biswal (2015) investigated the hydrodynamic damping potential of centrally installed objects in three different configurations–bottom mounted vertical baffles, surface-piercing vertical baffle, and bottom mounted submerged block–perpendicular to the lateral excitation in partially filled rectangular tanks. They indicated that the baffles can be effective for sloshing damping near the resonance conditions, yet surface-piercing baffles provide higher damping for similar physical setting. Yu *et al*. (2017) demonstrated both experimentally and numerically (through CFD) the effectiveness of floating plates on sloshing suppression in a membrane-type LNG tank subjected to harmonic rolling excitation. The test results showed that the suppressing device not only reduces the wave run-up along the longitudinal bulkhead, but can also decrease impact loads acting on the bulkhead. Xue *et al*. (2017) performed an extensive set of tests to study the sloshing damping effects associated with vertical baffles of different configurations in a rectangular tank subjected to a horizontal excitation of wide range of frequency. They found that the effectiveness of the baffles in sloshing suppression depends not only on the relations between forcing frequency and natural frequency of sloshing, but also on its configuration and location.

Coupling of the floodwater and rolling motion of a box shaped barge was experimentally studied by Manderbacka *et al*. (2015). They observed that the flooded water can act like a passive anti-rolling tank if the sloshing natural frequency is close to the roll frequency. Similarly, Bennett and Phillips (2017) experimentally investigated the effect of floodwater and transient flooding on the motions and structural response of a ship hull following a grounding. Their results indicated that the second order sloshing effects due to the movement of the floodwater free surface are present at encountered wave frequencies close to the peak response of the ship and they may dominate the severity of the responses around these frequencies.

3.2.3 Numerical Simulation

The numerical methods developed for sloshing simulation can be categorized under two groups: studies based on the potential flow assumption, with or without the inherent nonlinearities, and studies that involves the viscous effects. The fluid-structure interaction was also considered in some numerical models.

Lin et al. (2015) proposed a Scaled Boundary Finite Element Method (SBFEM) to obtain the sloshing frequencies and corresponding mode shapes of liquid storage tanks having arbitrary axisymmetric cross-section. Kolaei et al. (2015a) studied the sloshing problem of horizontal tanks subjected to simultaneous longitudinal and lateral excitations by first reducing the dimension of the computation domain by applying the separation of variables technique and then applying a higher-order Boundary Element Method (BEM) scheme in a multimodal setting. Their comparisons with CFD simulations revealed some of the problem-dependent limitations of the potential flow based solutions. Stephen et al. (2016) used the Finite Element Method (FEM) and mixed Eulerian-Lagrangian formalism within the fully nonlinear potential flow framework to study the sloshing of 2-D rectangular tanks under combined horizontal, vertical and rotational motions. They specially discussed the coupling effects on sloshing oscillation. A mesh-free potential flow based numerical model for simulating the free surface waves was developed by Wu et al. (2016b), where a local polynomial collocation method was applied for solving the Laplace equation at each time step. The method is applied to predict the liquid sloshing in rectangular and cylindrical swaying tanks. Chen et al. (2017b) provided a regularized boundary integral equation formulation for the nonlinear sloshing problem that avoids some of the drawbacks–regarding singularity and discretization–of the traditional BEM solutions. The energy dissipation neglected in the potential flow theory was taken into account in this study by assuming a linear damping term proportional to the particle velocity.

By adopting the linear potential theory and FEM, Bochkarev et al. (2016) investigated the interaction of sloshing and hydroelastic behavior of thin-walled cylindrical shells of arbitrary shape under the conditions of non-stationary loading and periodic excitation. Ravnik et al. (2016) studied the dynamics of a shell structure with partially filled compartments through the mode summation approach. The FEM and BEM were used for describing the structural response and linearized liquid sloshing, respectively.

It is well known that the meshless particle methods are better in modelling the merging and splitting in fluid domain and tracking the free surface. Luo et al. (2016) used the Consistent Particle Method (CPM) to study the sloshing problem in tanks under translational and rotational excitations with regular or random nature. Unlike the more traditional particle methods, i.e., Smoothed Particle Hydrodynamics (SPH), the spurious pressure fluctuation, resulting from the applied derivative approximation schemes, can be eliminated with the CPM. The technique was applied for the analysis of an LNG container in a real ship under typical sea conditions. Sufyan et al. (2017) proposed a local dynamic mesh refinement and coarsening technique for unstructured grids, where a level-set function was used as the criterion for the implementation of mesh refinement. The technique was implemented in the FEM solution of the sloshing problem in a rectangular tank. Grotle et al. (2017) studied sloshing at shallow-liquid depths in a rectangular container by using the Reynolds-averaged Navier-Stokes (RANS) equations with an open-source finite difference CFD solver REEF3D. They simulated the forced sloshing within the proximity of the fundamental mode and also provided experimental observations.

3.2.4 Sloshing Suppression

Baffled sloshing suppression is still a very active field that researchers proposed new analysis tools, relying on both potential and viscous flow models, to investigate the special aspects of the problem or to analyze different configurations.

Kolaei et al. (2015b) developed a BEM based multimodal numerical tool for simulating the fluid sloshing in baffled tanks by including the damping, induced by the baffles, from the mean energy dissipation rate. They studied partially filled circular tanks with three different longitudinal baffles (bottom-mounted, top-mounted, and center-mounted) and illustrated the effects of baffle designs on the sloshing modes, hydrodynamic coefficients, and damping ratio. Wang et al. (2016b) studied the transient lateral sloshing in a partially-filled cylindrical tank with multi baffles (as floating circular baffle, wall-mounted ring baffle, floating ring baffle and their combination) using the SBFEM with a multimodal approach. They concluded that the sloshing force monotonically increases with the length of the baffle, and its influence decreases with increasing the interspace between the baffle and the free surface, and also added that the consideration of only the first sloshing mass is adequate to represent the dynamic behavior.

Cho and Kim (2016) investigated the use of vertical porous baffles for the purpose of dissipating more energy. They used the matched eigenfunction expansion method within a potential flow setting, where the porosity is included by inertial and quadratic drag terms. Both numerical and experimental results indicated that the dual vertical porous baffles can significantly suppress sloshing. The impact of vertical porous baffles was further studied by Cho et al. (2017) using a similar numerical and experimental setting.

The effectiveness of the baffles for the suppression of the sloshing in a rolling 2-D rectangular tank was demonstrated by Tang et al. (2015) by using the Moving Particle Semi-implicit method. Yin et al. (2015) studied the sloshing in rectangular tanks with or without baffle both numerically and experimentally. They adopted the open source viscous flow solver OpenFOAM for numerical analysis and showed the influence of single baffle on reducing the dynamic pressure and sloshing amplitude. Lu et al. (2015) proposed a finite element based viscous numerical model for the sloshing problem in tanks with or without baffle. They investigated the role of sloshing frequency in dissipation, effect of the excitation amplitude on the sloshing response, and estimation of the damping. Their comparisons with respect to the solutions of the potential flow theory for baffled and non-baffled cases offer certain suggestions and limitations on the use of potential flow approximation for sloshing prediction. Hwang et al. (2016) developed a fluid-structure interaction solver based on Moving Particle Simulation to study the sloshing flows in rolling tanks with elastic baffles. They presented sloshing flow comparisons between tanks without baffle and with rigid and elastic baffles of different Young’s modulus. Liu et al. (2017) proposed a hybrid RANS/LES (Large Eddy Simulation) model in conjunction with the Volume Of Fluid (VOF) interface capturing technique to improve the predictive accuracy of RANS and the computational efficiency of LES for the numerical prediction of violent liquid sloshing. They employed the model to study a tank with a vertical baffle and a horizontal baffle.

3.2.5 Sloshing and Ship Motions

Regarding the designs of LNGC, FPSO, FLNG, and FSRU, and due to the increasing capacities and changes in operational conditions, the practical demand of sloshing analysis has been rising in recent times. In particular, the mutual interactions between the ship motion and liquid sloshing in tanks have been studied extensively. The numerical investigations for this coupled problem were usually performed by adopting different mathematical models or different types of solvers for individual analyses. This is mostly due to the dissimilar nature of the involved problems, i.e., highly nonlinear and small time scaled sloshing problem vs. the classical seakeeping problem (with or without considering nonlinearities), but partly dictated by achieving practical simulation times. Although the ship motion was assumed linear in most cases, considering the violent sloshing flow and resulting impact, it is not surprising that the majority of the theoretical development were in the form of time-domain approaches.

Wang and Arai (2015) analyzed the coupling problem of ship and sloshing tank for an LNGC in regular and irregular waves using a time domain model and considering four different loading conditions. They applied a 3-D finite difference scheme for the internal liquid movement and the strip method for the seakeeping problem. The predicted ship motion RAOs and sloshing wave amplitudes indicated that the influence of sloshing on ship response is significant for lateral motions and relatively weak for longitudinal motion.

Jia et al. (2015) investigated the dynamic response of liquid containers by applying a di-rect coupling scheme. Here, the CFD and FEM are applied for the sloshing liquid and tank structure, respectively, which were then related through the balances of force, heat flux and temperature and no-slip boundary condition. The presented results addressed three issues that might be critical in the design of FLNG tanks: the strength of the tank structure under the peak impact loads, the resonant vibration when the ship is excited near the natural frequencies of the tank, and fatigue of the tank structure caused by the periodic loads due to sloshing.

Bai *et al*. (2015) developed a numerical model to simulate the sloshing flows due to ship motions in 2-D rectangular tanks by applying the level set method to capture the complicated free surface motion. They studied an LNG tank excited by the realistic ship motions in sea conditions, where the RAOs of the LNG carrier were used directly to excite the sloshing in the tank. They concluded that the most critical sloshing wave is generated when the sea wave frequency approaches the resonant sloshing frequency and that the free surface elevation excited by each resonant frequency decreases with the increase of the filling depth due to the corresponding smaller RAOs applied.

Gao and Vassalos (2015) studied the coupled dynamics of the floodwater and damaged ship, where the water sloshing inside the compartments may significantly influence the ship motion. An integrated numerical method combining a Navier-Stokes solver and nonlinear 2-D seakeeping theory was used to simulate the behavior of the damaged ship response in waves. The numerical model was applied for a Ro-Ro ferry in regular beam sea state.

Paik *et al*. (2015) developed a probabilistic approach to determine the nominal values for tank sloshing loads in structural design of LNG FPSOs. They selected a limited number of sloshing scenarios according to the operative factors (such as wind speed and direction, wave height and period, etc.) using a probabilistic sampling technique. Vessel motion analysis is conducted for each scenario and the resulting vessel motions are applied to a RANS solver. The nominal values of sloshing loads can be determined based on the acceptance criteria for the exceedance curves that are formed in relation with the sloshing peak pressure, impulse, or rise time.

The coupling effect between the sloshing flow and global ship motions was investigated by Jiang et al. (2015); they adopted the VOF method for the internal flow (through OpenFOAM) and an impulse response function method for the external potential flow. The communication between separate flow problems was established by using the ship response as the moving-wall boundary condition for the internal problem and applying the computed pressure forces in return to the external problem, at proper time steps. The method was applied for the analysis of an LNG-FPSO model with two partially-filled prismatic tanks. They examined the effects of coupling on global response and sloshing impact loading, depending on the incident wave direction, frequency, amplitude, and liquid filling ratio. They found that the coupling effect is relatively small for heave and pitch motions of the ship in head seas, yet dominant at low-filling ratios in beam sea condition. Moreover, for low filling ratios, ship motion response is very sensitive to the incident wave steepness, especially at around the sloshing natural frequency and resonant ship motion frequency values, and also nonlinear effects due to sloshing become important on global response.

Servan-Camas *et al*. (2016) studied the coupled sloshing-seakeeping problem by employing an SPH solver for the sloshing flow in a weakly compressible Lagrangian setting and the FEM for the potential flow associated with the time dependent wave diffraction and radiation around the ship. The coupling between independent solvers was established by exchanging the body movement and force/moment data through adjusted time steps for each part. Cercos-Pita *et al*. (2016) improved the methodology by including empirical damping terms and considering the nonlinearities associated with the ship motions, i.e., calculating the diffraction and restoring forces at the instantaneous wetted surface.

Saripilli and Sen (2017) adopted a similar numerical setting to integrate the external and internal flow problems. They applied the time-domain boundary element method for the ship motion problem and used the OpenFOAM for the Finite Volume Method (FVM) based solution of sloshing fluid. They solved the coupled problem for a modified S175 and concluded that the sloshing-induced pressures on the interior of the tank can be much lower if the coupling effects are considered. Sen and Saripilli (2017) extended the study by focusing on the roll motion and studying the effect of multiple tanks.

Malenica *et al*. (2017) presented an overview of the current approaches and issues for the solution of the coupled ship motion-sloshing problem and assessment of the structural response of liquid tanks. They identified some complications regarding the model experiments for sloshing-induced impact and modeling of the hydro-structure interactions induced by the sloshing loads in the containment units of the LNG vessels.

If both the ship motion and internal tank sloshing problems are represented using the potential flow theory, more efficient computations can be realized. Particularly, under the assumption of linear motion, frequency-domain solutions for the coupled problem were presented in the past, e.g., Molin *et al*. (2002), Malenica *et al*. (2003), Newman (2005), Gou *et al*. (2011). The frequency-domain approach may function as a practical approximation tool for the coupled problem, yet the nonlinear features of the internal flow cannot be accurately captured and excessive coupling effects, such as singular solutions or abrupt fluctuations at the sloshing resonances, can be predicted. The BEM solution of Zhang (2015) aimed at avoiding the simultaneous occurrence of the sloshing in all the wedge-shaped tanks of a LNG carrier that may endanger ship stability. Special attention was given to identifying the effects of inclined tank walls on dynamic characteristics as well as studying the sloshing wave elevation histories due to sway, roll, surge, and pitch type motions at the fundamental frequencies. Lee *et al*. (2015a) numerically and experimentally investigated the linear hydroelastic analysis of floating structures with liquid tanks subjected to regular water waves. They applied the FEM for the floating structure and internal fluid, and the BEM for the external fluid, and considered the couplings between structural motion, sloshing, and water waves by incorporating al interaction terms. In the analytical investigation of the coupling between the vessel motion and liquid sloshing in multiple tanks, Zhang (2016a) focused on the coupling mechanism rather than targeting the whole problem. The external environment as well as disturbance factors that may alter the dynamic characteristics of the system were omitted and excitation of the ship was initiated by the internal free surface motion. Hu *et al*. (2017) applied a potential flow solver and conducted model tests to investigate the hydrodynamic characteristics of an FLNG under the condition of a sloshing LNG-tank. They indicated that the effect of sloshing on the global motion response in the modes of pitch, heave and yaw are negligible, yet for surge and sway motions, a noticeable peak response appears near the first-order resonant period of the LNG tank. Nonlinear potential flow solver for the sloshing problem is another option, which is more complex than linear solver but still computationally efficient compared to the viscous flow based computations. Su and Liu (2017) analytically solved the 2-D coupled problem for a barge in frequency- and time-domains. They adopted the nonlinear Boussinesq-type equations for simulating the internal flow and used the impulse response function, obtained from the frequency-domain solution, for the ship motion problem.

3.3 Green Water

Youn Kyung Song et al (2015) investigated green water velocities and impact pressures caused by the impact of over topping waves on a fixed deck structure in a large-scale, three-dimensional deep-water wave basin. Using the bubble image velocimetry technique, detailed two-dimensional surface flow pattern on a horizontal plane, including the temporal and spatial distributions of the maximum horizontal velocities are successfully obtained. Pressure measurements are also carried out along four different vertical positions at three different locations on the horizontal plane. Based on the mean velocity distributions on the deck surface, the most significant spatial variability of the propagating green water flow is the protruding wave front near the centre of the deck during the early stages of the wave over topping. The maximum front speed of 1.5C was observed first near the midpoint of the deck along the deck centreline with C being the wave phase speed. The flow velocities decreased to below 1C once the wave front passed the rear edge of the deck. Most of the measured pressures showed impulsive impacts characterized by a sudden rise of the pressure peak. The highest pressure was observed as 1.65ρC2 at a midpoint and at rear edge of the deck with ρ being the water density. Correlations between wave kinetic energy and dynamic pressure are examined to determine the impact coefficients. The phase speed based impact coefficient is found to vary within a narrow range between 0.29 and 1.69 and a practical value of 1.5 is suggested to be used in applications. It appears that the impact pressure on the structures is strongly affected by the changing front shape of the broken wave and the impulsiveness of the impinging wave that contains a considerable amount of air entrainment.

Daniel F.C. Silva et al (2017) presented the development of a methodology for detailed CFD simulation of green water events. Based on model test data, extreme green water events resulting from beam and quartering waves are selected and the wave vessel interaction is simulated, including the water on deck propagation. The commercial CFD code ANSYS FLUENT® was customized to have boundary conditions to represent specific wave intervals from irregular sea state realizations and vessel movements prescribed based on experiments. By using a VOF-multiphase and SST-turbulent setup, the accuracy of 2D and 3D simulations are evaluated by comparison with experimental data in terms of free surface evolution and loads, with good agreement in most cases. Some deviations on the loads were observed, but they are coherent with the complex local flow conditions of typical impact flows due to effects such as wave breaking and air entrapment. The methodology presented in this paper gives access to high spatial resolution free surface position, water velocities and load distribution, phenomena usually not available from experiments, which leads to new possibilities in the investigation of shadowing effects and dynamic loads during green water and wave impact extreme events.

Shuo Wang et al (2017) presented a numerical approach based on potential theory in frequency domain for FPSO green water assessment, considering nonlinear effects from bilge keels, spread mooring and asymmetrically arranged risers. Commercial radiation diffraction code ANSYS AQWA is used to find relative wave elevations. Damping coefficients are based on experimental decay tests. Comparison with experimental measurement shows that, by properly considering the linear and nonlinear effects due to appendages and attachments using proposed numerical approach, the relative wave elevation response of the FPSO in irregular wave can be predicted accurately and efficiently in frequency domain. The relative wave elevation response in oblique and beam sea wave is found to be affected by additional stiffness, added mass and damping from bilge keel, mooring and risers. Such results also suggest that the green water occurrence at side of FPSO in oblique wave may be reduced by bilge keel, mooring and risers. However, effects from these appendages and attachments are generally not affecting green water prediction at any location of FPSO in head sea/stern sea condition; prediction at centre of bow & stern in oblique wave and beam-sea are not affected either.

Gauanghua He et al (2017) have performed a time-domain simulation of green water on a Wigley hull sailing in regular head waves. To predict the strong non-linear phenomenon of green water, a numerical model is established by utilizing FINE/Marine, a multiphase-flow software based on free-surface capturing method. The problem of green water impacting on deck is systematically investigated by varying the wavelengths and wave amplitudes. Based on viscous flow theory, a solid-liquid-gas three-phase flow coupling model is developed for more realistic simulation by adopting the Blend Reconstruction Interface Capturing Scheme (BRICS) which reduces numerical diffusion near the free surface. This model can well process problems of breaking waves and evolution of complicated free surface. By using this numerical model, impact loads on deck and hull, ship-motion characteristics and hydrodynamic characteristics during the green water process are investigated. The emphasis of this paper locates on the analysis of dynamic pressure on deck and superstructure during the green water process and the influence of main characteristic parameters.

3.4 Experimental and Full Scale Measurements

Note that experiments on sloshing and green water loads are reviewed in Section 3.2 and 3.3.

Research on the measurement of loads on ships again focussed on the magnification of extreme and fatigue loads by wave induced vibration. A complete review of current experimental research in this field is beyond the scope of this Section and partly redundant with Section 3.1. Hence, only a very brief summary of current research is presented here.

Whipping and springing vibrations are randomly excited and thus the challenge is to condense the unknown modal parameters solely from the measured response. Therefore, Dessi and Faiella (2015) and Kim, Ahn and Park (2016) investigated methods to determine the natural vibration modes and damping characteristics for a slender and a blunt hull shape from the forced response measured at backbone models in regular and irregular waves. The authors found that the proper orthogonal decomposition method and the cross random decrement technique can be reliably used to identify the dominating natural vibration modes and the corresponding damping properties at a high confidence level.

Hong, Kim and Kim (2015a) discussed Systematic experiments on the bow flare slamming loads and resulting whipping vibration of a 10kTEU container ship. While, Kim, Ahn and Park, (2015) reported on a model test series regarding second order wave induced vibration of a large blunt vessel. Further, it has been reported on many model tests carried out to validate new numerical methods, covering different focus areas, ship types and vessel sizes: (Kim, Kim and Kim, 2015b), (Zhu and Moan, 2015), (Kim, 2015), (Wu, 2015), (Wang et al., 2016c), (Cai, Jiao and Ren, 2016) and (Zhang et al., 2016b).

In experiments on wave loads it is important that the desired wave parameters can be accurately simulated. Mozumi (2015) proposed a new method to measure the wave surface elevation in a wave basin by means of an array of small floats attached to a flexible net. Compared to conventional wave wire methods, this enables to trace oblique structures in three-dimensional, non-linear wave trains.

Full scale measurements of wave induced vibration give a better picture of the typical wave loads experienced during normal service than model tests since they must not rely on assumptions regarding the operational profile, the encountered wave environments etc.. Andersen and Jensen (2015) discussed that the expected extreme values of the wave bending moment are derived based on the dynamic hull stresses as monitored on three container ships over longer periods. In two cases the measured wave bending moments are shown to exceed the class design values, however, it must be considered that conventional class rules use safety factors on the quasi-static wave bending moment to account for whipping instead of explicitly increasing the rule design wave bending moment.

Storhaug and Kahl (2015) investigated the influence of wave induced torsional hull vibration on the fatigue damage of a 8.4kTEU and a 8.6kTEU vessel. Although similar in size, the ships were found to have strongly different torsional vibration damping, but for both vessels it was confirmed that torsional vibration damping significantly exceeded that of vertical vibration.

Ki, Park and Jang (2015) reported on measurements on a 14kTEU vessel during 1.3 years operation in Europe – Asia trade. Due to the mild encountered wave climate the highest measured wave bending moment was found to be only 70% of the design value. Further it was demonstrated that fatigue damage of the hull due to torsional vibration was insignificant.

Thanks to the advance of performance and condition monitoring systems in recent years, also hull load monitoring systems have become increasingly popular in shipping. As pointed out by Storhaug, Aagaard and Fredriksen (2016) such systems, due to their potential implications on ship safety, must be strictly quality controlled. A calibration procedure is proposed which accounts for the variation of the bending moment by static hull deflection ("hydroelastic effect") and the axial strains caused by the fluid pressures at the ship ends ("end effects").

Enhanced shipping activities in polar regions are expected in near future and thus also the monitoring of ice induced loads becomes increasingly important. E.g. (Suominen et al., 2015) reported on the determination of ice-induced loads by shear strain measurements at the main load carrying hull frames. The transfer functions between ice load and measured strains were reliably calculated for known location of the ice load, but if this is not the case the authors report on the risk of severely over- or underestimating the ice load.

Also warning systems on excessive ship motions and/or loads are further developed. Reliable far field wave observations are a prerequisite for a reliable system.

Yoshida, Orihara and Yamasaki (2015) summarise the findings of 5 years wave observations and motion monitoring by an onboard system. Wave height, period and direction measured by the wave radar showed fair agreement with crew observations and seaway forecasts. Also, the pitch motions computed from the measured wave data showed good agreement with the actually measured ones, however, agreement for rolling motions was less satisfactory.

Alford et al. (2015) implemented an environmental and ship motion forecasting system using a marine Doppler radar for far field wave observation, nonlinear wave theory to propagate the wave surface forward in time and seakeeping theory to predict vessel motions. Sea trials confirmed radar observations favourably comparing to in-situ buoy measurements, reasonable agreement of predicted and measured vessel motions and the ability of the forecast system to capture extreme waves during hurricane conditions.

Schwarz-Röhr, Ntambantamba and Härting (2016) addressed the inverse problem, i.e. to conclude from measured ship motions on the prevailing wave spectrum. Trials with a 20m vessel showed promising results but also demonstrated the need to consider the actual loading condition, inertia and speed dependent damping of the vessel in more detail.

3.5 Loads due to Damage following Collision / Grounding

Load implications on the ship after accidental damage remained an area of concern to the design and operation of ships. Accidental damage to ships and, subsequent, flooding can occur in a number of ways, but generally damages due to collision and grounding are most frequently observed and, hence, research focussed on these types of damage scenarios.

The study of Primorac Bužančić et al., (2015) investigated the effect on collision and grounding damage on the still water bending moment of a Suezmax double hull oil tanker. They employed a Monte Carlo simulation to generate possible damage scenarios and established histograms of relative bending moments considering the correlation between damage location and maximum bending load. They found that grounding damages in fully loaded condition can be expected to result in much stronger enhancement of the still water bending moments than collision damages.

Parunov, Corak and Gledic (2015) discuss the effect of collision and grounding damage on the vertical wave bending moment (VWBM) at the example of an Aframax tanker. They compare the widely used added mass method (mass of flooded seawater becomes a part of the ship mass) and the lost buoyancy method (damaged structure and tank contents are removed), the former being applicable for small damages and the latter better suited for large damage extents. The authors showed that RAOs of midship VWBM increase with increasing damage size and that the added mass method systematically provided larger maximum RAOs than the lost buoyancy method. Based on a comparison with model tests of a damaged warship, the authors concluded further that the RAOs of VWBM were overpredicted with the added mass method and slightly underpredicted by the lost buoyancy method.

Bennett and Phillips (2015b) report on an experimental investigation of the effect of damage on the motions and VWBM of a Leander Class frigate comparing the intact condition with one and two compartment damage conditions. Results show that the inclusion of an abnormal mass distribution due to damage has a significant effect on the magnitude of the motion and response RAOs in head and beam seas and that the severity of this effect increases with forward speed. For the two compartments damage case at higher wave frequencies up to 50–100% increases in the VWBM response were observed. Also, the advantages of digital imagery to analyse transient flooding processes is discussed. Numerical investigations for the same vessel and damage scenarios are dealt with in Bennett and Phillips (2015c). The results of the initial development of a two-dimensional hydroelastic model to predict the motions and global loads of the damaged ship in regular waves using a quasi-static approach are discussed and compared to the experimental data. Promising agreement between numerical method and experiments was found and thus, the ability to carry out systematic studies of the influence of damage location, severity and ship speed on the effect of damage on a vessel was demonstrated, however, presently under neglection of the transient flooding phase and three-dimensional effects. In future the authors aim to include these effects and to combine the method with a statistical analysis of the probability of occurrence of damage locations for collision or grounding. Thus a rational method to assess the consequences of collisions and groundings for the safety of individual ship designs may be developed.

4. OFFSHORE STRUCTURES - SPECIALIST TOPICS

Great advances in research for VIM in column stabilized platforms were observed. Driven by the crescent use those kinds of platform particularly by the petroleum, among other industry sectors, research was intensified, and important contributions are observed in the literature as described in bellow. Effort in development of mathematical models as well as CFD techniques through validations with laboratory experiment results, including real scale measurements were carried out in the last years. Main findings on those studies are evaluated as discussions presented in bellow. VIV is usually associated to underwater offshore structure with slender shapes, and, in its essence, it is the same what happens with the VIM in offshore floating platforms in sea current. Large effort has been made in the past to understand the physical phenomenon of the VIV, and fundamental studies are available obtained through scientific oriented research. Based on those results design oriented computer codes were developed for industry use. In this section, some studies related to mooring lines dynamics and coupled systems with floating structures are introduced.

Modeling of mooring lines dynamics due to direct waves and current, among others, and mainly those incoming from floating structure response to waves has been carefully studied. Investigations of nonlinear response of the mooring line dynamics as well as modeling of synthetic ropes were also observed.

Offshore operation to install equipment on to the seabed, and lifting operations to this purpose and other services in the open sea is always an important issue for the industry. Operational safety concerns and to make faster the operations are always key issues in the lifting operations. Active controlled lifting systems, numerical simulation models and tools and advanced study to develop reliable flexible multibodies system dynamic models were reported in the literature.

Advances were also observed on wave in deck loads issues in fixed platforms. This problem was taken in group research (JIP) projects, and main results have been reported in the literature. Based on those results and others reported in the literature, which including by means of CFD. Results also contributed for the establishment of procedures by the classification societies.

The large increase of interest for energy generated by the wind through national programs in different countries worldwide, many research have been developed. Prototype of floating wind turbines were installed with different type of floaters, and long term operational test in actual sea are being conducted, besides laboratory experiment to observe floating platform behaviour and performance and quality of energy generated by the wind turbines affected by platform motions.

4.1 Vortex-induced vibrations (VIV) and Vortex-induced motions (VIM)

4.1.1 VIV

Slender marine structures subjected to a flow, such as risers, may be subjected to vortex induced vibrations (VIV). This is a result of oscillating lift and drag forces related to shedding of vortices. Such vibrations may induce dynamic stresses and significantly contribute to fatigue damage. They may also lead to amplified drag loads. Uncertainties on the prediction of VIV are partly related to the very complex nature of the fully coupled hydro-elastic response, mainly in the hydrodynamic modelling. A simple and conservative approach consists of using empirical response based models, which predict the steady state VIV amplitude as a function of hydrodynamic and structural parameters. These are formulated in offshore design codes for most flow regimes. Vedeld et al. (2016) propose a new response model to conservatively calculate the cross-flow VIV at low KC number regime related to wave dominated flow conditions.

Some of the present challenges in terms of VIV prediction by "force based" and "flow based" numerical models consist of: identify the correct variation and interplay of excitation and responses in space and in time; capture the possible stochastic behaviour of the responses; represent the response of higher order modes; calculate the responses in time varying flows. Most of the recent work on calculation methods have been performed on: frequency domain (FD) or time domain (TD) semi-empirical models and computational fluid dynamics (CFD) methods. Semi-empirical methods represent the structural part by analytical models, finite elements (FEM), or finite differences, while the hydrodynamics is based on empirical data from model tests. Recently novle model test study on vessel motion-induced VIVs have been performed by Wang et al. (2015a, 2016e, 2017a) and Cheng, J. et al. (2016), ranging from steel catenary riser (SCR), the water intake riser (WIR), the free-hanging drilling riser (FHR) and the steel lazy wave riser (SLWR). ITTC (2017) presents a comprehensive review of the experimental work in this topic, while the following paragraphs focus more on numerical methods.

A joint industrial and academic effort has been made to provide “Guideline on analysis of vortex-induced vibrations in a riser and an umbilical” which includes best practices on structural modelling, current profile description, heave induced VIV, fatigue calculation and VIV suppression. This study aims to understand and eventually reduce the considerable variation that is often seen today in VIV predictions. Part of these results on the empirical parameters are presented by Voie at al. (2017).

State of the art engineering tools to calculate VIV mostly apply FD semi-empirical methods. The following paragraphs describe some of the latest investigations with FD methods. Accurate VIV predictions require a good structural damping model, which usually is contributed mainly from material damping. For umbilical, different layers of the riser can slip between each other which leads to additional slip damping. Often structural damping data is not available and must be estimated. Passano et al. (2016) generalized a FD semi-empirical code (VIVANA) by considering material and slip damping. The latter is an input dependent on the mean tension and curvature amplitude. A specific finite element software is applied to estimate the slip damping (UFLEX2D) as a function of several parameters. The new procedure was tested in a numerical study with an umbilical in a lazy wave configuration and the results show that VIV is sensitive to the structural damping level. Parts of the umbilical with low tension have significant larger damping due to slip.

Another dominant parameter for VIV prediction is the hydrodynamic coefficient data base, including both excitation/damping force and added mass coefficients. Recently a novel inverse finite element method has been developed by Song et.al 2016. With the application of this method, for the first time, the real hydrodynamic coefficients distribution along a flexible pipe undergoing VIV are presented. The results indicated great differences between the real coefficients on a vibrating 3D flexible pipe and conventional ones got through 2D forced oscillation tests. This new observation demonstrated us the huge differences between the reality and current practices, and it has been one of the significant progresses in the VIV field in last several years. Zhang et.al (2017a) and Fu.et.al (2017a) further discovered great ramps of VIV hydrodynamic coefficients between the bare cylinder and the adjacent buoyancy elements, where the added mass coefficient could reach up to 40, which has been proved to be within the same level as those observed by forced oscillation tests by Wu et al. (2017c). Furthermore, Zhang et.al (2017a) discovered that the sum of structural mass and added mass will be always continuous along the flexible pipe with staggered buoyancy modules under VIV conditions. This novel finding provides guidelines for the hydrodynamic coefficient model application in VIV predictions for risers with buoyancy elements, like steel laze wave risers.

The FD VIVANA software was applied by Wu et al. (2016b) to predict the VIV of a steel lazy-wave riser with staggered buoyancy elements in current. Due to different diameters, there is a competition between the vortex induced forces on the buoyancy elements and the riser. These effects are not considered by standard FD computer codes. Comparisons with experiments show that the response frequencies are over predicted, indicating that hydrodynamic force coefficients generalized from bare cylinder VIV tests may not be valid for riser segments with staggered buoyancy elements. Wu et al. (2017c) performed forced cross-flow (CF) VIV model tests with a rigid cylinder with staggered buoyancy elements. The forces on one of the buoyancy elements and on the complete test segment were measured and the related hydrodynamic data applied in VIVANA to predict the VIV response and fatigue damage of a flexible cylinder with staggered buoyancy elements previously model tested. Good predictions were achieved.

More recently, a unique modal space direct VIV prediction method has been developed and validated by Lu et.al (2017a). Different from the conventional empirical methods, this new method converted the VIV prediction problem into modal space, and solved the equations by graphically finding their crossing point of two curves of modal response and modal hydrodynamic force without any numerical iterations and calculation of energies. This method achieved 100% matches with those results by empirical method, but with clearer physical meanings and numerical stabilities, which will for sure advance the understandings of VIV prediction theories.

Although more focus has been given to CF vibrations in the past, in-line (IL) vibrations may contribute significantly to the fatigue damage of risers. IL vibrations are coupled to the CF motion and induce higher order harmonic loads in the CF direction. Wu et al. (2017d) present a combined IL and CF load model implemented into a frequency domain tool, together with validation by comparisons with test data with a flexible cylinder. A case study is also presented, consisting of a deepwater top tension riser subjected to sheared currents. The combined IL and CF response analysis gives less conservative estimation of the fatigue damage, as compared to pure CF analysis. Yin et al. (2017) performed model tests with a circular cylinder subjected to forced motions taken from measurements with a flexible pipe under VIV. The identified IL excitation coefficients were applied in VIVANA to predict the combined IL and CF VIV motions and compare with model test data. Application of the updated IL coefficients improves the prediction of the combined IL and CF VIV responses.

Time domain models allow the surrounding flow to be time varying, contrary to FD methods. Thorsen et al. (2016) applied a TD semi-empirical method with an improved hydrodynamic damping formulation and optimized exciting force model based on experiments. The resulting model is applied to simulate the CF oscillations of an elastic cylinder in stationary and oscillatory flows. Comparisons with experiments show good agreement in terms of frequency content, mode and amplitude of vibration. Thorsen and Sævik (2017a) used the same numerical model to investigate the VIV on a riser subjected to waves. The method was generalized in Thorsen et al. (2017b) by representing the structure by a nonlinear FEM and including the mean IL drag forces and related displacements and by Ulveseter et al. (2017a) to predict pure IL VIV. Further developments were presented by Ulveseter et al. (2017b) to investigate the stochastic response of long slender beams under stationary currents. The mean non-dimensional frequency of the synchronization is modelled as a simplified Gaussian process. The new model represents responses with jumps between eigen-frequencies and modes.

Comparisons with experimental data with a long riser in sheared current shows realistic predictions of the chaotic response.

Tsukada and Morooka (2016) present a numerical procedure to estimate VIV forces for a catenary riser, in the time domain, by applying the independence principle. Semi-empirical approach is adopted to estimate VIV forces, and it is proposed to be obtained them from lift coefficients (CL) and phases related to the riser movements determined from an experimental data set. And, Teixeira and Morooka (2017) present a TD semi-empirical method to calculate the CF VIV and IL displacement in uniform and sheared currents. The force model is selected depending whether the riser segment is on "power-in" (lock-in regions), or "power-out". Comparisons with experiments show good agreement in terms of VIV frequency, mode of vibration, envelops of maximum displacement and RMS of curvature. For sheared currents, the strain test data is underestimated, which is attributed to higher harmonic effects not correctly predicted.

Application of CFD is an alternative under development to the use of semi-empirical methods. Qiu et al. (2017a) presented a numerical benchmark study on the drag and lift coefficients of a marine riser with smooth surface. The flow was stationary and the Reynolds number range included the critical range. Eight organizations participated using methods based on Reynolds averaged Navier-Stokes equations (RANS), detached eddy simulation (DES) and large eddy simulation (LES). The dispersion of numerical results is very large. For example, the drag coefficient errors compared, to test data, are distributed from small values up to more than 250 %. Results from LES in general compare better with the experiments. It is possible to conclude that direct simulation of the flow around cylinders is still not mature.

As part of a study started several years ago, Constantinides et al. (2016) modelled a steel lazy wave riser subjected to in-plane current with 3D CFD simulations (AcuSolve). The software is based on a finite element solution of the Navier-Stokes equations. RANS is applied to model the turbulence. The structural problem is represented by linear superposition of natural modes calculated by the FEM code ABAQUS, while an iterative coupling scheme is used to couple with the hydrodynamic loading. Calculated strain standard deviations overpredict model test data, although the tendencies are correctly captured.

Tabib et al. (2017) conducted a fundamental study for the 3D flow past a fixed cylinder subjected to combined uniform and pulsating inflow conditions applying LES (OpenFOAM). Three Reynolds numbers are considered, including the transition regime. The pulsating inflow increases the asymmetry of the vortex shedding, the shedding frequency gets locked to the frequency of the pulsating inflow (for the cases studied) and the pulsating inflow increases the drag coefficient. Interaction between IL and CF VIV was investigated experimentally and with LES numerical simulations by Aronsen et al. (2017). Prescribed motion tests with "figure of eight" oscillations, in two opposite orbital directions, were performed with a rigid cylinder to measure IL and CF forces. The hydrodynamic forces are different for the two orbital directions. The forces present harmonics at multiples of the oscillation frequency, which are related to oscillations in the IL direction. LES predictions agree well in terms of global forces including higher order harmonics, vortex shedding modes and hydrodynamic coefficients.

4.1.2 VIM

Column supported offshore structures such as spars, tension leg platforms (TLPs) or semi-submersibles can experience vortex induced motions (VIM) when exposed to currents. VIM may occur for any oscillatory mode of the structure if the Eigenfrequency is close to the vortex shedding frequency from the structure. In areas such as the Gulf of Mexico where loop currents and associated eddies may occur, VIM may be an important design driver. Recommendations for taking VIM into account in the design of floating structures are given in DNVGL (2015), API (2015) and ISO (2013).

VIM may influence the design of mooring lines and risers of offshore structures in three ways. Firstly, the presence of VIM leads to an increased inline mean drag coefficient on the floater, secondly, the low frequency VIM motions of the floater may be large, and thirdly the VIM motions introduce additional low frequency load cycles in the mooring lines and risers. Susceptibility of a structure to VIM is conveniently expressed by the reduced velocity which is a measure of the ratio of vortex shedding frequency to Eigenfrequency in a relevant degree of freedom. In order to quantify VIM, model testing or, increasingly, Computational Fluid Dynamics (CFD) simulations are necessary since analytical methods are not generally available.

Whereas VIM has been observed in the laboratory for many types of column supported offshore structures, only Spar platforms have been observed to be subject to significant VIM in operational conditions. Generally, field observations show less VIM than prediction based on towing tests. Although this effect is not fully understood, it is clear that the full scale Reynolds Number (Re) is typically two orders of magnitude larger in the field than in the laboratory. Furthermore, the presence of waves and the variation in current in time and depth are typically ignored in model tests. Also, mooring lines, risers and other appurtenances which may not be modelled accurately in the laboratory may introduce significant additional damping in the full scale prototype.

The discrepancy between laboratory and full scale measurements has motivated a considerable research effort on the modelling of VIM by CFD. A project funded by the Research Partnership to Secure Energy for America (RPSEA) entitled 'Vortex Induced Motion Study for Deep Draft Column Stabilized Floater', has addressed the VIM response in detail through the use of both CFD and model scale testing (Antony et al., 2015). The project has produced a number of comprehensive CFD studies investigating the sensitivity of a deep draft semisubmersible to geometric parameters and to investigate the accuracy and modelling requirements of the CFD codes by comparing with model test results. The CFD codes which have been employed have been AcuSolve^{TM} from Altair Engineering, Fluent^{TM} from ANSYS, STAR CCM^{+TM} from CD-Adapco (Antony et al., 2015), and the open source program OpenFOAM^{TM} (Kara et al., 2016a).

An outcome of this work has been the publication of a best practice document for the analysis of VIV and VIM on offshore structures by CFD. Kara et al. (2016b) provide a summary of main techniques together with a discussion of their merits, give recommendations for modelling and quality assurance, and carry out a case study of a deep draft semisubmersible and compare the results with model test results.

In a more comprehensive Joint Industry Project, the VIM JIP managed by MARIN together with the University of Sao Paulo, the objective has been to compare CFD analysis with model test results and prototype data for a range of structures and provide recommendations for VIM quantification. Based on model testing, CFD analysis and full scale measurements on identical hull forms it was concluded that whereas scale effects, the presence of waves and the effect of current unsteadiness is of minor importance, the effect of additional damping from risers, mooring lines and other sources have a significant effect on the VIM amplitudes (Koop et al., 2016a). The accurate quantification of the prototype damping level is highlighted as a remaining challenge. Shear currents were not investigated as part of this JIP although it was suggested that this may not be a main explanation for lower VIM response in full scale, particularly not for relatively shallow multi column structures.

Scale effects were investigated directly by comparing CFD results at model scale and full scale Re (Koop et al., 2016b). It was stressed that the accurate calculation of VIM by CFD requires careful modelling and extensive validation of the results. It was concluded that the VIM amplitudes were quite similar in the two Re regimes but that a shift to lower reduced velocities occurs for the full scale case. It was acknowledged, however, that this observation is at odds with other published results and that further investigation is necessary (Koop et al., 2016a). Useful literature reviews of the effect of wave, damping and mass ratio on VIM are included as appendices in this paper.

The effect of damping was investigated further experimentally as part of the RPSEA project. Sterenborg et al. (2016) investigated two deep draft semisubmersibles at subcritical Re and at reduced velocities ranging between 3 and 10. An external active damping system was developed which provided linear damping of the motion normal to the flow. The damping system consisted of active linear actuators which provided forces at the fairlead positions so that additional added mass or damping could be introduced while ensuring that the system was non-intrusive when switched off. It was found that external damping greatly affected the VIM amplitudes with reductions of 60% of nominal response for 25% of equivalent critical damping.

The importance of including the significant contributions to damping was highlighted in both the RPSEA project and in the VIM JIP. Jang et al. (2017) investigated a deep draft semisubmersible in a careful CFD analysis fully coupled with the mooring and riser system and compared the VIM results with an uncoupled analysis. The CFD analysis was carried out using Star CCM^{+TM} and it was concluded that the damping introduced by the mooring lines and the risers had the potential to significantly reduce the VIM amplitudes. It was also recommended to account for the asymmetry in the restoring since this could affect the coupling between the horizontal degrees of freedom and thereby affect mooring line and riser fatigue life.

In a similar study, Tang et al. (2017) carried out a coupled analysis of a Spar-type wind turbine combining aerodynamic forces calculated by blade momentum theory, first and second order wave excitation forces calculated by 3D potential theory, and vortex induced loading calculated using CFD with a nonlinear response model including mooring lines and nonlinear restoring of the Spar. It was concluded that the vortex induced motions could be governing for roll and pitch motion and that they could also influence other degrees of freedom due to nonlinear coupling between the modes.

Suppression of VIM by active or passive means has received considerable attention in the last years and considerable work is ongoing both to fully understand the VIM phenomenon and to identify effective suppression devices which do not significantly increase the drag on the floater. An interesting development is studies of suppression of VIM by water jets in the near field. Guan et al. (2017) applied a LES solver to the problem of estimating VIM with a jet flow on the wake side of the columns. The method was applied to a low Re=2x10^2 four column configuration in 2D and a higher Re=2x10^4 3D analysis of a deep draft semisubmersible. They concluded that the VIM was significantly suppressed when a jet flow was present but found that the drag coefficient increased in the 3D case. Fu et al. (2016) used the Lattice Boltmann method to investigate 2D flow around a cylinder with a jet flow into the approach flow at Re=6x10^4. It was concluded that the jet flow resulted in a substantial reduction in the lift force on the cylinder and that further work is necessary to investigate this phenomenon in more detail.

4.2 Mooring Systems

ISSC (2015) presents a classification of methods available for solving the mooring lines dynamics and of methods for solving the coupled floater and mooring/riser systems dynamics, together with a discussion on the advantages and disadvantages of each approach. This Section starts directly with the latest developments on methods and tools for mooring analysis, namely for deterministic calculation of mooring line loads.

Existing lumped mass methods and finite element methods for cable dynamics provide accurate predictions of static and dynamic line tensions for many of the practical applications with chain and steel wire rope. Some of the present challenges include: modelling of snap loads, high frequency mooring line dynamics, correct modelling of synthetic ropes dynamic behaviour and accurate estimation of platform low frequency motions in high seastates.

Snap loads on mooring lines may have different origins and they are characterized by a large local increase in tension that propagates along the cable. Palm et al. (2017) present a high-order discontinuous Galerkin (DG) formulation for cable dynamics to capture snap loads in mooring cables with high accuracy. The DG method consists of a finite volume scheme with each cell approximated using finite elements. The problem is formulated in a conservative form. An *hp* adaptive scheme is used to dynamically change the mesh size *h* and the polynomial order *p*, based on the local solution quality. An error indicator and a shock identifier are implemented to capture shocks with slope-limited linear elements, while using high-order Legendre polynomials for smooth solution regions. The authors report very good modelling of idealized shock waves by the method, as well as very good agreement with experimental data with snap load propagation in a mooring chain.

Chen and Basu (2017) investigated the structural shock wave propagation in a mooring cable. The wave is generated by fairlead excitation, propagates to the anchor and reflected back. The equations representing the lines' dynamics are formulated in a Lagrangian frame and solved with a finite-differences method.

Jayasinghe at al. (2017) describe and discuss high frequency mooring line dynamics observed in two FPSO installations. While standard mooring analyses account for low frequency and wave frequency loading of the lines only, this study identified torsional vibrations in deep water wire rope sections and high frequency oscillations of chain links within the chain hawse tubes. The root reasons were pointed as coupled axial-torsion effects for the first and heave induced VIV for the latter. The frequencies are one order of magnitude higher than typical wave frequencies. The authors point out that the related degradation mechanisms cause damage to mooring systems and that the possibility of such vibrations needs to be assessed and evaluated during the design.

Ghoshal et al. (2016) investigate the instability of mooring cables induced by combined hydrodynamic and ice loads. The authors present an analytical method based on model superposition for the cable vibrations. The model considers the geometric nonlinearity (nonlinear strain), while most mooring analysis neglect this effect. This nonlinearity plays a role in the auto parametric excitation of the cable which, combined with out-of-plane pulse loads due to ice, may lead to vibrations and instability.

Design of marine energy converters mooring systems is challenging for several reasons, including the behaviour in relatively small water depth, possible influence on the device efficiency and significant contribution to global costs. Luxmoore et al. (2016) propose a new active mooring system for wave load reduction in marine energy systems. The system is named Intelligent Active Mooring System (IAMS) and it applies a nonlinear load-extension curve that is adjustable to the wave conditions. The IAMS system is represented in numerical simulations by an analytical model validated through comparisons with test data obtained at the Dynamic Marine Component test facility at the University of Exeter. The authors perform dynamic simulations for a moored buoy with the IAMS system incorporated into the mooring lines and compare the results with prototype test data for validation. Further numerical studies with the validated model show the IAMS system can reduce significantly the mooring line tensions.

Existing methods for line dynamics provide accurate predictions for many of the practical cases. Presently, the uncertainty in mooring analysis is mostly related to the fairleads forcing motions prediction, namely of the platform low frequency motions. Standard diffraction analysis under-predicts the low frequency motions of Semi-submersibles in high sea states. The same is observed for FPSOs under certain conditions. The EXWAVE JIP (Joint Industry Project), ran from 2015 to 2017, with the objective of improving methods, procedures and standard industry practice in design prediction of extreme mooring line loads (Fonseca 2016, 2017). The focus was on the prediction of low frequency wave excitation, including wave-current interaction effects. The project proposes a semi-empirical formula to correct potential flow wave drift forces on Semis by accounting for viscous drift and wave-current interaction effects (Fonseca and Stansberg, 2017). Regarding FPSOs, experimental and numerical evidence shows that Newman's approximation for calculation of wave drift forces may be unconservative, even for deep water conditions and long natural periods of the system (Fonseca and Stansberg, 2017).

One more challenge with mooring analysis is related to large computational effort required for systems with many mooring lines and risers, especially when coupled computations are needed, in combination with a large matrix of environmental conditions. de Pina et al. (2016) propose a method based on artificial neural networks (ANNs) for the analysis of mooring systems of floating production units. The approximation method is suggested for preliminary design of complex systems with many lines and risers, where accurate simulation tools require a very large computational effort. The ANN method mimics the behaviour of the simulation model by identifying the relationship between the given inputs and the outputs. The method is applied to a Semi-submersible spread moored in deep water with four clusters of four lines and comprising 25 flexible and rigid risers. The ANN is trained based on the outputs from a quasi-static mooring analysis code. It is concluded that the ANNs provide fairly accurate values for the mooring line tensions and platform offsets.

Sidarta et al. (2017) propose an ANN based procedure for prediction of mooring line tensions from the platform motions. Good accuracy of predicted tensions is achieved, when compared to numerical simulations for conditions not included in the training data. The authors suggest the procedure may be used to assist the monitoring of moored systems.

Synthetic fibre ropes have advantages for deep water moorings due to almost neutral submerged weight. Compared to chain and wire ropes, they are characterized by much more complex nonlinear dynamic behaviour and correct numerical modelling is still challenging. This is related to the material properties, namely time dependent characteristics, viscoelasticity, viscoplasticity and large stretch, which need to be taken into consideration. Relevant experimental and numerical work has been developed as described below.

The usual approach for mooring system analysis with respect to axial stiffness is to use the upper bound axial stiffness for calculation of extreme tensions and the lower bound stiffness for horizontal offsets. This approach is conservative. More accurate methods may be applied, provided the dynamic stiffness properties are known. The Syrope JIP performed extensive change in length testing and proposes a conceptual model for the behaviour of polyester ropes describing the length of the rope depending on the preceding largest mean tensions (Falkenberg et al. 2017). Guidance for use of the model in mooring analysis is given. The authors give also recommendations for testing of ropes and analysis of test data for identification of model parameters.

The viscoelastic properties of synthetic fiber ropes may result on creep behaviour and creep rupture. Lian et al. (2015) propose a creep–rupture model to represent the creep behaviour of synthetic fiber ropes. The method is based on continuum damage mechanics, consistent with the fundamental laws of thermodynamics. The authors describe the identification method to achieve the model parameters from test data.

Huang et al. (2015) propose a new stress-strain constitutive model which accounts for the loading history and the time-dependent property of synthetic fiber ropes under cyclic loading. The nonlinear constitutive model combines a viscoelastic theory with a viscoplastic spring-dashpot-slider model. An identification method based on the dynamic test data is also proposed to estimate the model parameters. Predictions from the model are compared with test data in terms of dynamic stiffness and hysteresis loop of aramid and polyester ropes under cyclic loading. The agreement is good.

The effects of aging and repeated load cycles on the rope performance is another research area. Lian et al. (2017) performed fatigue tests on high modulus polyethylene (HMPE) ropes. The analysis of test data shows the dynamic stiffness of HMPE ropes increases with increasing mean load and it decreases with increasing loading amplitude. The authors propose and empirical expression to predict the damage evolution under long term cycling loads. The expression accounts for the mean load and load amplitude. Flory at al. (2017) discuss axial compression fatigue in fibre mooring ropes, bringing analysis from recent failures. Axial compression should be avoided by proper rope design and operation of the lines, however, since the mechanisms leading to compression of fibers or yarns are not well known, problems related to axial compression fatigue are still reported. It is concluded that the rope structure, namely the rope and strand lay length, may cause axial compression fatigue when the subjected to many cycles and when the rope is prone to bend or rotate.

Synthetic ropes present advantages for floating marine renewable energy (MRE) systems, as compared to conventional chain or steel ropes. Since the requirements are different from those of the offshore oil and gas industry, specific studies are needed to assess the applicability of this technology to the MRE sector. Differences related to numerical modelling comprise, at least, highly dynamic loading characteristics, much lower water depths and different ratio horizontal offsets vs water depth. Weller et al. (2015) present a comprehensive review on the topic of synthetic ropes in the context of marine renewable energy systems. Focus in on the performance characteristics, classification, testing and application aspects.

Weller et al. (2014) present results and conclusions on the axial stiffness and damping for nylon 6 parallel stranded rope samples tested in the context of operational mooring loads representative of MRE devices. Harmonic and irregular loading regimes were applied to assess the influence of load history on time averaged and time varying performance. The authors conclude that the bedding-in level has significant influence on the short-term performance of the mooring system. It was also observed that the previous load history influences the instantaneous stiffness, which is in line with other studies, and it influences also the damping of the lines. The authors suggest that the rope performance is very much influenced by the instantaneous strain. A follow up investigation aimed at understanding the influence of aging on the rope performance (Weller et al. 2015). Tension-tension tests were performed on samples of a mooring line which was tested at sea for 18 months. The axial stiffness and line damping qualitative behaviour is qualitatively similar to that observed for the new samples. However, the aged samples show increased compliance, lower load capacity and reduced fatigue performance. Inspection showed fibre-on-fibre abrasion damage, with a contribution from debris found in the rope structure.

4.3 Lifting operations

Offshore lifting operations include air and subsea lifting. Two of its most important aspects are safety and operability. As the industry demands offshore operations with higher lifting capacities in deeper water depths and severe environment conditions, advanced technologies such as motion compensation systems, which are used to reduce the relative vertical motion of the load caused by the vessel-movement, time domain coupled vessel-lifting simulations and testing and verification methods have been developed and employed to support the lifting operations. Besides, regulatory bodies and industry have been updating the standards and guidelines for safer lifting operations.

The Bureau of Safety and Environmental Enforcement (BSEE) has initiated the lifting crane safety assessment study in 2014 and was carried out by ABSG (2015). The study involved analysis of lifting cranes and material handling equipment operating in the United States outer continental shelf (OCS), analysis of lifting incidents, and a review of industry standards and practices. More than nine hundreds of cranes have been analysed including their crane mount type, boom type, capacity, manufacture/service provider, crane age, and incident information. The study indicated that the most of the incidents occurred during material handling, followed by pipe handling. It also indicates that the failures resulted from human error are more than twice the equipment capacity/functionality deficiency failures. It has been indicated that previous standards and regulations may not sufficiently reflect the modern subsea lifting operations. To facilitate the industry needs, classification societies have been updating their guidelines to address design, operation, inspection, and maintenance requirements for lifting operations. ABS (2016) has made a major update of the ABS Guide for Certification of Lifting Appliances based on industry feedback. Among others, the update includes new sections about subsea lifting requirements, motion compensation and rope tensioning systems for cranes. The DNVGL (2016) has updated the standards for marine operations to reflect current industry practices.

Woodacrea et al. (2015) provided a comprehensive review of vertical heave motion compensation systems used in ocean vessels from the early 1970s to modern systems. The paper examined in details of passive, active and hybrid active-passive heave compensation systems, and compared hydraulic versus electric winch drive systems. The paper indicates that the phase lags between the sensors and the system may have been the main reason for limiting total compensation against heave motions. The paper suggests that the model-predictive control may be able to improve the performance of active heave compensation systems. Richtera et al. (2017) presented an active heave compensation system using motion predictions based on a least squares algorithm. Its overall promising performance is demonstrated using a full-scale test bench.

One of the modern offshore lifting operations is the installation of offshore wind farms, which includes lifting the foundations using floating crane vessels, deploying and retrieving jack-ups' legs, and lifting turbine nacelles and rotors at a large lift height. Numerical simulation of these critical installation scenarios in the planning phase is very important for the safe and effective operations. Although motion simulations of floating vessels in frequency or time domain are standard industrial tasks nowadays, for lifting operations, however, multibody simulations must be performed, because the vessel motions influence the motions of the free hanging crane load and vice versa. Li et al. (2015) presented a numerical modelling and time-domain simulations of the lowering operation of an offshore wind turbine monopole with a diameter of 5.7 m. The study indicates that when using a floating installation vessel, the interactions between the motions of the vessel/crane and the monopole is quite large. Vorhölter et al. (2015) reported a time-domain analysis of typical lifting operations for the offshore wind industry. The study includes the designs of crane vessels in a range from converted conventional heavy-lift carriers over offshore construction class vessels to crane derrick barges with crane capacities up to 3,000 t are compared to each other by simulating typical lifting operations in the offshore wind industry. The lifting operations are simulated with non-linear seakeeping tools and the motion of the free hanging load is computed for operational setups. The results from these analyses can be used for operational limits of existing crane vessels and for design of future crane vessels.

Jeong et al. (2016) presented the simulation of lifting operations in an offshore support vessel. The simulation includes the calculation of dynamic responses of the vessel and the equipment. It also includes analysis of the lifting wire rope tension and the potential collision of the lifting object with surrounding objects for various operating conditions. The dynamic responses of the motions, the wire tension, and the relative position of the lifting object to other structures were calculated based on a multibody system dynamics approach. The simulation includes the lifting in air, going through the splash zone and sinking in deep water. During the lifting in water, the slamming load is calculated including the lowering speed and the geometry of the object. The analysis results show that fast lowering speeds result in a large variation of wire tension. However, it should be pointed out that slamming load calculation is a complex process and the prediction of the slamming load in this study is quite preliminary and needs to be further improved.

A study of dynamic simulation of subsea equipment installation using an offshore support vessel based on flexible multibody system dynamics was carried out by Hong et al. (2016). In this study, the flexibility of the crane boom is included in the simulation model. The deformation of the crane boom varies during the lifting operation due to the vessel's motion induced by waves and winds. The flexible crane boom modelled using finite element approach is included in the equations of motion of a multibody system. The results indicate that using the flexible crane boom model resulted in higher dynamic amplification factors than using a rigid body model for the crane boom for various conditions analysed.

The offshore lifting operation is a complex process that involves multibody and control system. The consequence of an operation failure could be very costly. Testing and verifying the simulation tools and control systems is very important. However, it is difficult or expensive to establish certain test conditions to simulate real operations. The Hardware-In-the-Loop-Simulation (HILS) can be an effective method for testing the control system. Zhao et al. (2016) presented their study on the use of HILS for a heave compensator which is used to keep the position or the lowering speed of a lifting object. The HILS studied is composed of a control system and a HILS that is a simulation model of the support vessel by a software. The verification of the control system for the crane operation has been carried out with both a software programmable logic controller (software-in-the loop) and a hardware programmable logic controller (hardware-in-the-loop).

The safety of lifting operations and the up-time are very important for the offshore industry. The vessel up-time can be increased with heave compensation, particularly under adverse weather conditions. A robust simulation tool that can simulate the complete sequence of a lifting operation with all required details will increase the safety and efficiency of the real operation. Direct simulations should be performed during the planning of offshore crane operations as far as possible and feasible, especially for the complex lifting operations. Continuous improvement of the simulation tools to include all important parameters, such as the shielding effect from a large lifting object, damping, lifting speed and so on, may need to be included in the simulations.

4.4 Wave-in-deck loads

The problem of estimating the probability and magnitude of wave-in-deck loads on both fixed and floating structures has received considerable attention during the reporting period. The ShorTCresT Joint Industry Project (JIP) which was completed in 2014 concluded that whereas the crest height of the largest waves may not be significantly larger than second order predictions, the largest waves may be prone to wave breaking and thus have significantly larger particle velocities in the crest region (Hennig et al., 2015). This finding has given rise to the concern that the established practice for wave-in-deck loads on jacket structures may be significantly inaccurate. The established design practice involves calculating the crest elevation with the relevant return period for design and representing the associated wave-in-deck load with a regular wave with the same crest elevation and an associated period. If the wave which is governing for design is a breaking wave, the regular wave approach may give too low loads if the water velocity in the crest region is the governing property of load transfer.

Motivated by the concern that wave breaking is not adequately taken into account in structural evaluations of jacket structures, Mærsk Oil carried out the Tyra Field Extreme Wave Study 2013-2015 (Tychsen & Dixon, 2016, Tychsen et al., 2016). The aim of this project was to carry out a full long-term simulation of loading and structural response of the structures on the Tyra field at approximately 45 m water depth in order to verify their structural integrity. The study involved an extensive model test campaign, analysis work and CFD analysis in order to calibrate the models which were used in the Monte Carlo simulation of the structures. This study concluded that the existing industry practice has non-conservative shortcomings, particularly relating to the assumption of a deterministic link between the crest elevation and wave load, and the presence of wave breaking.

The findings from the ShorTCresT JIP and the Tyra study have motivated several follow up JIPs, notably the BreaKin JIP (www.marin.nl) and the LOADS JIP. The LOADS JIP (Swan et al., 2016) aims to further clarify the role of wave breaking for the structural reliability of jacket structures in deep and intermediate water depths, and to propose an efficient Monte Carlo simulation methodology which will incorporate the effect of nonlinear crest elevations, short-crestedness and the effect of wave breaking in load calculations.

On 30th of December 2015, the semisubmersible drilling rig COSL Innovator was hit by a large wave. The wave impacted against the front of the deck box on the lower deck and the mezzanine deck, broke 17 windows and caused one fatality. The Petroleum Safety Authority of Norway (PSA) has issued an investigative report about the incident (PSA, 2016). As a result of this accident, the air gap and the associated horizontal wave-in-deck impact loads for Mobile Offshore Units (MoUs) have received considerable attention in the reporting period.

DNVGL has issued two Offshore Technical Guidance notes in order to aid the analysis of MoUs. DNVGL-OTG-13 (2017) gives recommendations for air gap calculations whereas DNVGL-OTG-14 (2017) gives recommendations for horizontal wave impact loads, evaluation of global structural integrity and recommendations for model testing of MoUs with negative airgap in front of the deck box. DNVGL-OTG-14 provides generic load curves for horizontal wave impact loads conditional on the airgap exceedance in front of the deck box (Johannessen et al., 2017).

The recommendations in DNVGL-OTG-13 are based on linear radiation-diffraction analysis and gives recommendations for empirical corrections to these results in addition to considering effects due to slowly varying motion and static heel. A review of the methodology recommended in DNVGL-OTG-13 was presented by Pessoa & Moe (2017).

Linear radiation-diffraction methods have significant shortcomings in calculating air gap of semisubmersibles in storm conditions. The shallow pontoons and large column diameter of many modern MoUs, and the presence of currents, make the calculations particularly challenging. There is considerable work currently underway to improve the methodology of analysis and it is expected that several publications will be available in the next reporting period. There is ongoing work on weakly nonlinear time domain simulations for air gap predictions (Kvaleid et al., 2014), on the quantification of the effect of wave-current interaction on air gap (Hermundstad et al., 2017), and on air gap predictions by CFD methods, predominantly Volume of Fluid formulations.

There is also ongoing work on tackling the full problem of wave-in-deck and air gap calculation by CFD where the floater motion, the wave surface elevation and the wave-in-deck loads are solved simultaneously. CFD has been applied successfully (Pakozdi et al., 2015, 2017) to enhance model test results by iteratively matching measured surface elevation to the surface elevation calculated in CFD, thereby obtaining the wave properties and loads over the entire structure for a measured event.

Research about improved analysis techniques mainly focuses on the deterministic problem of air gap and wave impact loading. CFD is computationally intensive and only a relatively small number of wave events can be investigated. For wave-in-deck problems, the statistical problem of estimating the load or response within a prescribed annual probability of occurrence is a significant challenge. The problem of estimating wave impact loads with a prescribed annual probability of occurrence and the relative importance of the long term and short term variation in seastate parameters and individual waves respectively, has been discussed by Johannessen & Hagen (2016). The statistics of air gap and wave impact over a deck with a finite extent has been discussed by Hagen et al. (2016), whereas the safety of fixed and floating structures subject to wave-in-deck loads have been discussed in the context of uncertainties in metocean conditions by Haver (2017).

4.5 Floating Offshore Wind Turbines

With the first offshore wind farm stated delivering electricity in 2017, it has been predicted that the development of offshore wind farm will continue to grow. James and Costa Ros (2015) provided comprehensive market and technology review of floating offshore wind. It reported that semi-submersible, spar-buoy and tension-leg platform are three dominant floating wind concepts mainly due to their motion performance and relatively mature fabrication and installation technologies. It also reported that, among others, advanced modeling tools, including numerical and model testing, are very important for understanding and optimizing the performance of the offshore floating wind turbines.

A lot of studies on the simulations and model tests have been carried out recently. Caille et al (2017) reported the work on the model test and simulation comparison for a tension leg platform (TLP) floating wind system. The model test was conducted in 2015 at MARINs offshore basin with the model scale of 1/40. The model includes turbine, platform and moor-ing system. The simulation was performed with Ocaflex coupling with recorded aerodynamic forces at tower top and with DeepLinesWind use the aerodynamic loading computed with boundary element method from the measure wind. The paper indicates that for the loads on the platform by using aerodynamic forces inputs and using DeepLinesWind calculation from wind speeds are quite close are comparable with the measurement. to those for ations is very satisfactory for both the FCS and SCS approaches: mean values and RMS are in very good agreement as well as the frequency content of the signals. Oggiano et al. (2015) carried out an experimental investigation on a 1/40 model scale of two different tension-leg-buoy (TLB) platforms, including tower and mooring system, at a wave tank in Deep Wave Basin at IFREMER facilities in Brest, France. The test results are compared with CFD simulations, using Volume of Fluid (VOF) method included in the STAR-CCM+ code from CD-adapco. Good agreement were found for the tower motion and mooring line tension in regular wave by comparisons with heave free decay tests.

Lopez-Pavon and Souto-lglesias (2015) proposed improvement in the hydrodynamic design of semisubmersible concept by investigations of hyrdrodynamic coefficients of a semi-submersible floating offshore wind turbine through experiment and numerical simulations. Forced heave oscillation tests were conducted in a towing tank with a 1/20 model scale for one column of the platform, in order to compare hydrodynamic coefficients of a plain solid heave plate and a flapped reinforced one. Measurements of dynamic pressures on both heave plates, added mass and damping coefficients were also presented. Numerical simulations were conducted with a wide-spread frequency domain panel method (WADAM) and a RANS CFD commercial code (ANSYS CFX).

Allen et al (2017) reported the 6-year effort in research and scale model testing of floating wind turbines as part of the VolturnUS project from the DeepCwind Consortium. The 1/50 scale model tests have been carried out for a generic tension leg platform (TLP), a semi-submersible (semi), and a spar-buoy (spar) floating platform at MARINs test facility. In 2015, the University of Maine has established an advanced Wind/Wave test facility and a 1:52 scale model of the floating wind turbine of the Volturn as a final design was carried out in 2016. A number of model tests have provided the key insights into the behavior of floating offshore wind turbine (FOWT) platforms as well as improving the ability to perform model tests of FOWTs. Data from these tests has been used for numerical simulation validation for engineering software FAST and a number of other analysis tools. Viselli (2014) and Viselli et al (2015) reported the model test of a 1:8 scale floating wind turbine offshore in the Gulf of

Maine. In the summer of 2013, UMaine launched a 1:8-scale model VolturnUS offshore Castine, ME ([32], and [36]). This concrete semi-submersible platform supported a fully operational scaled wind turbine and was the first grid-connected floating offshore turbine deployed in the United States.

Tomasicchio et al (2017) published their work on the dynamic response of a spar buoy wind turbine under different wind and wave conditions. The responses were studied through model tests of 1/40 scale and numerical simulation using program FAST. The model tests were conducted at the Danish Hydraulic Institute (DHI) offshore wave basin. The simulation program FAST was calibrated using the measurement data and the mooring lines were modeled as quasit-static taut or catenary lines in the FAST simulation program to simulate the coupled system of mooring, platform and turbine. The paper indicates that the simulations shown a good agreement with the dynamic responses determined by the observed results in terms of displacements, rotations, forces accelerations. The paper also indicts that mooring line loads are overestimated in the range of higher frequencies.

Bayati et al (2017) provide their work on the use of numerical and experimental method to simulate the surge and pitch motions of a semi-submersible floating offshore wind turbine through the "hardware-in-the-loop (HIL)" approach. It is a hybrid approach that combines the measurements and computations in real time during the tests which allows some parameters obtained through computation for inputs to the testing, while the computation takes in the testing results, or say testing in the simulation loop. The HIP approach provides the possibility of exploring the advantages of each facility and overcoming the scaling issues when testing both wind and waves in a single test facility. The paper presented the validation of the approach using simplified cases of two degree of freedom system (surge and pitch) for free decays, regular and irregular waves. The results show the approach is promising and is possible for the application of 6-DoF system.

Karimirad et al (2017) presented the comparison of real-time hybrid model testing with numerical simulations. The experimental data is from a 1:30 scaled model of a semisubmersible wind turbine. Numerical simulations were performed by using software SIMA by MARINTEK that simulates the coupled aero-hydro-servo-elastic system. The results in terms of dynamic time series, spectra and statistics of the responses are compared between the two methods for different load cases considering irregular waves and turbulent wind. Test results agree with numerical simulations and that either Newman's approximation or the full second order QTF can give good agreement in the low-frequency responses for this platform when combined with the selected hydrodynamic viscous drag coefficients.

It has been indicated that the as wind farms are moving towards deeper water, the floating vertical axis wind turbine (VAWT) seems to be a very promising alternative to the floating horizontal axis wind turbine (HAWT) which has been widely studied. The development of floating VAWTs is still at its early stage. Borg and Collu (2015) presented a comparison between the dynamics of horizontal and vertical axis offshore floating wind turbines. Cheng, Y., Ji, C.Y., Zhai, G.J., et al. (2016) have developed fully coupled method for numerical modeling and dynamic analysis of floating vertical axis wind turbines. The actuator cylinder (AC) flow model for aerodynamics of floating VAWTs is established with the consideration of turbulence effects, dynamic inflow and dynamic stall. The aerodynamic code is then coupled with SIMO-RIFLEX to achieve a fully coupled simulation tool which can account for the aerodynamic, hydrodynamics, structural dynamics and controller dynamics in the system. The simulation tool has been validated with another software using a land based VAWT and a semi VAWT and good comparison was achieved.

Cheng et al (2015) also carried out study on the dynamic responses of three floating wind turbine concepts of VAWT with a two-bladed 5 MW Darrieus rotor. The turbine was mounted on floating support structures of spar buoy, semi-submersible, and tension leg platform (TLP).

Fully coupled nonlinear time domain simulations were conducted. A series of load cases with turbulent wind and irregular waves were carried out to investigate the dynamic responses of these three FVAWT concepts by estimating the generator power production, the platform motions, the tower base bending moments, and the mooring line loads. The findings indicate that the motions of the spar and semi-submersible may be higher, but the mooring line load are relatively low, while these findings are opposite for TLP concept. The paper does not recommend TLP as a good substructure for a vertical axis wind turbine unless the cyclic variation of aerodynamic loads is significantly reduced.

Overall, it has been indicated that there are integrated modeling tools exist and the accuracy of the software currently available are generally good or very good in comparison with model testing. However, industry modeling experts have suggested that some platform designers are not accurately capturing the holistic system response (e.g. coupled analysis of the turbine, platform, moorings, and anchors), and that further work is needed to improve modeling tools James and Costa Ros (2015). Such tools would need to incorporate all aspects of the floating wind system to undertake coupled analysis of the various components. Of particular importance maybe is the need to incorporate feedback from offshore demonstrations to validate the models. This may also need to be closely tied with efforts to develop advanced control systems. The modeling gap around the geotechnical conditions at a site, which greatly impacts the mooring and anchoring system, may need to be developed. Without the ability to model anchor geotechnical dynamics, there is a risk that this will result in conservative and more expensive designs.

Advanced tank testing facilities such as the University of Maine and others can help to de-risk and optimize the design as much as possible before moving to full-scale offshore demonstrations, which can ultimately lead to less conservative and more competitive designs.

5. PROBABILISTIC MODELLING OF LOADS ON SHIPS

The design process of ship structure requires knowledge of extreme lifetime loads, where wave induced loads contribute significantly. These wave loads represent the environmental conditions encountered through the entire life of the ship. The wave loads can be obtained from the processes of combined with the extreme of random process theory and long-term statistics. These techniques enable waves to be defined in a mathematical form that can be used to calculate wave loads on the ship and ultimately the response of the ship to these loads.

5.1 Probabilistic Methods

Because of a consequence of linearization, the linear superposition of hydrodynamic problems is allowed with the aid of perturbation analysis. Superposition plays a great and basic role in efforts towards the solution. The responses of a ship in irregular waves can be considered as the summation of the responses to regular waves of all frequencies. In this principle, obtaining the prediction of statistical characteristics of motions and structural responses of the ship is available in irregular waves.

Soukissian (2014) used two general bivariate probability models (significant wave height–wave direction, wind speed–wind direction and wave direction–wind direction) for the analytic description of the wind and wave climate of an area, taking account of directional characteristics in addition to the usual linear metocean parameters. The probabilistic description of the wind and wave regime is confined to the linear characteristics of sea states and wind conditions, i.e., the significant wave height, wave period and wind speed. Rapidly emerging applications, such as offshore wind and wave energy utilization, are largely dependent on the accurate description of the directional wind and wave characteristics of the areas.

C´orak et al. (2015) presented the article deals with correlation analysis between wave and whipping bending moments and their load combination factors. It is shown that reconstruction of the time signal from the frequency domain is suitable method for the prediction of the most probable values of bending moments and short-term load combination factors. The significant influence of the random phase angles on the extreme values of bending moments and load combination factors is confirmed. Since some realizations show a significant scatter, large number of time simulations are needed for the prediction of the most probable values. The comparison of a limited number of model test data with the most probable values derived from the numerical simulations has revealed a decreasing trend of the short-term load combination factors with the increasing ratio of the most probable extreme wave and whipping bending moments. It can be concluded that the overall whipping influence and the load combination factors are expectedly higher for the larger ship.

Lucas and Guedes Soares (2015) presented the results of the fit of three bivariate models to twelve years of significant wave height and mean zero-crossing period data of swell, wind sea components, and combined sea states from Australia. The conditional model with a lognormal distribution for the significant wave height and lognormal distributions for the zero-crossing period gave the best fit for the total sea states and for the wind component. In case of the swell component the conditional model with a Weibull distribution to the significant wave height and a lognormal distribution to the mean zero-crossing period gave a relatively close fit to the data.

Bitner-Gregersen et al. (2016) drawn attention on the uncertainties associated with wave description as this is an important input to assessment of loads and motions and fatigue damage of ships and offshore structures as well as to model testing. Several of these uncertainties still require further research and are not fully quantified herein. Effects of some of these uncertainties on assessment of loads and responses is demonstrated putting particular focuses on very steep waves, their impact is significant. The identified uncertainties related to the metocean description apply also to these structures. Awareness of importance of accounting for uncertainties associated with environmental description in risk assessment of ship, offshore and renewable energy structures is continuously increasing with in the marine and renewable energy industry.

Alibrandi and Koh (2017) presents the dynamic analysis of a deepwater floating production systems has many complexities.The sea state is random; hence the need of stochastic dynamic analysis. In the paper, the evaluation of the non-Gaussian distributions of the responses of the systems is developed through the well-known First-Order Reliability Method (FORM) and the recently proposed Secant Hyperplane Method (SHM). They give rise to two stochastic Equivalent Linear Systems (ELS) allowing to determine any quantity of engineering interest: The Tail Equivalent Linear System (TELS) based on FORM and the Tail Probability Equivalent Linear System (TPELS) based on SHM. The TELS is the Equivalent Linear System (ELS) having the same design point of the original nonlinear system. The Tail Probability Equivalent Linear System (TPELS) is the ELS where the difference in terms of tail probability between the TPELS and the original system is minimized. A simplified 2-degrees-offreedom model is used to demonstrate how these methods can be effective for stochastic dynamic analysis of a marine riser.

Silva-González et al. (2017) modelled the probability distribution of extreme values with the peaks over threshold method. It requires an appropriate estimation of the threshold above which exceedances are considered to be a sample from a generalized Pareto distribution. They used the applicability of four methods developed for hydrological, coastal engineering, financial and stock market purposes, to the case of wave heights from extreme sea conditions due to storms, where significantly less amount of data may be available. Based on the results of this assessment, an improved square error method is formulated, which further allows evaluating the uncertainty in threshold estimation, as well as the uncertainty in the estimation of wave heights for the given return periods.

5.2 Equivalent Design Waves

The concept of design waves is used in the direct calculations to reduce the number of load cases to be checked for yielding, buckling, ultimate or fatigue strengths of marine structures. A design wave is an equivalent wave or wave group representing the long-term response of the dominant load parameter under consideration. The equivalent design wave or response conditioned waves are then defined by the following parameters: ship speed, frequency, wave heading, wave amplitude and phase.

Fukasawa and Kadota (2015) presented the research on the method for determining significant short-term sea states for fatigue strength of a ship. In the paper, taking accounts of stress histories which would be effective in the crack initiation and propagation, the significant short-term sea states for fatigue strength of a Post-Panamax container ship was clarified by estimating the occurrence probability of the stress range of the ship in her lifetime. The dominant short-term sea state to each occurrence probability of stress range varies from the sea state of smaller significant wave height to that of larger ones. The mean wave period is not that much different but is slightly increasing with the decrease of probability.

Klein et al. (2016) introduced the Peregrine breather solution of the nonlinear Schrödinger-type equation as an innovative design wave. The major benefits are the potential to generate abnormal waves of certain frequency up to physically possible wave heights, the symmetrical abnormal wave shape and the availability of an analytical solution. To evaluate the applicability of the Peregrine breather solution as design wave, wave-structure investigations with a LNG carrier were performed in a set of Peregrine breathers at certain frequencies. The investigations comprised model tests as well as numerical simulations. Zhang and Guedes Soares (2016) studied the behaviour of an LNG carrier and chemical tanker responses to abnormal waves simulated by the nonlinear Schrödinger equation. Wang et al. (2016b) presented that the wave surfaces of extreme sea states are generated by a nonlinear Schrödinger equation, and the ship motions in thee xtreme waves are calculated numerically by a nonlinear time domain seakeeping code.

Fang and Chan (2016) presented that a three-dimensional linearised potential theory has been used for the investigations of wave load characteristics of the high speed trimaran travelling in short-term waves. The wave loads including the shear forces, bending moments and torsional moments at one transverse section of the trimaran ship hull and longitudinal section of connected deck are predicted at various wave heading and ship speeds. The characteristics of longitudinal and transverse sectional wave load responses of the trimaran ship have been discussed and can be used for the selection of ship speed and heading in design wave conditions.

Fukasawa and Hiranuma (2016) presented that the long-term prediction of vertical wave bending moment is made firstly for various size container ships. The time-domain nonlinear simulations are then conducted in design short-term sea states with the use of design irregular wave method. The vertical wave bending moment required by UR S11A is much larger than that by UR S11 in sagging side. With the increase of the size of container ship, the maximum vertical wave bending moment calculated by using the design irregular wave becomes larger in sagging side than that by IACS requirement S11A. The maximum vertical wave bending moment calculated by using the design irregular wave exceeds that by IACS requirement in hogging side in larger container ships.

Wang and Guedes Soares (2016a) presented calculations of ship motions, slamming occurrence probability and slamming loads on the bow of a ship hull in irregular waves. The results are compared with the experimental data from model tests of a 170m chemical tanker with Fn=0 in head seas. Ship motions are calculated by using a partially nonlinear time domain code based on strip theory. Two estimated significant slamming events are simulated by using the Arbitrary-Lagrangian Eulerian (ALE) algorithm, based on the calculated relative entry velocities in the numerical procedure. Hauteclocque et al. (2017) presented a systematic and consistent approach to develop new wave loads formulae, based on the direct computation. The rules are based on the equivalent design wave approach that has been shown accurate. The result is the new rule formulae that are implemented in the new BV rules for container ships. Those new load definitions match quite accurately to state-of-the-art calculations and are thus expected to reflect more closely the reality. The uncertainties of the derived formulae (compared to direct calculation) is well characterized, allowing further partial safety factor calibration.

Aggarwal et al. (2017) presented the dynamic characteristics of spar based floating 5 MW offshore wind turbine (OWT) under operational and survival conditions. The OWT is subjected to combined wind and wave loads according to irregular Pierson-Moskowitz spectrum. In this paper, the extreme values are obtained by fitting the peaks in the tail regime using a Weibull-distribution. While one obtains Gaussian responses under the survival loads, the operational conditions have non-Gaussian responses and also larger than survival ones.

Darie and Rörup (2017) presented the paper deals with the current efforts to address the complexity of calculation of extreme loads associated with non-linear finite element structural analysis. A hydrodynamic approach based on 3-D Rankine method is used. The generated loads for critical load case are transferred to a global structural FE model. Finally, using the non-linear finite element method, the hull girder ultimate capacity of container ship is calculated. Investigation on HGULS (Hull Girder Ultimate Strength) margins against the direct calculated load obtained by spectral approach was carried out for three large container ships. The calculated loads (EDW; Equivalent Design Wave) are higher than allowable loads given by UR S11 A, since the IACS routing factor is ignored in this investigation. The FE results, in terms of capacity usage factors, show for these three container ships, that the oblique seas, particularly 60 deg. wave heading can be important for HGULS assessment. The presented effects of oblique sea on HGULS assessment are covered in the existing rules, UR S11 A, by a partial safety factor for the vertical wave bending moment.

5.3 Design Load Cases and Ultimate Strength

Various design loads used in the strength assessment of ship structures have been introduced by classification societies. Most of these design loads have been determined as standard loads. Ultimate strength design assigns each load with a load factor and combines the resulting modified load values in various ways. The hull girder strength is the most critical failure mode for the hull structure and the design load conditions are the key factors for the ship ultimate strength analysis.

Ozdemir et al. (2015) presented the results of new method depends on the estimated buckling strength values. If the estimated buckling strength is closer to the those of FEM calculations, ultimate strength by the new method would be more accurate. However, in case of stiffened panels with many stiffeners and thinner plate, derived formula underestimated the buckling strength as well as ultimate strength. This may be attributed the underestimation of effective breadth of slender plates beyond local plate buckling.

Naruse and Kawamura (2015) presented that the reduction of ultimate strength and reliability index of the two bulk carriers after similar scale collision is computed and compared. Residual rate of ultimate strength, RSI. of the bulk canier after CSR is larger than the bulk carrier before CSR. However, reliability index of the bulk carrier before CSR is larger. Reduction of ultimate strength and reliability index after corrosion is computed and compared. It is found that good effect for corrosion by using double hull structure.

Tunea and Uguflu (2015) conducted a series of nonlinear finite element analyses to determine the effect of system parameters on load-carrying capacity of stiffened plates. Ultimate strength investigation on multi-parameter space is performed by regression analyses provided that the parameters have linear relation. The increase of both plate slenderness and stiffener slenderness affects the ultimate strength negatively. The ultimate strength is more sensitive to the variation of the stiffener slenderness compared to the plate slenderness. The stiffener-to-plate area ratio and slenderness ratio have similar influences on load-carrying capacity. The ultimate strength decreases with the increasing parameters.

Kotajima et al. (2016) presented that the non-linear FEA is carried out by using a commercial FEM software, LS-Dyna, in order to understand the longitudinal collapse behavior of the amidship section structure of a container ship under the dynamic loading. The half-sinusoidal loads of hogging moment with different period were applied to the ship structure. It is found that the residual deformation after the loading is different if the period or amplitude is different. It is concluded that the effect to the ultimate strength is very small, while there is a possibility of small increase of ultimate strength under the dynamic loading with short period compared with that under the quasi-static load.

Rajendran et al. (2016a) presented a body nonlinear numerical method based on strip theory to analyze the vertical responses of a bulk carrier, container ship and a passenger ship. The numerical ship responses in abnormal waves and extreme sea conditions are also compared with the measurements in a wave tank. The pronounced bow flare induces strong nonlinearities in the vertical responses in rough seas and the linear or evenpartially body nonlinear methods are not enough for accurate calculations in those conditions. Rajendran et al. (2016c) presented the same code was used to calculate the vertical responses of a container ship in extreme sea conditions including abnormal waves. The study emphasized that for ships with large bow flare and in extreme sea conditions, the body nonlinear hydrodynamic forces played a significant role on the load acting on ships.

Peschmann et al. (2016) presented the new developed requirements of the UR S11A on existing containership designs. It is shown that even though the load requirements have changed significantly, the impact on the existing designs is limited and the safety margin of existing ships can be judged as appropriate. It is emphasized that the consequence on actual design scantlings could be limited by considering permissible hull girder values that more closely reflect the actual still water bending moments and shear forces along the hull. The new developed requirements in the UR S11A are more transparent, consistent and ship specific. In addition, it extends and harmonises the application of some key elements of the CSR and applies them to container ships. In connection with the new requirement UR S34, a significant step has been made to align requirements to enhance the safety of new innovative containership designs.

Fischer et al. (2016) developed a simplified procedure for the determination of the ultimate load and associated spindle torque of propeller blades. Various FE analyses were carried out to investigate the elasticplastic load-carrying behavior of propeller blades. The results obtained with the simplified procedure show good agreement with nonlinear FE analyses of a blade candidate where reduced spindle torque is observed due to failing local section. The ultimate blade load associated with the bending moment may be calculated using the shortest distance between failing section and load application point, with an allowance of 5% to avoid nonconservative results in sections with pronounced curvature.

Peschmann and von Selle (2017) considered the experience gained during the implementation phase of the GBS Standards from a Classification Society perspective following the initial verification. The IMO Goal Based Standards for Bulk Carriers and Oil Tankers (GBS) were adopted and implemented in the SOLAS convention. IACS developed the Common Structural Rules for Bulk Carriers and Oil Tankers (CSR), which included GBS considerations. IACS and the individual member Classification Societies submitted the CSR to the IMO for the GBS verification audit and the GBS initial verification audit confirmed that the CSR complies with the GBS. Therefore, the linkage between the CSR and the GBS were confirmed.

Zhang et al. (2017) presented an overview of recent investigations on the ultimate strength of hull girders and the attention has been particularly paid on large container ships hogging bending. Through the limited number of analyses on larger container ships, it is seen that the CSR method gives 10% to 15% higher than FE results and the LR 20202 method for hull girders' ultimate capacity in hogging bending. For hull girder collapse analysis of large container ships in hogging conditions, a double bottom factor of 1.15 is a first good approximation. However, initial analysis using simplified analytical methods show that the double bottom factor is in the range of 1.1 to 1.2 for container ships between 3600 TEU to 22 000 TEU.

Fang et al. (2017) predicted the structural responses of a high-speed monohull with different wave amplitudes. The hydrodynamic loads of a high-speed monohull have been simulated with different wave amplitudes and applied to the FEM model for the structural response calculations in regular design waves. Based on the numerical predictions, the longitudinal stress RAO (Response Amplitude Operators) increase in sagging condition when the wave amplitudes increase. Furthermore, the longitudinal stress RAO decrease in hogging condition when the wave amplitudes increase. The nonlinear effects of structural responses for a high-speed monohull are significant with various wave amplitudes in design wave conditions.

Kim and Paik (2017) presented that the aim of this paper is to develop a fully automated methodology for the optimum design of hull structural scantlings for merchant cargo ships. The ships are modelled by plate-shell finite elements. A full optimization technique with multi-objectives is applied for minimizing structural weight and maximizing structural safety. The developed procedure is applied to the hull structural scantlings of a very large crude oil carrier (VLCC), and this test demonstrates the procedure's capacity to meet the strength requirements of common structural rules. The proposed procedure reduces the number of man-hours required by about 20%, lightens the structural weight by 3% and improves the safety factors for the critical members.

6. FATIGUE LOADS FOR SHIPS

It is understood from previous ISSC Loads Committee Section that fatigue design most often requires the assessment of a lifetime vertical bending moment histogram for a ship. The lifetime bending moment histogram summarizes the ranges of bending moment magnitudes and their corresponding number of cycles expected during the ship's service life. These bending moments include those due to changes in wave height and slam induced whipping. Typically, the longitudinal bending moments and shears are determined from the weight and buoyancy distributions, treating the ship as a free-free beam. In many cases, the effects of lateral bending and/or torsional loadings may not need to be included when computing the lifetime stress histogram for a monohull due to the fact that the most important internal forces and moment on a monohull are the vertical shear and longitudinal bending moment obtained in head and following sea. However, the effects of transverse moments, horizontal bending moment and torsion are significant for vessels with large deck openings, e.g. container ships, or also for multihull designs such as catamarans or trimarans due to the presence of side hulls and the cross structures between the hulls. Multihulls are subject to more primary types of wave loads than monohulls. Since the interaction and phasing of multihull loads cannot be easily described by generalized formula, it is expected that direct hydrodynamic and structural analysis methods will be increasingly used to determine the resulting spectrum of stress cycles at the locations of interest within the hull structure. The complication arises because the various primary loadings are acting at different magnitudes and frequencies that superimpose each other as they combine and interact to produce a certain stress variation at the structural detail of interest. Smaller cycles from the less dominant primary loads are expected to combine with the more dominant primary loads. The slowly varying narrowband response and associated Rayleigh distributed extreme assumptions usually made for monohull responses to an active seaway, would thus be inappropriate for multhulls. As a multihull form encounters and responds to an active seaway at specific speeds and headings, the main structural members of the ship are loaded in numerous ways. E.g. for a trimaran, the forward monohull portion of the hull is loaded by the familiar longitudinal vertical and longitudinal lateral bending moments produced by vertical and lateral shear forces, as well as torsion about the longitudinal axis. These loadings, of course, continue aft into the trimaran portion but are influenced by the presence of the outer hulls. The outer hulls themselves can respond in a number of ways, whether in-phase or out-of phase with one another and the center hull. In addition, the presence of the center hull obviously shelters one of the outer hulls depending on the heading, so there is likely also a leeward and waveward component to the outer hull loadings. Be that as it may, the loadings associated with the outer hulls are pitch connecting (torsional moment about the transverse axis relative to the center hull), transverse bending (prying and squeezing of the outer hulls about a longitudinal axis), and splaying (torsion of the outer hulls relative to the center hull about a vertical axis). Aside from identifying bending moments associated with each type of outer hull primary loading, it is not known whether these bending moments are the result of vertical forces, lateral forces, or some combination of both. In fatigue loading, for a trimaran there are six dominant types of loadings to consider; three associated with the center hull and three associated with the outer hulls. These six primary bending moments include vertical bending moment, lateral bending moment, torsion, transverse bending moment (prying and squeezing), pitch connecting moment (relative pitch) and splaying moment (relative yaw).

The majority of loads imposed on trimarans are cyclic in nature therefore the possibility of failure by fatigue is possibly higher. Indeed, in general, most structural failures that occur in service life of a ship result from fatigue. While there is a large knowledge on the fatigue performance of conventional designs, there is very little work done and little knowledge in relation to multihull structures.

In the study by Shehzad et al. (2013), an attempt has been made to utilize the linear seakeeping code ANSYS AQWA, 3D, potential flow theory, frequency response functions to compute the ship response to a sinusoidal wave with unit amplitude for different frequencies and wave headings. Then, the stress transfer functions are calculated by global FE analysis of the trimaran. The study also investigates the effect of Wirsching's rain flow cycle correction factor and contribution of fatigue damage caused by individual heading direction towards cumulative fatigue damage of the hot spots. According to the calculation results, it is also concluded that for the given structural design the connection of cross deck and wet deck with the main hull and the connection of the main hull with the wet deck at the transverse bulk head suffers maximum fatigue damage. Moreover, the predicted fatigue life was found to be considerably less than the design life of the vessel, which indicated the need to enhance the structural design at these particular locations. Therefore, the authors recommend that the fatigue strength assessment of trimaran cross structures should be analyzed by direct calculation methods at the initial design stage.

A study by Liao et al. (2015) compared different methods to determine the global loads for fatigue assessment and the resulting predicted fatigue life time. They compared the stillwater and wave loads provided in the IACS harmonized common structural rules (CSR-H) for bulk carriers and tankers with the loads from spectral analysis and an equivalent design wave approach. They observed significant differences in the load spectra derived by the different approaches and, consequently, also large variations regarding the predicted fatigue life time at the analyzed hot spots. The authors conclude that further work is necessary to ensure that similar results are obtained with different methods for load determination and that care must be taken that the differences of the approaches regarding the methodology to determine the overall fatigue life time, must be properly considered.

The study from Thompson (2015) validated the spectral fatigue analysis software, STRUC_R, developed by Cooperative Research Ships (CRS) using a naval vessel sea trial data. The root mean square (RMS) longitudinal stress and zero-crossing frequency calculated using spectral fatigue analysis software for one dimensional long crested sea and two-dimensional wave spectrum models are compared with measured data to better quantify the uncertainty introduced by one dimensional wave spectra. The comparison results indicated the use of one dimensional long crested wave spectra tended to over predict RMS stress and under predict zero-up-crossing frequency. Although the use of two-dimensional wave spectra reduces the uncertainty in spectral fatigue analysis, similar results are shown using either set of wave spectra.

Different to the work discussed so far the study from Bigot et al. (2016) focusses on local rather than global effects of wave induced loads. The authors discuss the influence of intermittent wetting at side shell stiffeners in vicinity of the waterline and several models which have been developed to account for the resulting nonlinear effect in fatigue strength evaluation procedures, emphasizing also the differences obtained by using regular and irregular seaway.

Also, Wang W. et al. (2016d) investigated local effects of cyclic wave loads. They evaluated the contribution of ship motions to the fatigue life reduction of pre-swirl stator fins (devices arranged upstream of the propeller to enhance propulsion efficiency) using a hybrid approach (potential viscous flow coupled CFD). The study also evaluated a boundary element method (BEM) on predicting the hydrodynamic loads on the fins. The BEM prediction was roughly 20% less than CFD which is considered a reasonable conservative fatigue life estimate given the advantage of much shorter computational time. Further it was shown that the cyclic loads on the fins caused by ship motions were very small, hence, ample safety margin against fatigue damage due to this kind of hydrodynamic load was found.

So far from most research has focused on providing more accurate experimental and/or numerical predictions of ship motions/vibration and thereby more reliable fatigue loading induced by wave loads. However, in recent years also the accompanying linear damage accumulation models have received some attention, discussing the influence of the time sequence of loads and the load history regarding acceleration/retardation of the propagation of wave induced cracks. In this context Oka et al. (2015) pointed out the importance of hull girder vibration on ship fatigue strength. The study examined the fatigue strength using three types of stress wave form, the measured time histories (RAW), the Low Frequency (LR) wave form obtained by removing the high frequency component by low-pass filter, and the envelope wave form of the measured time histories (ENV). The results showed that the fatigue damage) calculated by the RAW waveform was approximately twice the damage calculated with the LR wave form, however the difference between RAW and ENV was not significant. Furthermore, the authors discuss the differences in damage prediction using the conventional Miner approach in comparison with crack propagation analysis taking account of the time sequence of loads. They found significant differences regarding the predicted fatigue life time.

Hodapp et al. (2015) proposed a nonlinear crack growth model based on finite element analysis of plasticity-induced crack closure instead of the classical Miner approach for calculation of structural damage due to seaway loads. The authors claim that simple instances of variable amplitude loading are analogous to typical ship loading sequences through so-called “storm model” loading. In contrast to previous studies, this approach is readily generalized as it relies solely on material constitutive model. The proposed storm load model facilitates ship fatigue life prediction (crack propagation phase) in which both the order of the loading (load sequence effects) and material hysteresis (load interaction effects) are included. By application of the storm model it was shown that load sequence and load interactions effects are first order phenomena and must be considered in fatigue life prediction and that the results may differ considerably from those obtained with classical approaches.

Independently from the determination of wave induced fatigue loads or the different approaches for the estimation of the fatigue life time, in general, fatigue failure is prevented by controlling the working stress range. Usually the most efficient way to control stress is to either increase local scantlings or modify geometry to reduce stress concentrations and discontinuities. In the overall process of structural design the prevention of fatigue falls mainly within the scope of detail design. But for cyclic stresses that are not locally controllable, such as wave-induced hull girder stresses, care must be taken to ensure that these stresses remain sufficiently small so as not to cause fatigue in the hull girder.

7. UNCERTAINTY ANALYSIS

This section reviews only uncertainties related to wave-induced loads, loading conditions and uncertainties due to operational factor.

7.1 Load uncertainties

To assess the reliability and quantification of risks associated with complex marine structures and systems, it is essential to understand and quantify uncertainty involved (Papanicolaoua et al., 2014). For the design of a safe ship, it is necessary to assess the reliability of seakeeping analysis and wave load estimation as well as operational conditions in which the ship should perform its mission.

Wave loads uncertainty may be classified in two main groups (Guedes Soares, 1996): uncertainty of linear theory based model and uncertainty of non-linear effects. The main source of uncertainty in both linear theory and non-linear effects calculation is uncertainty related to metocean description. It is expected that this uncertainty will represent the largest challenge for the shipping, offshore and renewable energy industry in the future (Bitner-Gregersen at al., 2014). Generally speaking, uncertainties may be classified into two groups: aleatory and epistemic. Related to metocean description (Bitner-Gregersen at al., 2016), aleatory uncertainty (natural and physic) takes into account natural randomness of random variable, such as variability of wave intensity in time. This uncertainty is also known as intrinsic or inherent and cannot be reduced or eliminated. Epistemic (knowledge based) uncertainty can be reduced by collecting more information as well as by improving the applied models. This uncertainty can be: data related, statistic related, model related or due to climatic variability. Data related uncertainties refer to imperfection of measured data or numerically generated data (or combined – the gap between measured data is filled by numerically generated data). Uncertainties due to insufficient number of data and applied technique for obtaining the probability density function parameters are statistic uncertainties, while imperfection, simplification and idealisation made in physical model for an event, choice of probability density function as well as climate variability are model related uncertainties. Bitner-Gregersen at al. (2016) use different wave data and models for specifying design and operational criteria for two types of marine structures and discuss different associated uncertainties.

Lu et al., (2017) and Sasa et al. (2017) have analysed three extreme cases of bulk-carrier sailing during storms at Southern Hemisphere. They reproduced the environment by three different wind inputs with various spatial and temporal resolutions. The simulated waves (wave hindcasts) and ship responses were validated and compared using measured on-board ship motion data. The compared data show significant uncertainty related to weather database, as well as seakeeping theory and speed prediction technique.

It is important to assign an uncertainty measure to the waves and responses that are being estimated as a base for ship motion and loads evaluation. Real time estimation of waves and ship responses using on-board measurements has been under investigation in recent years (Nielsen, 2006; Montazeri et al., 2015; Pascoal et al., 2017). In general, two main concepts have been applied to estimate the on-site directional wave spectrum on the basis of ship response measurements: a parametric method which assumes the wave spectrum to be composed by parameterised wave spectra; or a non-parametric method where the directional wave spectrum is found directly as the values in a completely discretised frequency-directional domain without a priori assumptions on the spectrum.

A proper prediction of responses due to extreme waves is important for ship safety in extreme sea. Guo et al. (2016) address statistical description of heave and pitch motions and vertical bending moment in extreme sea states by taking an LNG tanker as an example. Wada et al. (2017) proposes a practical approach to extreme value estimation for small samples of observations with truncated values, or high measurement uncertainty, facilitating reasonable estimation of epistemic uncertainty.

Uncertainty in linear theory calculation is closely related to calculation of transfer functions. According to Temarel et al. (2016) primary uncertainties sources in numerical seakeeping analysis are related to different mathematical modelling of (initial) boundary value problem, different numerical modelling of the assumed mathematical model, non-converged or in accurate hull geometry modelling, insufficient or incorrect knowledge regarding mass distribution and human, i.e., user error.

Uncertainty of non-linear effects may be classified in two groups: different sagging and hogging value in bending moment and influence of slamming and whipping on extreme bending model.

Numerical nonlinear time domain simulation methods is developed to assess slamming-induced hull whipping on sectional loads of three containerships in head seas (el Moctar et al., 2017). The effect of the nonlinear vertical wave-induced bending moments on the chemical tanker hull girder reliability are accounted for in the reliability assessment problem through model correction factors, which are estimated using direct calculation methods based on linear and nonlinear strip theory formulations and the most likely response wave method (Gaspar et al., 2016).

As a part of an ISSC–ITTC benchmark study which was intended to analyse the accuracy of the numerical methods and the uncertainty involved with the predictions of the ship responses, Rajendran and Guedes Soares (2016a) analysed the symmetric distortions of a container ship in large amplitude waves which are by means of time domain code coupled with a finite element model. Rajendran et al., (2016b) used linear to fully body nonlinear numerical methods based on strip theory to analyse the vertical responses of a bulk carrier, containership and a passenger ship. The ships are categorized based on their bow flare angles and the effects of the bow flare variation on the vertical responses are investigated numerically. It is proved that pronounced bow flare induces strong nonlinearities in the vertical responses in rough seas and the linear or even partially body nonlinear methods are not enough for accurate calculations in those conditions.

7.2 Uncertainties in Loading conditions

Loading conditions and the corresponding loads are important for the safety of ships. Although uncertainty of loading condition have been identified by industry as a considerable problem, and not only in the context of the recent ship accidents of MOL COMFORT and MSC NAPOLI (Temeral at al. (2016)), these uncertainties are rarely covered by scientific research. The problem is difficult to analyse because of lack of statistical data related to problem. Such data is difficult to collect partly because of the difficulty in fully understanding the loading/unloading operation process and partly because of intrinsic uncertainties in measuring cargo loading conditions data.

The study of Gaggero et al. (2017) reports a analysis on the uncertainties in assessing loading conditions of handy size bulk carriers. The authors analyse the uncertainties in hold/tank filling level and uncertainties in centre of gravity. In an investigation on loading conditions of three handy size bulk carriers, a total number of 209 voyages was considered in a span of 22 months. Statistical analyses were carried out, aimed at providing information on the uncertainties in the calculations of the hull girder still water loads. Probability distribution functions were proposed to statistically describe the uncertainties of ship draft, filling level of cargo holds and tanks, corresponding weights and centre of gravity positions.

7.3 Uncertainties due to operational factor

The long-term prediction of wave induced hull girder loads considering the effect of various operational circumstances should give a relatively more realistic evaluation of the extreme hull girder loads. However, these circumstances are not easy to foresee. Acero et al. (2016) developed the methodology for assessment of the operational limits and the operability of marine operations during the planning phase. Prpić-Oršić et al. (2014) have presented the real life operation of ultra large container ships from the point of view of shipmasters. The paper provides some insight in uncertainty related to master decisions during voyage.

The speed at which ship would sale is important parameter in seakeeping analysis especially whenever the nonlinear effects are taken into consideration (Guedes Soares, 1996). The choice of design speed or speed profile during life time of the ship is important decision which have consequences in long term predictions and it is a key factor for ship route planning (Mao et al., 2016) and ship route optimization (Vettor&Guedes Soares, 2016).

8. CONCLUSIONS

Regarding computation of wave induced loads, the potential flow model remains, in general, one of the dominated efficient solvers for numerical simulation of wave-body interactions at zero speed, including the influence of a range of nonlinearities. Therefore, further development of 3D potential theory method is still valuable. The versatility and increased accuracy of RANS solvers for capturing important characteristics of wave-body interactions has been demonstrated. For further development and enhancement of numerical methods for the computation of wave loads should continue. For the further investigations to establish more reliable numerical tools, experimental and numerical study should cover a variety range of nonlinearities.

Regarding Slamming and Whipping, Studies in this reporting period was focused on improving the Generalized Wagner Model and CFD tool. Furthermore, some studies focused on the application of CFD tool on investigation of slamming and whipping related phenomena. It is expected that further study should be continuously conducted to clarify slamming phenomena itself and the effect of whipping on real ship such as container ships.

Regarding Sloshing, main theoretical and experimental interests were on the interaction between sloshing and global ship motions and sloshing suppression using baffles in this reporting period. Model testing has been mostly used to observe the physics of the sloshing-coupled ship motion problems, to investigate the efficiency of sloshing suppression, and to obtain validation data for the numerical tools.

Not only theoretical and experimental study but also numerical studies for various type of numerical approach were investigated. Numerical methods developed for sloshing simulation can be categorized under two groups: studies based on the potential flow assumption, with or without the inherent nonlinearities, and studies that involves the viscous effects. The fluid-structure interaction was also considered in some numerical models.

In addition to above studies, Baffled sloshing suppression is still a very active field that researchers proposed new analysis tools, relying on both potential and viscous flow models, to investigate the special aspects of the problem or to analyse different configurations.

Regarding Green Water, some numerical studies were conducted in this reporting period. Because green water is very difficult to measure either under laboratory conditions or in the field, and very difficult to simulate numerically, it is expected that continuous studies should be conducted.

Regarding full scale measurement, it is remarkable that most of measurements focused on wave induced vibration. It is preferable that full scale measurement for wave induced vibration gives a better picture of the typical wave loads experienced during normal service than model tests since they must not rely on assumptions regarding the operational profile, the encountered wave environments and so on. It is expected that further investigation should be continued.

Furthermore, further utilization for warning systems on excessive ship motions and/or loads are focused in this reporting period. It is remarkable to clarify the relation between ship response and encounter wave quantitively in some of those studies.

Regarding Loads following damage, load implications on the ship after accidental damage remained an area of concern to the design and operation of ships. Accidental damage to ships and, subsequent, flooding can occur in number of ways, but generally damages due to collision and grounding are most frequently observed. Based on these background, research focused on these types of damage scenarios in this reporting period.

Regarding VIV, many studies are conducted in this reporting period. Most of the recent works on calculation methods, which were focused in this report, have been performed on: frequency domain (FD) or time domain (TD) semi-empirical models and computational fluid dynamics (CFD) methods. At this moment, there is still rooms for the modification of the accuracy of direct simulations due to the very complex nature of the fully coupled hydro-elastic response. On the other hand, a joint industrial and academic effort has focused on providing the guideline on analysis of vortex-induced vibrations in a riser and an umbilical for best practices in terms of structural modelling, current profile description, heave induced VIV, fatigue calculation and VIV suppression.

Regarding VIM, through comparison CFD analysis with model test results and prototype data for a range of structures, it was concluded that whereas scale effects, the presence of waves and the effect of current unsteadiness is of minor importance, the effect of additional damping from risers, mooring lines and other sources have a significant effect on the VIM amplitudes.

Scale effects were investigated directly by comparing CFD results at model scale and full-scale Reynolds number. It was acknowledged, however, that this observation is at odds with other published results and that further investigation is necessary.

The accurate quantification of the prototype damping level has been highlighted as a remaining challenge. Particularly, importance on a deep draft semisubmersible has been highlighted. Through a careful CFD analysis fully coupled with the mooring and riser system and compared the VIM results with an uncoupled analysis, it was concluded that the damping introduced by the mooring lines and the risers had the potential to significantly reduce the VIM amplitudes.

Regarding Mooring Systems, research generally focuses on a range of methods for coupling the dynamics of mooring lines, floaters and risers and assessing the validity of partly, fully coupling methods, as well as frequency, time and hybrid frequency/time domain approaches. In addition to the continuous those studies, challenging studies were conducted for design of marine energy converters mooring systems and effective computation for mooring systems with many mooring lines and risers, especially when coupled computations are needed.

Furthermore, research into different materials, and their properties, used in mooring lines, e.g. Synthetic fibre ropes, high modulus polyethylene (HMPE) ropes and so on, is of great importance in terms of including in the dynamic simulations and assessment of fatigue damage.

Regarding lifting systems, numerical simulation models and tools and advanced study to develop reliable flexible multibodies system dynamic models were reported in this reporting period.

Regarding wave in deck loads in fixed platforms, intensive studies were conducted and in this reporting period by Joint Industry Project (JIP). Remarkable outcomes were obtained both of methodology including by means of CFD and of the establishment of procedures by the classification societies.

Regarding floating wind turbines, prototype of floating wind turbines were installed with different type of floaters, and long term operational tests in actual sea are being conducted in this reporting period. It is necessary to assess the validity of design wave and design loads based on the feedback of full scale measurement of constructed floating wind turbines in near future.

Regarding probabilistic model of loads on ships, the focus of investigations within this reporting period has been on equivalent design waves and evaluation of design loads introduced by classification societies. It is expected that further investigation on probabilistic methods which can assess design waves and design loads more quantitatively in near future.

Regarding fatigue loads for ships, efforts within this reporting period were focused not only on providing more accurate experimental and/or numerical predictions of ship motions/vibration and more reliable fatigue loading induced by wave loads but also on investigating the influence of the time sequence of loads and of the load history relating with the propagation of wave induced cracks. Further investigations are expected to clarify the fatigue strength of a ship by accounting for stress histories which are effective in crack initiation and propagation.

Regarding uncertainties analysis, some analysis related to wave-induced loads, loading conditions and uncertainties due to operational factor were conducted. However, findings are limited in some parts of uncertainties. It is preferable that further study should be conducted particularly, for example, uncertainties in the application of model tests and numerical results in real operation of ship and floating structure.

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