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COMMITTEE II.2
DYNAMIC RESPONSE

COMMITTEE MANDATE

Concern for the dynamic structural response of ship and floating offshore structures as required for safety and serviceability assessments, including habitability. This should include steady state, transient and random responses. Attention shall be given to dynamic responses resulting from environmental, machinery and propeller excitation. Uncertainties associated with modelling should be highlighted.

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KEYWORDS

Dynamic response, springing, slamming, whipping, hydroelastic response, vibration, natural frequency, noise, underwater noise, sloshing impact, blast, underwater explosion, ice, wind, wave, current, internal flow, vortex, damping, excitation, propeller, machinery, numerical model, model test, full-scale measurement, monitoring, resonance, fatigue damage, assessment, acceptance criteria, countermeasures, uncertainty.

CONTENTS

1. INTRODUCTION

In the recent years major challenges of marine industry, as observed by the 2009 and 2012 II.2 Dynamic Response committee, were originated from energy and environment issues: to enhance energy efficiency in shipping, to explore and produce resources in deeper sea and arctic region, to reduce adverse impact on environment, especially as regards the emission of greenhouse gases and noise, and to utilize the Northern Sea Route in commerce. These have motivated the following trends:

- increase in ship sizes to benefit from economy of scale,
- modification in ship propulsion system including energy-saving devices mainly aiming at reduction of fuel consumption and use of cleaner fuels instead of bunker-C oil,
- development of larger vessels for shipping in ice-covered and/or ice-infested waters,
- development of offshore structures for deeper water and Arctic Ocean mining against extreme environmental loads,
- production of offshore renewable energy, especially through offshore wind farms,
- safer shipping and ocean mining against environmental, operational or accidental loads,
- introduction of new mandatory or stricter regulations, standards and rules to protect environment or to reduce adverse impact on human beings and ocean wild life.

These trends were also reflected in the active research and their publications concerning the dynamic response of ships and offshore structures in the review period. This report is divided into two Chapters to account for the difference of dynamic responses between ship structures and offshore structures. The Chapter on ship structures was subdivided into 9 Sections that range from environment-induced vibration (wave- and ice-induced vibration) to standards and acceptance criteria. Special attention is paid to the Sections for environment-induced vibration, noise, sloshing impact and monitoring since they have been main research topics of the past years. The Sections for sloshing impact and monitoring to avoid repetition introduce a few literatures related to offshore structures because their technologies can be applicable for both ship and offshore structures. The Chapter on offshore structures was subdivided into 7 Sections. The Section on vibrations treats dynamic response to environmental excitations (wind, wave, vortex, ice) and operational excitation (internal flow), in which the 2015 II.2 Committee has reviewed vortex-induced motion of large floating offshore structure instead of vortex-induced vibration of slender structure since a new special V.8 Risers and Pipelines committee in ISSC 2015 was mandated to covering their dynamic response. This report cites and reviews 503 references of which 418 references are published from 2012 to 2014.

2. SHIP STRUCTURES

Dynamic response of ship structures can be caused by environmental condition such as wave, ice, machinery, propeller, and impact loads due to sloshing, air blast, under water explosion and so forth. Many researches have been carried out mainly from the viewpoint of structure excitation load and structural response. Aspects of them are various in type of ship. In this period, many researches in terms of dynamic response have been mainly focused on unconventional ships and large ships.

2.1 Environmental-induced vibrations

2.1.1 Wave-induced vibration

Wave-induced vibration of ships can occur in two different forms, denoted as springing and whipping. Whereas springing is a resonance phenomenon, where the wave loads excite one of the lowest natural frequencies of the hull girder, whipping is a transient phenomenon, where rapidly changing wave loads excite one or more vibration modes. In both cases, the fundamental 2-node vertical mode is the most important, although higher bending modes as well as torsion modes may also be excited. Also, researchers differentiate between linear springing, where the encounter frequency of seaway components with short wave lengths is in resonance with the natural frequency of the basic hull girder mode, and nonlinear or sum frequency springing, where the periodic vibration excitation forces act with a higher order of the wave encounter frequency. The former can be predicted by linear hydrodynamic theories, while the latter depends on second order hydrodynamic effects; e.g., superposition of different wave systems. Whipping responses may arise due to different impulsive loads, such as underwater explosions (see e.g. Liu et al. 2012), but in this section we consider whipping due to wave loads only.

In the last decade we have seen an increasing concern for springing and whipping in very large containerships (VLCS) and ultra-large containerships (ULCS). These ships have very pronounced bow flare, high speeds and relatively low natural frequencies in the lowest bending and torsion modes.

There seems to be a common agreement that the springing and whipping vibrations can contribute significantly to the fatigue damage of large containerships. This is supported by a number of full-scale measurements.

It is also evident that the high-frequency component of the vertical bending moment due to whipping can be about as large as the wave-frequency component due to the continuous wave-loads, and that the total bending moment can sometimes exceed the rule design values.

However, the importance of the high-frequency oscillations in the bending moment for the collapse mechanism of the hull girder is not yet fully investigated. It is not clear how much the limited energy associated with the high-frequency whipping vibrations contribute to the global hull girder collapse. Iijima et al. (2011), Iijima & Fujikubo (2012), Xu et al. (2012) and Iijima et al. (2013) found through experiments that the hull girder collapse mechanism will not have time to develop significantly before the whipping load starts to decrease, and that the extent of the collapse under whipping is much smaller than under conventional wave loads. Hence, they state that the risk of collapse in an extreme slamming event is much smaller than that under wave-frequency loads with the same amplitude.

Jiang & White (2012) studied stiffened panels under dynamic compression loading by a non-linear finite element code and they found that the ultimate strength under dynamic load is higher than under a static load; partly due to strain-rate effects and partly due to inertia effects.

Some questions have also been raised to the estimated importance of the springing and whipping vibrations for the fatigue damage based on rainflow counting and the Miner-Palmgren rule. Kahl et al. (2013) comment that the fatigue damage rates estimated based on full-scale measurements on containerships subjected to wave-induced vibrations are not reflected in the observed damages on the fleet in service. Hence, fatigue tests were undertaken with stress histories simulating wave-frequency and high-frequency stresses (Fricke & Paetzold 2012) and with stress histories from full-scale measurements (Fricke & Paetzold 2013, 2014, Kahl et al. 2014). They found that most of the fatigue damage is caused by the wave-frequency stress cycles, enlarged by whipping, as long as the whipping stress amplitudes are smaller than the wave-frequency stress amplitudes. The contribution from the additional small stress cycles due to whipping is rather small. A similar conclusion was also reached by Fukasawa & Mukai (2013).

Full-scale measurements

A large number of full-scale measurement campaigns have been reported recently. Analysis of these data gives information on the contribution of ship vibrations to fatigue and extreme loads for various ship types, as well as information on the importance of different parameters such as ship length, speed, bow flare angle, wave and wind conditions and trade area. Some recently reported measurements are:

- 2800 TEU containership (Storhaug 2012)
- 4400 TEU containership (Storhaug 2012)
- 4600 TEU containership (Kahl et al. 2013)
- 278 m containership (Nielsen et al. 2011)
- 281 m containership (Toyoda et al. 2012)
- 284 m containership (Toyoda et al. 2012, Ogawa et al. 2012)
- 302 m containership (Ogawa et al. 2012)
- 8000 TEU containership (Koo et al. 2011)
- 8600 TEU containership (Barhoumi & Storhaug 2013)
- 9300 TEU containership (Koning & Kapsenberg 2012)
- 9400 TEU containership (Renaud et al. 2013, Andersen & Jensen 2013, 2014)
- 14,000 TEU containership (Kahl et al. 2013)
- 98 m wave-piercer catamaran (Jacobi et al. 2014)
- 119 m Cutter monohull (Drummen et al. 2014)
- 274 m LNG (Storhaug et al. 2012, 2013)
- Large blunt vessel (Storhaug & Hareide 2013)

Many of these papers report that, for large containerships, high-frequency vibrations contribute significantly to the fatigue damage (typically 30–50%) and quite a few of them report that the IACS rule bending moments are exceeded; some even in relatively moderate conditions (e.g. Barhoumi & Storhaug 2013). Storhaug et al. (2013) reported that vibrations contribute in the range 30–50% to the fatigue damage also for a 274 m LNG vessel with lower flare angle than a containership. Also for a blunt ship, the contribution from high-frequency vibrations in fatigue was in the same order (Storhaug & Hareide 2013), and whipping stresses in excess of the rule-value were reported.

Andersen & Jensen (2014) found that even if the ship was sailing in bow quartering seas, only the 2-node mode seemed to be excited. This was also observed by Koning & Kapsenberg (2012), and by Storhaug & Moe (2007). Koning and Kapsenberg suggest that it can be a consequence of large damping in torsion due to the container stacks. The structural damping in steel is low, and a significant contribution to the total structural damping comes from the cargo. Typical damping is in the range 1–3% of critical damping (Storhaug & Moe 2007). A method for estimation of damping from full-scale measurements using Proper Orthogonal Decomposition (POD) is described by Dessi (2013).

Model tests

Model tests described in the recent literature mainly concern segmented models with an elastic backbone (BB), or with flexible hinges. The use of fully flexible models has not been reported during the last few years. A major portion of the models represent large containerships, but some other vessel types have also been studied. Some of the model tests referenced in the recent literature are:

- 130 m River-Sea link, Segmented BB (Peng et al. 2014)
- 290 m academic design, Segmented BB (Iijima et al. 2009)
- 4400 TEU containership, Hinged (Storhaug 2007)
- 5000 TEU containership, Segmented BB (Takaoka et al. 2012)
- 8600 TEU containership, Hinged (Storhaug et al. 2010a)
- 9300 TEU containership, Segmented BB (Kobayakawa et al. 2012)
- 9400 TEU containership, Segmented BB (Maron 2012)
- 10,000 TEU containership, Segmented BB (Kim, B.W. et al. 2014)
- 13,000 TEU containership, Hinged (Storhaug et al. 2010b)
- 13,000 TEU containership, Segmented BB (Takaoka et al. 2012)
- 112 m high speed catamaran (Lavroff 2009, Davidson et al. 2013, Thomas et al. 2011)
- 45 m high speed monohull, Hinged (Wu & Stambaugh 2013)
- 113 m monohull (frigate), Segmented BB (Bennett et al. 2014b)
- 125 m monohull (cutter) (Drummen et al. 2014)
- 260 m monohull (JHSS), Segmented BB (Piro et al. 2012)
- 333 m VLCC, Segmented BB (Wang, X. et al. 2014)
- High speed ferry, Segmented BB (Dessi & Ciappi 2013)

Practically all these models were instrumented for vertical hull girder responses, such as the Vertical Bending Moment (VBM). Some of the containership tests also focus on asymmetric responses in oblique seas. This introduces challenges in the model design, since the shear center of the open ship sections is located below the hull bottom. Kim, B.W. et al. (2014) tested a 10,000 TEU containership segmented backbone model with two different backbone cross sections: U-shaped and H-shaped. Whereas the vertical responses were not influenced by the cross section types, the measured torsional responses were significantly influenced. Another challenge with torsion measurements is how to derive the torsional moments at stations along the hull from the measured strains in the backbone. Kim, B.W. et al. (2014) investigated different loading modes used in converting strains to torsional moments. Hong et al. (2011) reported, for the same model (with H-backbone), that direct use of torsion strains instead of torsion moments may give a more accurate interpretation of the torsion response. Tiphine et al. (2014) report from the same model (with U-backbone), and they demonstrate that different longitudinal distributions of the torsional moment can give rise to the same strains at a particular cross section. Hence, they recommend and validate a new method (Bigot et al. 2011) using a base of distortion modes to take all strain gauges into account simultaneously.

The models with flexible hinges have the advantage that the hinges can be made with adjustable stiffness. The problem of connecting the backbone to the hull segments without disturbing the measurements is also avoided. However, modelling torsion with a low shear center and appropriate coupling with horizontal bending seems difficult with hinged models. It was shown by Wu et al. (2012) that for a monohull it is sufficient to use 3 hinges if the hydroelastic effects mainly originate from the 2-node vertical mode. It was also shown that hydroelastic effects in the vertical bending moment are not sensitive to the stiffness distribution among the flexible hinges, so the same stiffness may be used for all 3 hinges. This conclusion was also made by Takaoka et al. (2012) based on tests with segmented backbone models of 5000 TEU and 13,000 TEU containerships.

Methods for assessment of mode shapes and associated damping during model and full-scale tests are presented and discussed in Mariani & Dessi (2012), Dessi & D'Orazio (2012), Dessi (2013). A new system for measuring motions and hull girder deformations during springing and whipping model tests was presented by Bennett et al. (2014a), while Kim, Y.I. et al. (2013) described a method for identifying whipping events using wavelet cross-correlation.

Zhu & Moan (2013a) analysed the test data from the 8600 TEU and the 13,000 TEU hinged models (Storhaug et al., 2010a, b) in head seas. They found that while the total dynamic sagging moment amidships is significantly larger than the total dynamic hogging moment at a forward speed of 25 knots, the difference is insignificant at a speed of 15 knots. Nonlinear wave forces that increase the sagging moment, such as bow flare slamming, increase more rapidly with the speed than do the forces which increase the hogging moment. Hence, with a realistically moderate speed in severe seas, accounting for voluntary speed reduction, the difference between the dynamic sagging and hogging moments may be lower than reflected by current computer tools and rule formulas. Zhu & Moan (2013b) discuss possible reasons for the relatively high nonlinear hogging moments observed in some model tests and full-scale measurements, and they suspect that it may be due to the suction force in the bow during water exit. It is well known that there is a downwards added mass force during water exit, and this force increases if the hull has a relatively wide flat bottom in the foreship. It was observed by Zhu et al. (2011) that for a model with such a flat forward bottom area, the dynamic hogging moment was approximately 30% higher than the sagging moment. The difference disappeared when the bow was replaced by a version with smaller flat bottom and larger flare (Zhu & Moan 2012).

Zhu & Moan (2013b) analysed the test data from the 13,000 TEU hinged model in oblique seas (Storhaug et al. 2010b). It was found that the nonlinearities causing ship vibrations are more pronounced in long crested seas than in short crested seas. Hence, model tests in long crested seas may slightly exaggerate the effect of the high-frequency vibrations.

It was observed by Zhu & Moan (2012) that whipping vibrations in torsion are sensitive to bow shape. When a bow with larger flare was introduced, the torsional whipping increased significantly. From the same model tests, Zhu et al. (2011) found that the hydrodynamic damping in the torsion modes is almost negligible compared to that in the vertical and horizontal bending modes. Torsional vibrations were most pronounced in waves from 30 degrees off the bow.

Based on the tests of 4400 TEU, 8600 TEU and 13,000 TEU hinged models, Storhaug (2014) concluded that bow flare angle is the main factor for the importance of whipping, whereas vessel size is less important. Similar findings were reported by Takaoka et al. (2012) from tests with 5000 TEU and 13,000 TEU ship models. Storhaug (2014) also found that extrapolating 20-year design values from a Weibull-fit of the model test data gave dynamic hogging moments that were well above the IACS URS11 design moments. Voluntary speed reduction will influence the results and should be further documented.

Piro et al. (2012) observed whipping responses in head irregular waves that reached almost the same amplitudes as the wave-induced bending moment. The tests were done with a segmented backbone model of a 260 m monohull. The backbone had non-uniform stiffness along the length.

Tests of a segmented monohull with a non-uniform-stiffness backbone were also reported by Dessi & Ciappi (2013). They found that the slams were grouped into clusters, and thus violating the hypothesis of mutual independence between successive impacts that form the basis of many statistical models. Hence, within a cluster, the whipping oscillations are not damped out before the next slam occurs.

Bennett et al. (2012, 2014b) used a segmented flexible backbone model with uniform stiffness of a 113 m frigate to measure hull girder bending moments in head seas and study the effect of abnormal waves.

Thomas et al. (2011, 2012) and Lavroff et al. (2013) reported on model tests with a segmented flexible-hinge model of a 112 m high-speed wave-piercer catamaran in head regular and irregular waves.

Hong et al. (2014) studied bow flare slamming forces and pressures from experiments with a 10,000 TEU containership. They concluded that slamming pressures increase strongly with ship forward speed, and that they are sensitive to variations in the instant surge velocity.

Numerical methods

Hydroelastic response calculations involve a structural model of the ship, a hydrodynamic model of the fluid and a method for coupling the two models to ensure that the interaction effects are properly captured. The following paragraphs give a summary of the status and recent developments in these methods.

The structural model is usually a 3D Finite Element Model (FEM) or, for monohull, a beam model. The most common beam model is based on the Timoshenko theory, but for cases involving torsion and warping, more advanced models are applied (e.g. Vlasov theory). Senjanovic et al. (2012a, b) present a new theory for thin-walled girders taking into account shear influence on torsion as well as the contribution from structural discontinuities, such as bulkheads and the engine room structure, to the hull stiffness. A new structural model that accounts for warping and structural discontinuities is presented and compared with alternative methods in Miao et al. (2012). Alternative methods for structural modelling are also discussed in Kim, J.H. et al. (2013a).

A common method for fluid-structure coupling is the modal approach. An aggregate of the natural modes of the "dry" structure is used to represent the global structural deformations. To avoid convergence problems it may be useful to apply the hybrid method presented by Wu & Moan (2005). Alternatively, the pressure distribution from the fluid model is transferred to the structural model (together with accelerations) and the hull deformations are transferred from the structural model to the fluid model for every time-step. Comparison of different structural modelling methods and coupling methods used with a RANSE-solver for the fluid are presented by Oberhagemann & El Moctar (2012) and Oberhagemann et al. (2012a). Based on the modal approach Senjanović et al. (2012a, b, 2014a, b) performed linear springing analyses of 7800 TEU and 11,400 TEU container ships combining advanced beam model, with the above mentioned improvements and 3D potential flow code. Firstly, they compared their results with rigid body calculations, and secondly a comparison with fully coupled 3D FEM-BEM (Boundary Element Method) from Bureau Veritas tool is done. They reported good correlation at the global assessment level. However, for stress concentration assessment and fatigue analysis some improvements are still necessary.

Lee, Y.W. et al. (2014) investigated methods to determine the springing response for fatigue assessment. Fluid Structure Interaction (FSI) models are used to investigate nonlinear wave actions and wave induced global loads acting on large container ships. Time domain simulation techniques in critical wave frequencies are employed to investigate effects of springing on design bending moments of a large container ship based on the Lloyd's Register 2014 Rule requirements for container ships that mandate springing fatigue analysis for large container ships. It was found that the fatigue life is reduced due to the inclusion of springing effects on a large container ship. The analysis indicated that the effects of springing for the sample container ship accounted for approximately 20 per cent of the predicted fatigue life for the components considered. Hence the fatigue life calculated by standard methods which do not include springing effects have to be multiplied by 0.8 to obtain an estimate of the fatigue life including springing.

Kashiwagi & Hara (2012) presented a computer code for the analysis of ship hydroelastic problems, based on the Rankine panel method in the frequency domain and the mode superposition method for representing the elastic deformation of a ship. 3D FEM commercial code is used to compute the dry eigen-frequencies and corresponding elastic mode shapes. As a numerical example, a 2-meter modified Wigley model advancing in head waves at Fn = 0.2 is considered, and verification has been made by presenting the wave pattern on the free surface generated by the forced oscillation with elastic modes and by confirming the convergence in the amplitudes of elastic modes as the mode number increases.

Kim, J.H. et al. (2012) performed springing analysis of a VLCS based on hybrid BEM-FEM method, investigating influence of different beam modelling and structural damping on the results. They compared motion RAO and the load signal time-histories with experimental data, providing discussion on discrepancies.

Kim, K.H. et al. (2013) analysed hydroelastic response of two real container ships in head seas, i.e. 6500 TEU and 10,000 TEU, respectively, using partitioned method, where the fluid domain surrounding a flexible body is solved using a B-spline Rankine panel method, and the structural domain is handled with a three-dimensional finite element method. The two distinct methods are fully coupled in the time domain by using an implicit iterative scheme. The numerical results of natural frequency and the motion responses of simple and segmented barges are computed to validate the present method through comparisons with experimental and numerical results.

Proper assessment of vessel motions is a prerequisite for correct slamming and whipping calculations. Hence, the developments in seakeeping methods described in the report of the Loads committee are also relevant for whipping. In whipping calculations two main types of fluid methods are applied: (i) boundary methods, where the unknowns are on the boundaries of the different domains and (ii) field methods, where the unknowns are distributed throughout the volume of the domains.

When using the boundary methods, like strip theory or 3D panel methods, violent local flow phenomena, such as slamming is treated by separate methods and the associated forces are added to the forces obtained from the global boundary method. For the field methods, like RANSE-solvers, the violent local flow phenomena are in principle implicitly included in the overall method, but these phenomena may still need special attention regarding grid and time-step resolution.

Since slamming in the bow is the main source of wave-induced whipping responses, it is important to assess the slamming forces in a sufficiently accurate and practical manner. Water entry is often studied by 2D methods, since 3D calculations add significant complexity the problem.

The most common method for calculation of the slamming forces has been the von Karman momentum approach, where the forces are obtained as the rate of change of the high-frequency added mass as the bow enters the water. The method is normally applied to ship sections in a two-dimensional manner, as recently exemplified in Wu et al. (2012), Wu & Stambaugh (2013) and Rubanenco et al. (2013). The method may also be applied in three dimensions, as in Ćorak et al. (2013), where they approximate the bow of a containership with a half-cone, which in turn is represented by a half-disc for which an analytic added mass formula is used (Jensen & Pedersen 2009).

In the von Karman approach, the pile-up of water around the body is neglected, and this is known to give too low slamming forces. Hence, the two-dimensional Generalized Wagner Method (GWM), first introduced by Zhao et al. (1996), has become popular. In contrast to the momentum methods, the GWM also gives the pressure distribution on the hull section and it can therefore be used in local slamming analyses as well as in whipping assessment. Application of the GWM in head seas whipping analysis of large containerships is presented by Kim, J.H. et al. (2013a, b) and Kim & Kim (2014). They also do calculations with a 2D von Karman based momentum method, where the added mass is calculated analytically by approximating the section with a wedge. From analyses of 6500 TEU, 10,000 TEU and 18,000 TEU containerships they concluded that both these 2D slamming methods give similar whipping responses, and that they compare reasonably well with experiments for low and moderate ship speed. For a speed above 20 knots, the methods tend to overestimate the whipping responses. It was assumed that this could be attributed to the exclusion of 3D flow effects.

In some recent whipping calculations (e.g. Tiphine et al. 2014) the so-called Modified Logvinovich Model (MLM) has been used. The MLM (Korobkin & Malenica 2005) is a simplification of the GWM in the sense that it includes the water pile-up, but the pressure is calculated on a flat-plate extending between the two body-water intersection points, rather than on the exact body surface. Hence, the MLM is primarily applicable to blunt sections.

Ogawa & Takagi (2012) use the "Displacement Potential Approach" (Takagi & Ogawa 2007, Ogawa & Takagi 2009) for slamming force calculation on a large containership. From comparison with measurements in regular head waves they concluded that the agreement was good for the whipping responses. Lee, Y.W. et al. (2012) use "Generalized Momentum Theory" (Tuitman 2008) in whipping analysis of a 13,000 TEU containership, but no validation is presented. This latter theory is also used by Lee et al. (2011) on the WILS-II 10,000 TEU containership in head regular and irregular waves, and reasonable agreement with measurements was reported.

A 2D slamming method is expected to give too high slamming loads, since the flow is restricted to a 2D plane. This was pointed out as a possible reason for overestimation of whipping responses by Kim, J.H. et al. (2013a, b) and Kim & Kim (2014) when using a 2D GWM. On the other hand, a von Karman momentum approach will underestimate the slamming loads since the water pile-up is neglected. This was pointed out as a possible reason for underestimation of whipping responses by Andersen & Jensen (2012) when using a 2D momentum method. Since the effects of the 2D approximation and the von Karman approximation act in opposite directions, one could have hoped that a 2D von Karman method would give reasonable results for practical applications. However, this is apparently not the case in general. Another alternative is to use the GWM and then apply correction factors for 3D effects based on geometric considerations (e.g. Hermundstad & Moan 2005), but there are many uncertainties in using such correction factors.

Another aspect related to whipping is that a 2D slamming analysis for a vertical ship section will produce only vertical slamming forces, while a bow slamming event would also give forces in the ship's longitudinal direction. Wu & Stambaugh (2013) made an empirical correction to the 2D bow slamming forces on a high speed monohull, so that the slamming force got a component in the longitudinal direction, and this improved the agreement between the measured and calculated vertical bending moments. A more rational correction could have been obtained with a 2D GWM, since the pressure distribution is then available and the longitudinal force could have been found from integration on the 3D geometry of a slice of the ship. Again there are uncertainties associated with such corrections.

Another way of adjusting the 2D slamming methods to better account for the realistic flow pattern and the effects of forward speed, is to use 2D sections that are inclined towards aft rather than being vertical. This is used by Bigot et al. (2011) with a 2D GWM, and reasonable agreement for whipping in head seas is obtained for the WILS-II 10,000 TEU containership. The same method is used by Tuitman et al. (2013), and they also do analyses in oblique waves where the sections are rotated about a vertical axis, so that they become parallel with the wave crests. The method is applied to a 144 m frigate, but no validation is presented. Tilting the 2D sections in order to better capture the direction of the main flow during slamming is an engineering approach, but it is difficult to determine what is the most appropriate tilt angles (see e.g. Hermundstad et al. 2002). Hence, this is yet another approach associated with uncertainties.

To overcome the problems associated with the 2D methods, efforts are made to develop practical 3D boundary methods for slamming. Introducing the third dimension into e.g. the generalized Wagner formulation, adds considerable complexity to the problem. One example is the work of Chezhian (2003). Recently however, Tassin et al. (2012) have presented some promising results for a 3D generalized Wagner formulation.

Due to the difficulties of generalizing the boundary methods for slamming from 2D to 3D, it is tempting to resolve to a field method, like e.g. a Finite Volume Method (FVM) solving the RANS equations. Hence, there are many papers on field methods applied to bow slamming. Another advantage of these methods is that they can generally handle flow separation from e.g. bulbous bows during violent slamming events.

Many studies of 2D problems, with the purpose of validating field methods, have been presented. Wang & Soares (2013) compared results from the FEM code LS-DYNA with the 2D ship-section drop tests of Aarsnes (1996). The results from LS-DYNA do not appear to compare better with experiments than do those from a BEM based on GWM. Yoshikawa & Maeda (2013) applied LS-DYNA to water entry of a rigid and an elastic wedge. Good agreement with a Wagner solution for the rigid wedge was documented, but no other validation was presented.

Veen & Gourlay (2012) use a 2D Smoothed Particle Hydrodynamics (SPH) method and compare with the 2D drop tests of Aarsnes (1996), and quite good agreement was reported. They also applied the method to a hull section with a relative velocity taken from seakeeping experiments with a 120 m monohull by Hermundstad & Moan (2005), and the agreement was good. The method was also combined with a strip theory and pressures were compared to tests by Ochi (1958), but then the agreement was less favourable. It was recommended to extend the SPH method to 3D and to use it for slamming calculations together with a less resource demanding method for ship motion calculations.

Southall et al. (2014) applied a FVM-based RANSE-solver (based on OpenFOAM) to wedge impacts at different angles and compared with model tests (MOERI 2013). The Volume of Fluid Method (VOF) is used for free surface capturing. The intention is to use the method together with ship motion software to predict whipping. However, some discrepancies with the 2D wedge tests were found.

Another application of OpenFOAM software is presented by Piro & Maki (2011, 2013). The method is applied to a rigid and an elastic 2D wedge. Good agreement with a Wagner solution for the rigid wedge during water entry is documented. They also study water exit and it is shown that large forces occur in this phase. It can be important to account for these water exit forces in practical whipping analysis in order to accurately predict the hogging moments. A 2D method for water exit was presented by Korobkin (2012), and results agreed well with those from OpenFOAM (Piro & Maki 2011).

Rahaman et al. (2012) use a FVM-VOF-based RANSE-solver (WISDAM-X) to study the bow flare slamming on a containership. Good agreement is found when comparing with results for a 2D section from Zhao et al. (1996). In the 3D containership case, results are compared with 2D analyses with the commercial code FLUENT, and differences are documented. This may be due to 3D effects.

An overset grid method with a level set function for free surface capturing (FANS) is applied by Lee, S.K. et al. (2012) and by Chen & Chen (2014) to study bow and stern slamming of a containership. Yang et al. (2013) use the commercial FVM-VOF-based RANSE-solver STAR-CCM+ together with FEM to analyse slamming pressures and structural responses in the bow of a containership. In these papers, no validation is presented.

A common approach in whipping analysis is to first calculate the linear hydrodynamic forces in frequency domain using a 2D strip theory formulation or a 3D panel method. Next, the linear frequency-domain results are transferred into time-domain, as proposed by Cummins (1962). The motion equations are then integrated in time, and nonlinear modifications to the forces are added to the linear force vector at each time-step. Nonlinear hydrostatic forces and Froude-Krylov forces are normally included, since this is straight forward. Moreover, slamming forces must be included. An overview of different refinements in the use of boundary methods in hydroelastic analyses is given by Malenica & Derbanne (2012).

Tiphine et al. (2014) analyse the 10,000 TEU WILS III-JIP containership model (U-backbone) by using a 3D BEM method combined with a 3D FEM model of the structure. Coupling is performed by the modal approach. The frequency-domain hydrodynamic solution is transformed to time-domain and nonlinear Froude-Krylov forces are added. Slamming forces are calculated by the 2D MLM. Quite good agreement with experimental VBM whipping responses in head and oblique regular waves is obtained, while the agreement for the torsional whipping responses is less favourable. A similar approach is used for the same containership by Bigot et al. (2011), except that they used 2D GWM for slamming. Some limited comparisons are made with earlier model tests (with H-backbone) and reasonable agreement is found for VBM whipping in head and oblique regular and irregular waves. Torsion whipping in oblique irregular waves shows less agreement. More validation is needed to conclude on the performance of this method.

The same 10,000 TEU containership is analysed by Lee et al. (2011) using a similar method, but with a Timoshenko beam for the structure and a “Generalized Momentum Theory” for slamming. Reasonable agreement for VBM whipping in head regular and irregular waves was demonstrated for a few sample time-windows. The same method is used by Lee, Y.W. et al. (2012) for a 13,000 TEU containership in head seas without comparing with measurements.

Kim, J.H. et al. (2013a, b) and Kim & Kim (2014) use a method similar to that of Bigot et al. (2011) in the analysis of the same containership. They found quite good agreement for the whipping VBM in head waves, but they concluded that the whipping responses at the highest speed (20.3 knots) were slightly overestimated when using the 2D GWM. A simplified 2D von Karman based momentum formulation for slamming with wedge-approximation of the section gave slightly better agreement. It was suspected that 3D effects reduced the slamming loads in the experiment, as discussed above.

Wu & Stambaugh (2013) apply the nonlinear strip theory code WINSIR to a 25 m high speed monohull in head seas. A beam model is used for the structure, and coupling is performed by the hybrid modal approach (Wu & Moan 2005). The frequency-domain solution is transformed to time-domain and nonlinear modifications to the hydrostatic and Froude-Krylov forces, as well as 2D von Karman momentum-based slamming loads are added. Comparisons with model tests of a 25 m high-speed monohull in irregular waves showed that the measured and simulated standard deviations of the wave-frequency and the high-frequency part of the VBM agreed well. However, it was found that the theory generally underestimated the extreme sagging moments, while it overestimated the extreme hogging moments in various sea-states. One possible explanation was that the longitudinal component of the bow slamming force is neglected in the 2D slamming calculations. By using an empirical adjustment of the slamming force, the simulated sagging moments increased and compared better with experiments.

Field methods have become increasingly popular in recent years, and e.g. FVM-VOF-based RANSE-solvers are applied to slamming and whipping problems by several research groups.

Ship motion and whipping analyses with RANSE-solvers have been performed in regular and in irregular long crested waves. The main focus has been on head seas (e.g. Oberhagemann & El Moctar 2012, Oberhagemann et al. 2012a, Seng et al. 2012) , but recently Oberhagemann et al. (2012b) present results from oblique regular waves for the 10,000 TEU ULCS tested in WILS-II. Results are promising, but there is little severe slamming and whipping in the cases studied. An exception is Bertram et al. (2011) that show a time series including a few whipping events in head waves. They also discuss the challenges related to calculation of the bow flare slamming forces with the VOF-method due to the transition between fluids with two different densities. Forces during water exit however, are not discussed, although the simulations include water exit events.

Instead of using a RANSE-solver for the complete whipping problem, one may use a simpler method, e.g. strip theory, for ship motion calculations and then apply the RANSE-solver to the local bow slamming problem only (e.g. Rahaman & Akimoto 2012).

An alternative field method is presented by Mutsuda et al. (2012). This is a coupling of the SPH particle method and the Constrained Interpolation Profile (CIP) grid method, and it is partly motivated by the challenges of accurately capturing violent free surface flows, like slamming, with the VOF-method. Some comparisons with model tests where a segmented backbone model is dropped into calm water show quite good agreement in hull girder load effects. The method is also applied to simulate an elastic ship in waves involving bow slamming and wave breaking, but without comparison with measurements.

Practical assessment of extreme hull girder load effects including whipping

The available computer tools for assessment of wave-induced load effects differ significantly in computational efficiency. The linear frequency-domain strip theories are efficient and can be used to estimate load effects in a large number of combinations of loading condition, speed, wave heading and sea-state. The nonlinear time-domain boundary methods require higher resources and can be used to generate long time-series in a number of selected conditions. Finally, some of the most refined methods, like the RANSE-solvers, can only be used to study a few events covering a few wave cycles. There are several recent papers focusing on ways of using the various simulation methods in a practical design process.

A review of alternative ways of using a combination of fast and computationally demanding simulation tools is given by Schellin et al. (2013).

Oberhagemann et al. (2012c) use two different methods, the coefficient of contribution method (Baarholm & Moan 2000) and the response conditioned wave episodes method, together with two computer codes; a linear zero-speed 3D BEM and a RANSE-solver, in order to obtain extreme load effects in ships. A method based on extrapolation of response upcrossing rates in sea-states is applied by Oberhagemann et al. (2013) to study hogging moments in two containerships. It is based on analysis of available Monte Carlo simulation results and the application of a RANSE-solver. Another method based on upcrossing rates is presented in Mao & Rychlik (2012).

Derbanne et al. (2012) and De Hauteclocque et al. (2012) discuss and compare different ways of establishing design waves. They conclude that the static regular design wave gives very poor results for the effect of nonlinear Froude-Krylov loads, and it is unable to compute whipping responses. Methods based on a dynamic response on a regular design wave or a response conditioned wave give better results, even for extreme whipping responses. The latter of these two is not much more demanding to apply, and it is therefore recommended even though it does not give significantly better results. It is reported that much more accurate results are obtained when the simulations are done in an irregular sea-state with an increased wave height. Increasing the wave height decreases the return period of a given linear extreme, and hence decreases the required duration of the simulation. Using simulations in artificially increased wave heights is also discussed by Jensen (2010).

2.1.2 Ice-induced vibration

Compared to operation in open water, vibrations of vessel operating in ice conditions are significantly increased because of the ship hull and propellers interacting with ice. These increased vibrations may cause fatigue damage of structures, equipment failure and also create unfavourable conditions for crew habitation. Belov & Spiridonov (2012) analysed features of vibrations recorded on icebreakers and ice-going ships and the reasons for its amplifications, and presented estimation methods for excitation forces and vibration levels in ice conditions. Some methods of reducing hull vibration and the effects of vibration on the crew were proposed in the paper.

Pressure distribution and structural response in ship-ice interaction are two important topics in model tests and numerical simulation of ship-ice studies.

Kujala & Arughadhoss (2012) conducted a series of model tests for two different ship models to measure ice-induced pressure distribution using I-Scan 210 tactile sensors which were placed in bow, bow shoulder, midship, and aft of the models. A statistical method was used to analyse ice crushing pressure in level ice and compared with full-scale measurements. It was found that the line load shape as a function of the nominal load width and load level was comparable with the full scale data, and the crushing pressure can be compared with full scale data.

Sawamura (2013) predicted distribution of ice pressure along the waterline when a ship advanced into level ice based on his numerical code for ship maneuvering in level ice. The structural response of a stiffened panel under the calculated ice pressure distribution was analysed by a linear elastic FEM. He pointed out that the shape and the location of the ice pressure area had strong influence on the structural response.

Quinton et al. (2012) conducted a numerical study of ship structural response by using two 'realistic' ice load models (crushable-foam ice model and 4D ice pressure model) in LS-DYNA software. In the simulation, these two 'realistic' moving ice load models generated ice pressure distributions in accordance with actual laboratory and field observations and coupled the normal and tangential components of the moving loads. Simulation results showed that these realistic models agreed with the findings of the previous work, that is, moving loads cause substantially more damage than stationary loads.

Gagnon & Wang (2012) conducted numerical simulations of a tanker collision with a bergy bit. The ship response in the ice contact part was predicted. In the simulation, the major portion of the vessel was treated as a rigid body and a portion of its bow where the ice contact occurred was modelled as a typical ship grillage that could deform and sustain damage. A load measurement from the laboratory tests compared reasonably well with a rough estimate from the simulation. The numerical techniques should make simulating a wide variety of ice interactions with vessels feasible.

2.2 Machinery or propeller-induced vibrations

2.2.1 Propeller-induced vibration

For the propeller-induced vibrations, the excitation forces are transmitted into the ship via the shaft line and in the form of pressure pulses acting on the ship hull. The shaft line forces are mainly responsible from the vibrations of shaft lines, and the propeller-induced pressure fluctuations from the vibrations of ship structures.

Van Esch et al. (2013) used CFD to compute the hydrodynamic coefficients for torsional and axial vibrations for a Wageningen B-series of ship propellers in open-water condition. In their method of analysis, the coefficients for added mass and quasi-steady fluid induced damping are determined by a proper selection of the value of the reduced frequency. It was shown that the unsteady vortices in the wake of the propeller have an effect on both magnitude and the phase of the fluid induced fluctuations in thrust and torque.

Zhang, G. et al. (2014) introduced a transfer matrix method for a propulsion shafting system in order to describe its dynamic behaviour. Using hydrodynamic lubrication theory and small perturbation method, the axial stiffness and oil damping were deduced and the foundation stiffness was estimated by finite element method. Based upon these values, the Campbell diagram describing natural frequencies in terms of shafting rotating speed were obtained. The effect on the 1st natural frequency of considerable variations in thrust bearing stiffness was investigated. It was found that the amplitude of variation of the 1st natural frequency in range of low rotating speeds was great.

Lee, K.H. et al. (2014) developed a numerical prediction method for estimating the hull pressure fluctuation induced by propeller sheet cavitation. In this study, the combined hydrodynamic and hydro-acoustic method was employed to predict the pressure fluctuation caused by a volume variation in the propeller sheet cavitation. The developed numerical method and findings are useful sources for predicting the hull pressure fluctuations induced by a propeller at the design stage.

Song et al. (2014) investigated a performance of a periodic isolator to reduce the vibration and noise radiation of an underwater vehicle caused by propeller forces. A simplified physical model of the underwater vehicle is developed first. The isolation performance of the periodic isolator is investigated and compared with the traditional homogenous isolator. In the study, an integrated isolation device was proposed.

Wei & Wang (2013) investigated the unsteady hydrodynamics of the excitations from a 5-bladed propeller at two rotating speeds running in the wake of a small-scaled submarine and the behaviour of the submarine's structure and acoustic responses under the propeller excitations. The propulsion is simulated using computational fluid dynamics, so as to obtain the transient responses of the propeller excitations. Finally, the structure and acoustic responses are predicted using a finite element/boundary element model in the frequency domain.

Lee et al. (2013) studied the correlations between the propeller cavitation induced pressure fluctuation measurement in a cavitation tunnel and full-scale data. Two major considerations were attempted for the conventional test technique. One is to immerse the model ship deeper than its scaled design draught so that the boundary layer effect can be minimized in the area of propeller disk. The second is to avoid the resonance frequency range of model ship by adjusting propeller RPM. The approaches taken in this study would provide a systematic method for a full scale correlation enhancement.

2.2.2 Machinery-induced vibration

The trend in shipping towards larger and more fuel efficient ships with lower speeds led to new engine developments with ultra-long stroke and low revolution rate, e.g. like the MAN G-type engines. Compared with the former engines like MAN's S-type engine, the new G-type engines offer a higher power at lower engine speeds. As expected, this changes the main engine's external forces and moments transmitted to the ship hull. The increase in guide force moment between the G and S type can be a factor of 1.25 to 1.5, depending on ratings.

In MAN Diesel & Turbo (2014), a study with special attention towards the structural vibrations related to this excitation source is given. Both global hull vibration response and local main engine vibration performance was measured and analysed for a 64,000 dwt bulk carrier equipped with a 5G60ME-C9 engine. For this class the 5S60ME-C8 type engine was a widely applied for propulsion plant. Compared with an average vibration level for an S-type engine, it is stated that the hull and engine vibration performance has been improved for the G-type engine based on a comparison of the 5th order vibration levels at the same percent of MCR speed (100% G-type 77rpm at 8500kW; 100% S-type 105rpm at 11,300 kW). A possible explanation might be that the disadvantage of higher forces is compensated by lower rpm and also possibly higher safety margin to engine's H-type natural frequency.

Engine excited vibration of slow running two stroke engines is mainly transmitted into the hull structure via their foundations and top bracings. Top bracings are widely used to control H-mode resonance of large two stroke main engines and to reduce the vibration of the engine itself in transverse and sometimes also in longitudinal direction. Two types of top bracings have been widely used: the Mechanical type Top Bracing (MTB) with a friction connection and the Hydraulic type Top Bracing (HTB). When MTBs are installed, it is relatively easy to predict vibration characteristics through modal analyses with the assumption of linear axial stiffness. However, because a HTB includes mechanical, hydraulic, and pneumatic valve and chamber systems, the nonlinearity of the axial stiffness makes it difficult to quantitatively estimate the detuning effect.

Lee et al. (2010) carried out dynamic compression tests of HTB. They proved that the axial stiffness of HTB, which shows high nonlinearity according to exciting amplitudes, is independent of exciting frequencies. Jin et al. (2010) tried to prove the force-carrying mechanism by deriving the equivalent compressive stiffness of the HTB. Choung (2013) reports that the complex operation mechanism can be idealized by a piecewise linear stiffness curve. However, if the excitation force at the running speed range does not exceed the static setting force the operating mechanism will stay within the static load stage so that the HTB behaves like the MTB. The setting force is expected to be exceeded in case of resonance condition only. In this case, the governing load stage will be shifted to the light load stage, and thus the natural frequency of the system will be changed. Since the aim of the HTB is to detune the system a high setting force may be preferable. It should be noted that the dynamic behaviour of the HTB will strongly vary depending on its individual design being different for different suppliers. None of the publications addresses the damping effect of hydraulic top bracings.

Behaviour of passive resilient mountings changes according to the frequency of the exciting force and may be not accurately predicted by numerical simulations. However these data are needed for appropriate selection with respect to structureborne noise and vibration. In order to achieve the dynamic transfer properties of resilient mountings for medium speed marine diesel engines, laboratory tests are to be carried out. Moro et al. (2013) describe the theoretical background for evaluating the interaction between the resilient mounting and the diesel engine foundation along with the fundamentals for acquiring data on the dynamic behaviour of resilient mountings by means of laboratory tests.

2.2.3 Numerical and analytical vibration studies of ship structures

Due to increased awareness of comfort issues it would be beneficial to begin vibration analyses already in the earliest design phase. However, limited time and resources prevents usage of detailed finite elements analyses. Method suitable for conceptual design should produce reliable and useful information in basis of limited knowledge about the structure.

Laakso et al. (2013) introduce an analytical method for calculating the fundamental frequency of an orthotropic stiffened cabin deck. The fundamental mode is assumed to be either transversal or longitudinal global mode, or local deck plate mode. Shapes of the global modes are approximated by applying Newton's laws of motion, and static beam and plate theories. The shape approximations include local deformations of the deck plate and its stiffeners. Rayleigh's method is used to calculate corresponding eigen-frequencies of the approximated mode shapes. The presented method is validated by finite elements method. Sufficient accuracy is obtained for structural analyses in conceptual design. Furthermore, the paper shows that the effect of local deformations is significant in certain cases.

Brubak et al. (2013) present an approximate, semi-analytical computational model to solve the eigenvalue problem based on the Rayleigh-Ritz method for plates subjected to in-plane loading. The model may handle complex plate geometries, by using inclined stiffeners to enclose irregular plate shapes. Relatively high numerical accuracy is achieved with low computational efforts.

Cho et al. (2014b) present a procedure for the vibration analysis of stiffened panels with arbitrary edge constraints. It is based on the assumed mode method, where natural frequencies and modes are determined by solving an eigenvalue problem of a multi-degree-of-freedom system matrix equation derived by using Lagrange's equations of motion. The Mindlin thick plate theory is applied for a plate, while the effect of stiffeners having the properties of Timoshenko beams is accounted for by adding their strain and kinetic energies to the corresponding plate energies. A comparison of results with those obtained by the finite element method is provided and good agreement is achieved. An extension of this procedure for vibration analysis of plates with openings and arbitrary edge constraints is presented by Cho et al. (2014c) as well as the consideration of contact with fluid on one side by Cho et al. (2014a).

Senjanović et al. (2013) deal with simplified geometric stiffness formulation which has some advantages in hydroelastic analysis comparing to the consistent mass matrix determined by the shape functions of all degrees of freedom used for construction of conventional stiffness matrix, or with a lumped mass matrix related to deflection degrees of freedom.

Jeong et al. (2013) investigated the fluid coupling effects in tank with stiffened plates by measurement and numerical analysis through FEM applying the Helmholtz method used by MSC.Nastran. The natural frequency in first mode of the measured is near in phase mode of FEM analysis. The analysis results show that the effect of added mass parameter increases according to the fluid depth and the increase is steady at some extend depth. Also the natural frequency of out-of-phase mode decreases lower than that of in-phase mode because the out-of- phase mode makes the fluid movement restrained more and the inertial force larger.

Neto et al. (2012) analysed the influence of the kinetic energy of the fluid adjacent to the hull of a tanker ship in its vertical vibration frequencies and compared them with experimental measurements obtained during sea-trials. The calculations were performed by the added mass formulations from different referenced approximations like Burrill, Todd, Kumai and Lewis/Landweber. The results showed that the theoretical formulations for obtaining added mass provide reliable results. The formulation of Kumai for this case was the most suitable, probably because it is a specific formula for oil vessels. The other formulations also showed comparatively close to the measurement results, although they are more indicated for general cargo ships.

Generators can be a serious vibration source, giving the supporting structure is an important role in ensuring an acceptable vibration level e.g. at the crew's working and livings spaces. Daifuku et al. (2014) studied on a bulk carrier the optimization of the reinforcement configuration of the engine room using topology optimization to improve the anti-vibration characteristics. The vibrations were reduced by about 10% while the total weight was reduced by 8% of the original structure.

2.3 Noise

Traditionally, ship noise control is intended as protection of crew and passengers and improvement of habitability and comfort on board, as well as reduction of underwater noise for navy vessels. As already pointed out in the last ISSC 2012 report, the recent trend in this field is to regard noise as a large spectrum problem, thus including also the protection of the external environment intended as coastal environment (ports, coastal aerial) and underwater wildlife.

As showed by many researchers, the actual status of the research in those different directions is not consistent and reflects the different histories that every field had in the past.

The interior noise has been studied since the first vessel has been fitted with an engine, initially with regard to the protection of the seafarers and later to establish comfort criteria for both passengers and crew. A complete set of design tools and regulations are available and so broadly used that today arises the question if they are still valid or need to be refreshed.

The exterior airborne noise is, on the opposite side, the newest field of application and suffers of a big lack in design tools and rules. It has been recognized to be a problem only recently and efforts are being made to establish a common basis to deal with it.

Underwater Radiated Noise (URN) has been studied since many years mainly within the scope of military application and consequently many results are not public. The civil application of studies in URN is mainly addressed to the protection of the wildlife fauna from the noise pollution and so also the research method and scopes are rather different.

2.3.1 Interior noise

The interior noise is maybe the oldest field of application and has a complete set of regulations, which are nowadays put under discussion to prove their response to the actual status of the technological development.

Analysis methods and applications

In Seiler & Holbach (2013a, b) the A-weighted sound pressure level is put under discussion to check if it is still a suitable parameter for the judgment of the overall noise comfort on board. With the help of audio records on a real ship and with a listening test of 30 people, they tested different psychoacoustic parameters like loudness, sharpness and other more, to find out whether more sophisticated indicators can better describe the noise situation of a vessel. The result was that, even if some parameters can be taken into account, the A-weighted sound pressure level confirms its validity.

A similar interrogative is studied in Badino et al. (2012a) where a large overview among the existing regulations and limits for the different impact fields of ship noise is presented. With regard to the internal noise, several methods and well established normatives are present. However, there are still some aspects of the characterization of the internal noise that are unclear and for which a more detailed description is missing (e.g. tonal components of noise). Also the well-known overall dB(A) level is put under discussion with regard to its capability to describe the noise phenomena on board. The authors also presented a wide study on the existing regulation framework for the noise emitted from ships, both radiated inside and outside the ship, as well as underwater. They argue that the actual degree of knowledge (and consequently of active regulations) of the different impacts of the noise emitted is quite different and reflects the different amount of time elapsed since their effects have been recognized to be negative. Airborne noise transmitted and radiated inside the ship has been broadly studied since many years and from different points of view, ranging from the safety and health in the crew's working areas to the comfort of passengers on board. Regulation on the matter are well established and constantly updated.

On the other side, Badino et al. (2012f) presented psychoacoustic criteria taken from the civil engineering field, and particularly the Room Criteria Mark II as highly valuable to describe the acoustic comfort on board due to their improved capability to describe side effects like spectrum characteristics, low frequency annoyance, etc.

Turan et al. (2011) have performed a comparative study regarding the effectiveness of IMO 468 among other normative, confirming the need for an update of the IMO rule. Noise measurements have been carried out on six ships of similar characteristics (oil and chemical tankers, LOA ranging between 106 and 148 m) during sea trials and the results analysed with IMO 468 and EU directive 2003/10/EC on noise exposure of workers finding that ships easily fulfilling the IMO limits are not compliant with the EU rule.

Stritzelberger et al. (2013) proposed an alternative method to the classical FEA/SEA (Finite Element Analysis/Statistical Energy Analysis) based numerical approaches, namely the wave based Energy Finite Element Method (EFEM); the method is based on a finite element mesh and, due to the nature of the solution, the mesh refinement is not dependent on the frequency of interest, which makes the method capable of handle big sized/high frequency models. They also highlight the necessity to model correctly the nature of the coupling between structural elements as the biggest limit of the method today.

Boroditsky & Fischer (2012) presented an algorithm based on the Smith's transfer function prediction procedure, relating the vibration response to an airborne noise excitation. The authors discussed especially the mechanism of structural excitation below the structure resonance, where a multimodal approach is not possible.

Seok et al. (2011) presented a case study regarding an excessive noise level inside the engine control room of a LNG carrier, due to a steam dumping line excited by a control valve. The authors conducted a comparison between measured noise levels on board and a structural analysis of the steam dumping line, sorting out that the structureborne noise generated by an airborne noise excitation caused by the steam valve as the root of the problem.

Marchesini & Piana (2012) studied an improvement to an existing luxury yacht in order to obtain a higher class comfort, showing how intensity measurements can be effective in problem solving related problems.

Performance of acoustic insulation components

The improvement of the acoustic behaviour of insulation panels and partitions walls is still a major trend, as pointed out by many research works. Kim, S.R. et al. (2012) performed a comparative study of a prefabricated cabin mock-up made of sandwich panels, whose insulation characteristics had been previously measured in laboratory. They explained the difference in the Weighted Sound Reduction Index RW of almost 9 dB with both the construction gaps and irregularities of a real construction, but also with the flanking paths. With the help of structureborne noise measurements and SEA analysis they identify the transmission of the steel floor is the biggest responsible of the radiation in the receiving room.

Cho (2013) presents an experimental and analytical investigation of the low frequency vibro-acoustic characteristics of a massive floating floor with resilient layer, leading to the conclusion that the highest transmissibility of the system is when the bending modal frequency of the floating floor plate matches the in-situ natural frequency of the isolator which is different from what calculated with the method of ISO 9052–1 (1989). The study indicates that some contributory factors such as plate dimension and location of impact may be added to the assessment factor of 63 Hz.

Patraquim et al. (2011) analysed the influence of the lining materials usually present between a perforated panel and the mineral wool beneath. This material, usually a thin fabric sheet, is found to have a large influence on the resulting acoustic absorption of the system. Materials with high air-flow resistivity lower the absorption of the panels, particularly at mid frequencies. Comparison between measured data and theoretically calculated data were found in good agreement in the case of small resistivity.

In Borelli et al. (2013) a study of the effect of different perforated facing panel sheet in sound absorption panels is experimentally investigated and the different behaviour due to different combinations of percent of open area and air gap between insulation material and facing panel are discussed. Experimental data shows good agreement with literature, showing that for ratios perforated/total area greater than 20% the effect of the perforations doesn't vary anymore and on the other side, air gaps seems to have little influence, at least in the range considered.

2.3.2 Air radiated noise

The study of the noise emitted from the ship in the external space, regarded as noise pollution affecting coastal inhabited areas and harbours, is a relative young field of application. As a consequence of that, on one side there is a big lack of normative regarding the protection of such areas and methods and parameters to be used to assess the radiated noise, on the other a lot of scientific works are in progress.

In particular, the ongoing European project SILENV (Ship Innovative Solutions to Reduce Noise) is largely described and presented in Badino et al. (2013). The aim of the project is to define a sort of "green label" in which noise target for every topic and guidelines to reach them are provided. The project is organized in 5 Work Packages (WP) that are briefly described within the article: (i) noise related needs, (ii) noise measurements, (iii) solutions, (iv) models and (v) green label requirements.

Within the framework of the SILENV project, again Badino et al. (2012c) propose an assessment criterion for the airborne noise emitted by sea-going ships. Such method has been based on similar ones already existing for similar purposes such as the ISO 3746 (2010a) norm and has been adapted to take into consideration the dimension of the measured object and the particular ambient condition.

In another study, Badino et al. (2012b) presented the European Directive 2002/49/EC of which aim is to assess and to control the environmental noise due to the main sources, including ports and port activities. The Directive prescribes the development of a Noise Strategic Mapping (NSM) by superimposing the contribution of every single source. The authors proposed a method to achieve this goal. Moreover, limits to be applied to the port noise pollution are proposed.

Badino et al. (2012e) observe that the noise emitted from a ship has different impacts on the different receivers that are affected by this noise: underwater with regard to the marine fauna as well as for military purposes, inside the vessel for the comfort and safety of crew and passengers and outside the vessel in coastal inhabited areas. They analysed the relevant normative framework that regulates such different fields, observing that the state of the art of the regulation is very different and being very different the time elapsed since those fields have been studied.

Di Bella & Remigi (2013b) propose a method to evaluate, with a retrofit procedure, the sound power level of a cruise ship starting from sound pressure level measurements. The spectrum obtained can be used as a point source in a mathematical model to further analyse the noise impact of a ship on a coastal urban area. Di Bella & Remigi (2013a) conducted a study on the noise pollution over the historical city of Venice due to the cruise ships sailing in the internal waters of the city or moored at harbour. Even if the ambient situation of Venice is not simple, due to the heavy traffic (from both large cruise ships as well as public water transportation), they demonstrated that an accurate and precise planning of such activities can help to control effectively the total amount of noise affecting the urban population. Moreover, they propose a "buffer" zone, in analogy with what existing for railways, where target noise limits should be fulfilled.

Draganchev et al. (2012) conducted a comparative study on the noise emitted from three different merchant ships while moored. Besides the differences between the three ships, they found out that for every ship the main noise source was the ventilation fans (engine and cargo rooms) and that the response on the environment was strongly dependent on the presence of surrounding reflecting surfaces, including the container carried on the main deck of one of the three ships. A numerical simulation of that has shown good agreement with the experimental data.

Badino et al. (2012d) made a comparison between measured and calculated data for two different ships. They used a commercial available software to model ship geometry and surrounding ambient and obtained good correlation with the measured data, although they pointed out that the correct modelling of the ship geometry is a critical point since it has a rather large effect on the results.

2.3.3 Underwater radiated noise

The underwater radiated noise has been studied since a very long time for military applications: as a consequence of that, there is lack of publication since the results of those studies cannot often be published being covered by secret. The study of underwater radiated noise as a civil application is more recent and is focused mainly in the protection of the marine environment from noise pollution.

In this sense, there is a fundamental difference with the studies developed in military application: the requirement for a naval vessel to comply with is always clear, being represented by the “state of the art” of the detection devices sensitivity. Being the progress in the technology of those systems always running, there is virtually no limit in lowering the level of noise radiated by a ship: the more silent, the better.

In civil applications, where time schedules and involved costs for a construction are normally tighter than in a naval vessel, the question of how to tune up correctly the noise emission arises. How much a ship must be silenced depends upon the target threshold level which is represented by the level of annoyance/pain of the marine fauna.

Many of the most recent studies have focused to establish the correct limit to be taken into account and in finding a correlation between such limit and the behaviour of the marine fauna.

Regarding the noise sources on a ship, the study of the propeller’s behaviour confirms to be a major issue, both from the point of view of the numerical idealization and of the development of new materials. The interaction of propeller and hull has been regarded as well as secondary noise source and studied in many works.

Shipping noise and marine life

Scheer & Ritter (2013) have conducted a study on the underwater radiated noise of different kind of ferries on their routes out of the Canary Islands (Spain) and compared the result with the ambient noise and the audibility threshold of some marine mammals. They calculated the theoretical time available to the cetacean to escape from an incoming vessel, that appears to be in most cases long enough for the animal to move, thus coming to the conclusion that other factors, like the audiogram of the cetacean, need deeply to be investigated

Allen et al. (2012) analysed noise emitted from several ships cruising in the Gulf of Maine and compared those with ship´s routes and hearing threshold of whales, concluding that mysticetes should be physically capable to detect ships. Nevertheless, many collisions between marine mammals and ships occur and they can be explained with several effects like shadow zones or background noise especially in shallow waters. The authors recommend that future studies focus on accurate 3D modelling of the acoustic environment as well as on hearing capability of mysticetes.

Erbe et al. (2012) developed a simple method to derive a large scale noise map of the oceans, matching AIS data from ships with marine wildlife distribution maps thus providing a tool to establish areas where the underwater noise is - or is not- a problem.

Starting from a long term observation and measurement of ship’s traffic, McKenna et al. (2012) propose a method to calculate Sound Exposure Level (SEL) for different kind of ships. The equation is a simple and useful tool to input shipping noise in modelling the marine environment.

Baudin et al. (2014) describe the European research project AQUO (Achieve QUiter Oceans by shipping noise footprint reduction) and propose to use a description of the oceans environment as noise mapping in order to establish the effect of the anthropogenic sound on marine life.

Numerical methods

Salio (2013) presented a study where semi-empirical methods and BEM numerical simulation of a marine propeller are compared to a series of measurements taken on different ships (cruise/patrol vessel/ megayacht). Results show that the reliability of such methods is not fully satisfactory even if they are commonly used in the early design stage practice.

Peters et al. (2014) investigated the effect of the internal mass distribution on the radiated sound power of a submerged hull due to external excitation. They used a fully coupled FE/BE analysis of a submarine, modelled as a stiffened cylinder with hemispherical ends, and investigated the response of such model to different distribution of the internal masses, taking into account the relevant damping ratio, since the masses are often resiliently mounted. The obtained results showed a significant contribution of such internal distribution of “dumped masses” on the total acoustic radiation of the structure.

Pereira & Cordioli (2011) presented a comparison between a procedure based on a hybrid FE-SEA method and an uncoupled BEM analysis for the prediction of the structural and acoustical response of a submerged structure, where fluid impedance must be taken into account. They observed that the results of the hybrid FE-SEA method are poor when used to calculate the structural response but are in good agreement when concerning the acoustic dynamic stiffness.

Wei & Wang (2013) made a study on a scaled submarine model, pointing out as the axial forces, normally taken in less consideration in such studies, can have a big contribution in the excitation of the submarine hull, in both breathing and bending modes, contributing a lot to the total noise emitted from the hull. However, the authors point out the fact that the model used in such study is a small scale model, with no internal machinery and ballast tanks, excited from an unskewed propeller, being that slightly different from the real applications.

Lee, K.H. et al. (2014) presented an inversion procedure for sheet cavitation propeller noise based on a nonlinear optimization algorithm and acoustic BEM. The cavitation noise is modelled by mean of single, double and triple monopole sources. Inversion is performed with an ASSA (Adaptive Simplex Simulated Annealing) algorithm. The procedure enables the inversion of the source strength and positions using data measured above the propeller. The double monopole model shows the best accuracy and the result obtained by an acoustic BEM model are in good agreement with the measured data.

URN due to hydrodynamic forces of propellers

Paik et al. (2013) have investigated the behaviour of three kind of flexible propeller, measuring also the emitted noise, reporting a good acoustic behaviour in case of glass fiber propeller construction. Bertetta et al. (2012) carried out a CPP propeller optimization with a cavitating panel code coupled with an optimization tool, at two very different design points with different pitches. The procedure showed good results not only in the cavitation behaviour of the propeller but also with a significant reduction of the emitted noise. They concluded that if the same approach is used to a simpler, one working point problem, the improvement should be even better.

Takinacı & Taralp (2013) have developed an empirical model of broadband noise for marine propellers, based on a common formulation from Brown (1976). In addition to that, they modulated the obtained spectrum to obtain a realistic audible signal to be used in a sonar simulator for training purposes. The results of such empirical prediction model are found to be in good agreement with the available experimental data.

Korkut & Atlar (2012) studied the effect of foul release paint on propellers, finding a beneficial effect with regard to the noise emitted in non-cavitating conditions while an increase of noise in fully developed cavitation condition.

Lee, J.H. et al. (2014) proposed a single nozzle air injection system to reduce the propeller cavitation inducing hull excitation pressure. They found a significant degree of reduction even outside the air bubble layer that cannot be explained with a simple “air-cushion insulation” effect. They developed a theoretical model to describe the scattering behaviour of a simplified air bubble thus explaining such reduction with a destructive interference effect.

In order to override the difficulties related to an underwater noise measurement, Jeon & Joo (2014) developed a method to predict the underwater noise radiated by a propeller by mean of onboard measurements. The method, which takes place from the measurements of the transfer function of the hull in a dry dock, has been verified in a tank test experiment and applied to the prediction of real ships, with good correlation.

URN due to other sources

Kellett et al. (2013) presented a study based on a CFD approach predicting URN of an LNG carrier, compared with measured data. They pointed out how some modelling parameter such as the presence of the free surface or the way to model the propeller can influence the accuracy of the result, thus giving indications to designers in building their models.

Merz et al. (2013) studied the effectiveness of the active control of the sound power radiated from a submarine hull excited by propeller forces. The control is achieved by two different systems and can be implemented with a resonance changer, thus reaching the maximum performance. A similar study, based on the effectiveness of a resonance changer, is described in Caresta & Kessissoglou (2011) who propose a dynamic model of a submarine hull coupled to a propeller shafting system. A resonance changer is also included in the system and the steady state response of the hull under harmonic excitation from the propeller is calculated. The introduction of the resonance changer reduces the radiated sound pressure level in both narrow and broadband frequency ranges significantly.

Roth et al. (2013) have conducted a comparative study of the noise emitted from an ice-breaker in standard operation vs. during ice-breaking operation. They found that ice-breaking operation will increase the noise emitted up to 10 dB, especially in backing and ramming maneuvers. They recommended an improvement of the study of the underwater noise propagation in iced sea, as well as the development of measurement protocols being the increase of arctic traffic a consolidated trend.

Traverso & Trucco (2014) presented a method to measure the underwater noise emitted from a ship, measured from the ship’s bow. The method has the advantage to measure the radiated noise directly close to its origin, avoiding the uncertainty connected to the calculation of the transmission loss.

2.4 Sloshing impact

This section is devoted to the dynamic structural response of the Cargo Containment System (CCS) inside the membrane type LNG tanks of different floating units (ships, FPSO's, etc.). Membrane type LNG tanks are currently dominating the LNG market and the correct assessment methodology for verification of structural integrity of both CCS and the associated hull structure is critical for their design. Unfortunately it appears that both the reliable deterministic models of hydro-structure interactions during the sloshing impacts as well as the overall rational methodology for determination of the representative design conditions are still missing, at least from the direct calculation point of view. The classical engineering methods (laboratory tests, numerical simulations and full scale measurements) show to be of limited use for several reasons, namely: scaling issues for small scale model tests, numerical inaccuracies and huge CPU time requirements for numerical methods and inexistence of proper sensors and risks associated with the instrumentation at full scale. In addition to the difficulties in evaluating the hydro-structure interactions during the deterministic sloshing impacts conditions, the consistent design methodology, which should combine the different deterministic results in order to calculate the overall safety index is also missing. The overview of the different issues related to the direct assessment methodology for sloshing was discussed in Malenica & Diebold (2013).

During the last 3 years lot of effort has been done for better understanding of this problem but unfortunately, and in spite of all the efforts, we can say that, at least from direct assessment methodology point of view, the problem still remains open and relatively simple design methods are exclusively in use today. Very important activities related to better understanding of the hydro-structure interactions during the sloshing impacts were initiated by Gaztransport & Technigaz (GTT) who owns the patent of the two most important CCS's i.e. MarkIII and NO96. The main part of the results of these investigations was presented at the different ISOPE Conferences. These investigations concern all the aspects of the problem (experimental, numerical full-scale, methodology) and very good interaction of GTT with other research groups allowed to make significant progress in this field.

2.4.1 Experimental approaches

There has been lot of work in the last years regarding the improvements of the small scale model tests procedures (Baudin et al. 2012, 2013, Diebold & Baudin 2014, Kayal & Berthon 2013, Kimmoun et al. 2012, Mehl et al. 2013, 2014, Neugebauer et al. 2014, Song et al. 2013, Wei et al. 2012, 2014, Loysel et al. 2012, 2013, Choi et al. 2012, Kim, S.Y. et al. 2013, Kim, Y. et al. 2013, Souto-Iglesias et al. 2011). In particular a so called ISOPE sloshing benchmark study was organized by GTT and several institutions participated (Loysel et al. 2012, 2013). The principle of these benchmarks was to compare the measurements, especially impact pressures, from sloshing model tests performed by different laboratories involving the same nominal input conditions which were chosen as simple and as controlled as possible. In spite of the relatively simple experimental conditions (2D tank and simple excitations) the overall conclusions of these comparisons are not very encouraging at least when the impact pressure measurements are concerned. However, the results for more stable quantities (events rate, global forces, etc.) shows relatively good agreement.

The sensitivity of the model test results to the type of sensors which is used was investigated by Ahn et al. (2013), Baudin et al. (2012) and Razzak et al. (2013). The conclusions from these investigations are rather pessimistic and large differences in measuring pressures are obtained using the different sensors.

Statistical post processing of the pressure measurements represents the challenge in itself. The effects of the test duration and the sampling rate were investigated by many researchers (Bulian et al. 2012, Dematteo & Ratouis 2013, Diebold et al. 2013, Fillon et al. 2012, 2013) and the conclusions are not very encouraging concerning the evaluation of the maximum pressures neither concerning their time evolution.

It is important to understand that even if we would have acceptable pressure measurements we could not use them directly in the design process because of the important scaling problems. Indeed, due to a very complex physics involved during the sloshing impacts there is no single scaling factor but this factor(s) depends on the type of impact and often the combined scaling should be used for single impact. All this means that the difference between the full scale values of the pressure, obtained by applying different scaling laws, may be significant. Different aspects of the scaling of the small scale model tests were considered in numerous publications (Ahn et al. 2012, Karimi et al. 2013, 2014). The scaling issues are investigated by means of performing the small scale model tests at different scales typically 1:10, 1:20 and 1:40. In addition, since the scaling does not depend on the scale only but also on the types of fluids which are employed, some authors performed the model tests with the fluid and gas of different density. In particular the care was taken to properly scale the density ratio in between the liquid and gaseous phases since some theoretical investigations indicated the importance of this effect for pressure measurements of certain impact types.

It is necessary to mention another physical effect which is extremely difficult to model at small scale and which concerns the hydroelasticity. Indeed, when the typical temporal duration of the local impact loading is comparable with natural periods of the surrounding structure hydroelasticity matters and can significantly affect the structural response. Due to the chaotic nature of the sloshing loading, these situations can occur very often so that hydroelasticity effects cannot be ignored. In Bardazzi et al. (2012a, b) and Lugni et al. (2012, 2013) these effects were investigated both experimentally and numerically for the flip through type of impact situation. One of the main conclusions of these investigations was that the hydroelasticity plays a critical role in the evolution of the structural response and that the maximum structural response occurs during the fully coupled hydroelastic interaction regime. This means that the pressure measurements using the rigid tank structure, which is the common practice nowadays, cannot be used directly for design and should be supplemented by the evaluation of the dynamic amplification of the response due to hydroelasticity. In their conclusions the authors also indicates the huge numerical difficulties to correctly reproduce the structural response numerically.

Important effort to classify the different impacts according to dominant physical characteristics was made by GTT research team (Lafeber et al. 2012a) who introduced the different Elementary Loading Processes (ELP), combination of which can eventually cover any type of impact conditions. One of the interesting results from these investigations was the development of the improved Bagnold model for impacts with the air cavity, which allowed for more realistic scaling of the associated pressures in the air pocket (Ancellin et al. 2012, Brosset et al. 2013). These investigations were mainly applied to the quasi full scale model tests by a so called Sloshel project (Lafeber et al. 2012b, Pasquier & Berthon 2012) and their application to small scale model tests was not considered yet. This work is still in progress and no conclusive results were obtained yet.

Finally it is also important to mention that the small scale sloshing measurements are performed using the flat tank wall surfaces while in the real, full scale, situation the tank walls are not flat and contains the corrugations in the case of MarkIII and raised edges for NO96. Knowing the sensitivity of the pressure measurements to small local geometrical changes, we can easily imagine how difficult it would be to take these effects into account when scaling the pressure.

2.4.2 Numerical modelling

All sort of numerical methods for sloshing simulations were proposed in the past: Boundary Element Method (BEM), Constrained Interpolation Profile method (CIP), Finite Difference Method (FDM), Finite Element Method (FEM), Finite Volume Method (FVM), Level-Set method (LS), Marker-and-Cell method (MAC), Moving Particle Semi-implicit method (MPS), Smoothed Particle Hydrodynamics method (SPH), Volume-of-Fluid method (VOF) and others. In spite of the recent improvements of these methods the results are still far from satisfactory (Bai et al. 2013, Baeten 2012, Cao et al. 2013, Colicchio et al. 2013, Costes et al. 2014, De Chowdhury & Sannasiraj 2013, Fossa et al. 2012, Gazzola & Diebold 2013, Hashimoto & Le Touzé 2014, He & Kashiwagi 2014, Hwang et al. 2012, Hwang, J.O. et al. 2014, İtibar et al. 2012, Jeong et al. 2012, Lindberg et al. 2012, Luppes et al. 2013, Rafiee et al. 2013, Xue et al. 2014, Zhang & Wan 2012, Zhang, Y. et al. 2014, Zheng et al. 2013, Zhu et al. 2014). This is not only because of the prohibitive CPU time requirements but also because of the complexity of the physical phenomena which are involved (violent free surface deformations, hydroelasticity, phase transition, compressibility, 3D effects, low temperature, etc.). However, it should be noted that these comments concern the evaluation of the local pressures and the local structural responses and the modelling of the global sloshing behaviour in terms of the quantities such as overall forces on the tank, global evolution of the free surface, global and local kinetic energy, impact occurrences, etc. shows relatively good results for almost all methods. This means that CFD can be safely used for the evaluation of the sloshing severity and for the identification of the critical sloshing conditions in a qualitative manner. An interesting example of using the OpenFOAM software was presented in Gazzola & Diebold (2013) where a simple method was proposed to identify the severity and number of impacts for given tank motion.

The reasons for relatively poor quality of the CFD simulations, when evaluating the local impact pressures are similar to those associated with the pressure measurements at small scale. Indeed, the maximum impact pressures are usually extremely localized in space and in time which makes their numerical evaluation or measurement extremely difficult. This is probably one of the main reasons for very particular statistical properties of the measured and/or calculated impact pressures. Indeed the quantities such as the global forces and even local fluid velocities show the typical statistical behaviour with Weibull shape parameter greater than 1, while the local pressures have this parameter less than 1 leading to very extreme long term values. In addition the associated confidence interval for pressures is much larger which makes the direct use of the measured pressures for design purposes almost impossible (Diebold et al. 2013).

Due to the difficulties associated with the simultaneous direct evaluation of the local pressures together with the global sloshing behaviour, the actual research seems to be more oriented to a kind of hybrid approach where the problem is subdivided into global and local parts. Within this approach the representative impact conditions are identified by either the model tests or CFD calculations, and they are subsequently simplified and treated using the dedicated local hydro-structure interaction models. This idea was first introduced by Korobkin & Malenica (2006) and very simple impact situations were proposed together with the corresponding semi-analytical hydro-structure interaction models. Recently this approach was expanded to the more realistic impact situations and the combined potential flow and CFD approaches were proposed for local hydro-structure interactions. In this context an important work was initiated by GTT and the coupling of the nonlinear potential flow model for wave propagation with the complex CFD model, based either on SPH or VOF technique, for impact simulations, are under development (Guilcher et al. 2012, 2014, Costes et al. 2013, Scolan et al. 2014).

2.4.3 CCS structural response

In addition to the complex hydrodynamic loading which occurs during the sloshing impacts a complex structure of CCS introduce the additional huge difficulties in the evaluation of the structural response. Indeed, the CCS is composed of the plywood, foam, perlite, special steel, triplex, invar, F and is attached to the hull structure by the resin rope and special couplers in the case of NO96. Several publications addressed this problem during the last 3 years, Chun et al. (2013), Dobashi & Usami (2012), Hwang, S.Y. et al. (2013a, b, 2014), Jeong & Yang (2013, 2014), Hwang, S.Y. et al. (2014), 2014, Kim, D.H. et al. 2014, Kim, J.M. et al. (2013), Kim & Paik (2013), Lee, D.J. et al. (2014), Lee & Zhao (2013), Lee, S.G. et al. (2012), Nho et al. (2012), Paik et al. (2014), Wang, B. et al. (2012), but it seems that there is still no fully reliable numerical model and we can say that the numerical modelling of the CCS structure still remains big challenge which makes the solution of the fully coupled hydro-structure interaction model almost impossible for the time being.

2.4.4 Current approaches for sloshing assessment

Due to the technical difficulties discussed above it is clear that the direct calculation approach for sloshing assessment is still not ready. That is why the current procedures of Classification Societies for sloshing assessment are manly based on the so called comparative approach (e.g. see Bureau Veritas 2011, Det Norske Veritas 2014). Philosophy of this approach is relatively simple and consists in comparing the loading and capacity of the new design with the reference ship which has never sustained damages due to sloshing impact loads. The capacity of the containment system is evaluated using the nonlinear dynamic finite element model for different loading scenarios leading to the identified failure modes (bending of the cover plate, buckling of the vertical bulkhead, residual compression of the foam, etc.). As already indicated, CCS is a very complex structure composed of different materials connected together by special procedures and the representativity of the classical finite element models need to be checked very carefully. The loading scenarios are chosen in such a way to cover the typical loading patterns observed in small scale model tests. This means that the different combinations of pressure amplitudes, time histories and loaded surfaces have to be considered. Once the capacity curve identified the last step is the determination of the scaling factor. The reference vessel is used for that purpose. The scaling factor λ is chosen so that the scaled design load curve of the reference vessel is tangent to the corresponding capacity curve. Finally, to assess the target vessel, the small scale design loads are scaled by the same factor λ obtained previously and by the safety factor, and are compared to the capacity of the target vessel.

2.5 Air blast and underwater explosion

2.5.1 Air blast

Previous ISSC committee V.I report (2012) provided a benchmark study for shock response of plate panel to blast load. Figure 1 shows a typical pressure pulse curve; in which t_m represents rising time, t_{dur} is the duration time and t_{term} is the termination time of the time–pressure history curve. The idealized blast load with triangle shape can be applied to the shock response analysis of structures.

Longère et al. (2013) dealt with the numerical simulation of the dynamic failure of a ship structure steel plate under near-field air-blast loading. Various energetic levels of air-blast loading, involving variable explosive mass and charge-plate distance were tested. The results show that the equivalent plastic strain in the highly deformed area can reach 1.3, the maximum equivalent plastic strain rate 3700 s^{-1} and the temperature value 470°C. These values are greater than the maximum values of strain rate and temperature considered for the material thermo mechanical characterization.

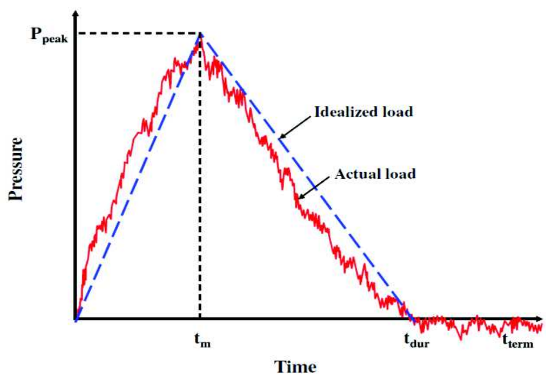

Figure 1. Dynamic pressure pulse generated by the PPLR and idealized pressure (Sohn et al. 2013)

Alireza & Ahmad (2014) investigated the dynamic response of corroded plates subjected to blast loads. The results show that a reduction in the dynamic load carrying capacity of 8% can occur due to corrosion in plates with 50% degree of pitting. Corrosion pattern has significant effect on reduction of load carrying capacity. Maximum reduction occurs when pits are concentrated at the center of plate.

Internal blast

Several major international design methods of Explosion Containment Vessels (ECVs) refer to the items of pressure vessel codes and standards, where the fracture mechanics analysis of pressurized components should be performed to prevent the occurrence of brittle fracture. Ma et al. (2013) proposed a rate-dependent failure criterion to account for Adiabatic Shear Band (ASB) propagation, and a finite element analysis of a cylindrical containment vessel with different size of cracks was performed. The failure assessments based on ASB mode and Failure Assessment Diagram (FAD) method were conducted, respectively. The results show that the strain rate on representative point is not influenced by local crack size, which is only related with load conditions. The assessment result based on FAD method is in agreement with that of ASB at low or intermediate strain-rate (lower than 85 s^{-1}). When strain rate exceeds 85 s^{-1}, the assessment results based on two methods became different. For single-used ECV, where plastic deformation is allowable, FAD assessment may lead to conservative result, thus assessment based on ASB damage mode is recommended to give more comprehensive estimations. For the multi-used ECV, the two methods incline to a consistent result.

Lee, S.G. et al. (2014) developed a shock analysis technique of blast hardened bulkhead under internal blast using multi-material arbitrary Lagrangian Eulerian formulation and fluid-structure interaction technique. Shock response analysis for a part chamber model was carried out under internal blast. The calculated pressure and acceleration response, as well as damage and deformation configuration of bulkhead have good agreement with test results.

Weapons attack on ship structures

The damage effect of weapons on ship structures mainly comes from the blast wave and fragments. When stiffened plates subjected to the loading of blast wave and fragments, it can be easily penetrated by fragments. The perforations on the stiffened plate act as the crack initiation locations due to the stress concentrations. Soon afterwards, blast wave in confined space would aggravate the deformation of the weakened stiffened plates and large vent appears. Blast wave propagates through the vent and exerts on adjacent cabins. Kong et al. (2014) conducted experimental investigation and numerical simulations of a cased charge exploded inside a multi-layer protective structure, the synergistic effect of blast and fragment loadings were considered. The liquid cabin plays an important role in the enhancement of the anti-explosion capacity of the multi-layer protective structure. The liquid in the cabin can effectively absorb the energy of high speed fragments and prevent them from punching into internal cabins.

2.5.2 Underwater explosion

In the UNDerwater EXplosion (UNDEX), various combination of charge weight (W) and standoff distance (R), can generate various pressure versus time curves and its related energy density (energy pass through unit area) of shock wave. For a far field UNDEX, the shock wave can be taken as plan wave, the energy flux is proportional to W/R^2. And the shock factor ($SF = C\sqrt{W}/R$) is widely used to study the shock resistance of a hull plate and also used as attack severity index. If the standoff is smaller than the dimensions of target, e.g. ship length, the spherical wave effect should be taken into consideration. If the standoff smaller than twice the radius of the explosion gas bubble, the UNDEX are referred to as close-proximity explosions. At these ranges, the dynamics of the gas bubble are influenced by the geometry of the target (in the case of a rigid target), and possibly also by the deformation of the target (in the case of a responding target). Riley et al. (2012) describes the experimental results and Chinook (an Eulerian computational fluid dynamics code). The predictions were compared with analytical and similitude-based models of bubble growth. It was also shown that a hemispherical close-proximity analytical model was found to predict the first bubble period for initial standoffs within one bubble radius somewhat better than the free field models.

Response of ship hull subjected to close-in UNDEX

The bubble load in a close-in UNDEX can cause the ship hull global response and local response. For global response analysis the ship hull can be simplified as a hull girder model, for the local response the 3D model of surface hull is needed. The vertical response of ship hull subjected to an UNDEX bubble is mainly the global response, which is composed of rigid body motion and elastic deformation. Large local vertical response appears at some locations when the ship model is subjected to the bubble load.

Zhang & Zong (2012) investigated the elastic and plastic response, resonance mechanism in hull girder whipping response to an underwater bubble. The results show that the hull girder sustains significant elastic response of low-order mode. When the bubble load is large enough, the bending moment in the mid-ship may exceed the ultimate bending moment. And a single plastic hinge will form at center of hull girder.

Zhang, N. et al. (2014) used a procedure which couples the FEM with Doubly Asymptotic Approximation (DAA) method to study the transient response of ship hull structures subjected to an UNDEX bubble. The numerical results show that besides global whipping response, the ship hull also sustains severe local response in different directions subjected to UNDEX bubble jetting. Severe local transverse and longitudinal response also exist at some special location of the ship model. Large local transverse responses take place at side plates.

Zong et al. (2013) analysed the impact response of full-scale surface ship (Length × Breadth × Draft = 55 m × 9.5 m × 2.5 m) subjected to non-contact close-in UNDEX. Three damage modes of whole ship are specified according to the standoff distance, shown in Figure 2. For an explosive with equivalent 400 kg TNT, the responses of the analysed ship under different standoff (R) are:

a) R > 10 m: damage mode I: the hull plate suffer dishing damage. This is familiar with far field UNDEX. Especially when the deformation appears at shell plate and superstructures.
b) 6.5 m < R < 10 m: damage mode II: Buckled-frame deformation.
c) R < 6.5 m: damage mode III: bottom-indented mode. The part of hull close to the charge indent rapidity when the shock hit the ship. Damage takes place on the local parts of ship, local crack and fracture will appear.

Wang, H. et al. (2014) investigated the dynamic response of a ship-type box girder model (Length × Breadth × Depth × Draft = 2.8 m × 0.8 × 0.3 m × 0.04 m) subjected to close-in non- contact UNDEX with experimental test and numerical analysis. The results reveal that global longitudinal strength collapse combined with the local wrinkling, the plastic deformation of hull between bulkhead and plastic deformation of local bottom hull are the mainly three damage modes.

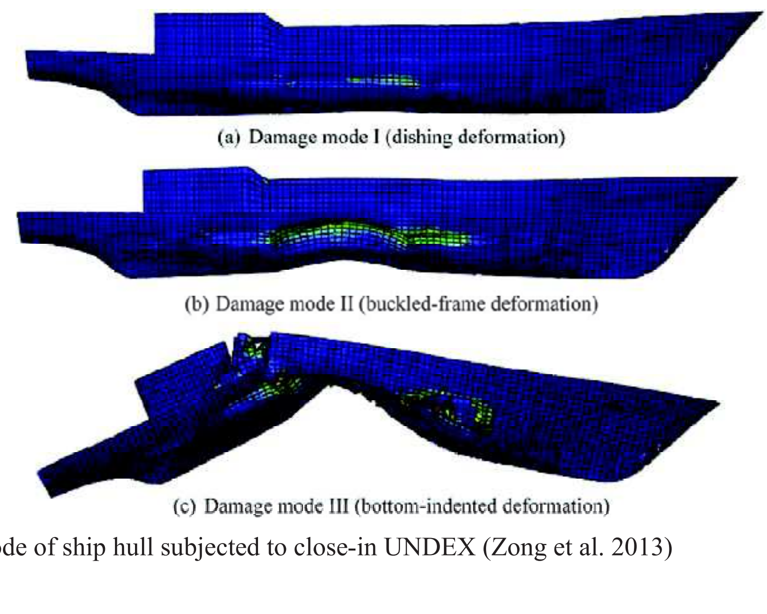

Figure 2. Damage mode of ship hull subjected to close-in UNDEX (Zong et al. 2013)

If the UNDEX bubble effects are not incorporated in the analysis, the damage severity will be underestimated. As the pulsation periods are close to the two-node bending vibration of test model, the resonant result cause large amplitude whipping displacement. The ratio *R/Rmax* (standoff to maximum radium of gas bubble) has important effects on the response and damage modes of structures. Experimental data and numerical analysis reveal the structural collapse modes are different when *R/Rmax* increases.

Shock resistance

When naval ship is attacked by an UNDEX, the ship can be severely damaged by shock waves and gas bubble pulse; such an attack can put the crew in danger and possibly destroy the ship. Preventing damage to ships is of great interest in naval ship design. Elastomers, or rubber-like materials, and core sandwich structure are often used to mitigate damage caused by impulsive or impact loads because of their low stiffness and high damping characteristics.

Kim & Shin (2013) investigated the rubber coated plate and sandwich structure with core. The results indicate that the rubber coating effectively mitigates plate stress by impact loading in an elastic regime and, in a plastic regime, the rubber seemed not to be effective. The sandwich structure is useful in an impact environment. The highest priority factor to consider in constructing a sandwich structure was the number of cells. Core height and core thickness were secondary considerations.

Xiao et al. (2014) investigated the rubber protective coatings with different structures under compression load and water blast shock wave. It is concluded that when under dynamic compressive load, the cell topology played an important role at high speed, and when under UNDEX, the honeycomb coatings can improve the shock resistance significantly at the initial stage. Although structural absorbed energy has a significant contribution in the shock resistance, soft coating can significantly reduce the total incident impulse at the initial fluid-structure interaction stage.

Schiffer & Tagarielli (2014b) performed a laboratory-scale Fluid-Structure Interaction (FSI) experiments and finite element simulations to examine the one-dimensional blast response of double-walled hulls, consisting of two skins sandwiching a layer of water. It is found that for the outer skin, cavitation processes initiate in the water very close to the front face sheet of the sandwich hull and result in a dramatic reduction of the impulse imparted to the inner hull (–60% compared to the case of a monolithic outer skin). Schiffer & Tagarielli (2014a) have constructed and validated theoretical models for the dynamic deflection of fully clamped, circular elastic composite plates loaded by planar, exponentially decaying underwater shock waves. Design charts are constructed and used to determine plate designs which maximize the resistance to underwater blast for a given mass.

Avachat & Zhou (2012) analysed the response of sandwich composite structures to underwater blast loading. Results reveal a significant difference between the responses of air-backed and water-backed/submerged structures. In general, thick and low-density cores provide superior blast mitigation and failure resistance.

Shallow water bottom contour effects

In most deep water UNDEX events, the contour of the ocean bottom is trivial as the bottom reflection of the shockwave is of minimal magnitude. This assumption may not be true for littoral waters. Walters et al. (2013) used Lagrangian solid bottom modelling approach to compare with the current bottom modelling technique to determine its validity and potential benefits. Five different bottom contours and one flat bottom model were simulated with a Floating Shock Platform (FSP) serving as the ship model. A parametric study was conducted to determine the effect that contoured bottom profiles on the response of a ship subjected to an UNDEX event in littoral waters. The initial analysis of the FSP response showed only slight differences between the various contour models. This was caused by the buffer created by the bulk cavitation zone. The effect was specific only to the particular geometry selection. Modifications of the charge size, target separation, or bottom depth could diminish the effect, but to what extent needs is left for future study.

2.6 Damping and countermeasures

With increases in ship size and speed, shipboard vibration becomes a significant concern in the design and construction of vessels. In the theoretical prediction and numerical simulation of dynamic ship responses, the damping characteristics of ships and their surrounding fluid are key issue and major reason for the inaccuracies encountered. Various methods are available for modelling ship vibration damping.

The total damping associated with overall ship hull structure vibration is generally considered as a combination of the following components:

- Structural damping;
- Cargo damping;

- Water friction;
- Pressure wave generation;
- Surface wave generation.

For the forced vibration analysis, it is assumed that the effects due to structural damping, cargo damping, water friction and pressure wave generation can be lumped together. The effect of surface wave generation needs only to be considered for very low frequencies of vibration. This effect is generally neglected. For simplification, a constant damping coefficient of 1.5 percent of the critical damping is suggested by ABS Guidance Notes on Ship Vibration (updated in 2014) for the entire range of propeller rpm and main engine orders. Otherwise, more detail frequency-dependent damping coefficients may be used, if applicable. In the forced vibration analysis of ship structures by Yucel & Arpaci (2013), the total damping associated with overall ship hull structure vibration was considered as a combination of the several damping components. The propeller-induced forced vibration responses of local ship structures were determined using finite element method.

For hydrodynamic hull damping, Kim & Park (2014) used a random decrement technique together with continuous wavelet transform to estimate the wet damping of a segmented hull model. The 16 sea states were grouped together based on the speed of the ship to determine the possible influence of the ship speed on the damping ratio. The wet damping ratios for each sea state group, as well as precise wet natural frequencies, were estimated using a continuous wavelet transform.

Based on Statistical Energy Analysis method, the vibro-acoustic characteristics of a composite cabin segment are investigated by Pang et al. (2014), in which the influence of different constraint damping structure parameters and laying positions on the ship vibration radiation are analysed.

Various countermeasures for vibration damping and control have been reported. Vibration isolation using passive isolators is widely used in marine applications through different configurations, such as single-stage, two-stage and floating raft isolation system. By using hybrid genetic algorithm, modelling and optimization of floating raft systems in submarines under different objectives was reported by Huang et al. (2012), in which different vibro-acoustic objectives were considered and vibro-acoustic behaviour of the fluid-loaded cylindrical structure is investigated. Applying the power flow mode theory, Xiong (2014) recently proposed a new Power Flow Mode Dynamic Topology Optimization (PFMTOP) approach to topologically optimise systems' damping material distributions achieving enhanced vibration suppression capability. This approach can maximize the energy dissipation for a given volume of the material to achieve minimum power flow response. Kang et al. (2012) used structural vibration at specified positions level as design objective for topology optimization by distributing a given amount of damping material. Teng et al. (2014) proposed the method of determining the adhesion position of the damping material, which is applicable to the vibration damping of ship plate based on the Bi-directional Evolutionary Structural Optimization (BESO). In this method, the needed amount of damping material is taken as the constraint condition, and the maximization of one natural vibration frequency of the structure is taken as the target function.

Low-frequency passive vibration isolation is challenging and nonlinear power flow behaviour is less understood. Yang et al. (2012) investigated a nonlinear isolation system with a Negative Stiffness Mechanism (NSM) using nonlinear power flow approach because of the traditional force or displacement transmissibility is not valid in nonlinear domain. Adding NSM can greatly enlarge the frequency band for effective vibration isolation. By connecting a negative stiffness corrector to a linear isolator, a High-Static-Low-Dynamic Stiffness (HSLDS) isolator can be formed and investigated by Huang et al. (2014). The HSLDS isolator with quasi-zero stiffness characteristics can offer the lowest resonance frequency provided that there is only stiffness or load imperfection.

Regarding to active vibration control, experimental study for an active floating raft vibration isolation system was conducted based on a flexible hull structure by Zhou et al. (2013). An analytical study of active structural acoustic control of an elastic cylindrical shell coupled to a two-stage vibration isolation system is reported by Ma et al. (2014) to minimize the vibratory power transmitted to the foundation and the acoustic power radiated from the supporting shell. Ahuja & Gupta (2014) studied a simplified semi-active floating raft vibration isolation system with the objective of mitigating the acoustic signature of a warship by minimizing the transmission of forces, resulting from operation of on board machinery, to the foundation.

It is worth noting that a newer type of smart Magneto-Rheological Elastomer (MRE) materials have attracted much attention in recent year due to their stiffness and damping properties can be changed instantly responding to applied external magnetic field. Research on MRE smart materials for adaptive vibration control has attracted EU FP7 funding-ADAM4EVE project to develop such adaptive materials and structures for vibration damping. Application of MREs to a two-stage vibration isolation system was examined by Zhu et al. (2012) with the developed non-linear mathematical model of MREs for damping and stiffness based on experimental characterizations.

2.7 Monitoring

2.7.1 Hull structural monitoring system

The technology for Hull Structural Monitoring System (HSMS) for ships and offshore structures is rapidly growing, in the wake of the advancements in new sensors, large data handling and wireless communication networks. Results of long monitoring periods of ship stress more frequently appear in the literature. The most relevant and newest results are presented later on in this section.

Systems configurations range from the well consolidated systems to monitor hull girder bending moment, to complex experimental systems based on fiber-optic sensors and wireless data transmission, used to investigate dynamic responses to local loads. The general high level architecture of a modern HSMS system acquires heterogeneous signals coming from various sensors distributed in the ship and processes the signals in real time by local processing unit. Then each Peripheral (local) Processing Unit (PPU) communicates data via a wired (Ethernet) network to the Main Processing Unit (MPU) which also acquires other types of signals, coming from wave radar, ship speed log, etc. and processes them all in real time.

The current trend is to substitute the wired copper-based network communication between the PPU and the MPU with wireless or fiber-optic cables. Prospected future developments in the area of HSMS by Cusano & La Marca (2014), pursued by others, aim to transform the interaction between the user onboard and the HSMS system from a passive experience, i.e. the user decides to read and analyse the (real-time) results of HSMS measurements, to an active role of the HSMS which will be able to supply active guidance to the board to minimize the predicted ship structural response based on the real time sensors data. The new systems would be able to incorporate virtual sensors, i.e. information on stresses of structural details obtained by real time numerical prediction.

As often in naval architecture, two different fields of application are generally discerned: merchant ships and naval vessels. The HSMS systems used in the navy vessels often capitalize on systems developed in the merchant ship world, enhancing them with modification. The research in the two fields is driven by several motivations which are shared at different level of importance by the two market sectors: improved safety, reduced life costs and better characterization of hull loads and remaining fatigue life aimed a more effective strategic fleet planning.

A recent report from Department of Defence (2013), presents the architecture and main components of a modern HSMS with particular attention to configurations and features of interest for application in navy ships. After a general introduction on the static and dynamic loads acting on a hull structure, they reported a detailed panoramic on a large series of HSMS commercially available for installation on merchant ships and navy vessels. The list of available systems is also reported with their main specifications including integrated sensors types and number.

2.7.2 New sensors technology and application

This paragraph is dedicated to the review of the state of the art and recent developments in sensors technology and systems for data transmission and acquisition on board of ships. Few references to other application sectors which may have a relevant impact on the development in the shipping world were also included. Knowledge of other systems used for monitoring other types of structures can bring inspiration and accelerate the development also in the maritime world. Interesting indications can come from the aeronautical engineering community. A good review of the state of the art in this specialized field complemented by interesting propositions of new technologies can be found in Brigman (2012), who analysed different systems: from those based on vibration based monitoring, to fiber optic sensors, and high frequency wave propagation techniques including acoustic emission, ultrasonic, Lamb waves, piezoelectric and Micro-Electro-Mechanical System (MEMS) actuator/sensors. The research study of Brigman terminates with a critical discussion on the challenges and restrictions facing implementation of proposed structural health monitoring in commercial aviation (as opposed to military), some of these issues and remedies are shared by the maritime community which introduces additional challenges, such as the much harsher and stochastic environment and the complexity of structural detail and diversity of environmental loads.

Again, a good review of the state of the art of sensors technology for marine applications can be found in the report of Department of Defence (2013). Strain gauges confirm to be the primary sensor utilized by HSMS and these are broadly separated in Long Base Strain Gauges (LBSGs) and Short Base Strain Gauges (SBSGs). New types of strain sensors are based on fiber optic technology. Table 1, extracted from their report, gives a list of various sensors used in modern HSMS systems and cross correlate them with parameters of interest and type of derived information that can be obtained.

Optic-based sensors

Optical-based sensors for monitoring the dynamic behaviour of structures are gaining popularity in this period as they offer a series of advantages over conventional copper-wired based sensors. First the electro-magnetic compatibility: sensors and cables do not induce Electro-Magnetic Field (EMF) and uninfluenced by any EMF. This is particularly important to avoid interference with other wired-based vital systems of the ship, such as the ship automation system or combat system in military ships. Secondly they are intrinsically safe for potential application in explosive environments, avoiding the need for Zener barriers required by copper based sensors. Additionally this type of sensors is light, can be easily embedded into composite structures and they achieve high gains in noise to signal ratio in transmission and do not suffer from any drift which typically affects copper wired system.

Qiu et al. (2013) reviewed the latest research of the Fiber Bragg Grating (FBG)-based Structural Health Monitoring (SHM) technique for composite structures in various fields of applications, including ocean vehicles and offshore structures but also civil engineering, aviation and aerospace. The rapid development of the network promotes the expansion of the optical fiber telecommunication industry, which has substantially driven down the cost of optical components, making optical fiber sensors, particularly FBG sensors, more economically viable. The installation issues and standards of optic sensors for various types of measurements, including structure monitoring, are well addressed in the NATO technical report RTO AG–160 (2012).

Wireless sensors

Wireless data transmission is also a recent development for HSMS, developed first for monitoring large number of hotspots in static civil structures (Lynch & Loh 2006, Swartz et al. 2012) report on a prototype hybrid (wireless/fiber optic) system installed on the high speed littoral combat vessel FSF–1 Sea Fighter, an aluminum catamaran and it is cited as an option for the Hull Monitoring System (HMS). The system is a hybrid, where strain monitoring is provided through Narada wireless data acquisition and control units linked to a ship-board fiber-optic data network. The Narada units are low-cost wireless devices developed at the University of Michigan for the routine monitoring of large, complex structures such as buildings and bridges.

Table 1. Sensors typology and support information as a function of the monitoring parameter in modern Hull Structural Monitoring Systems (Department of Defence 2013).

Monitoring Parameter	Sensors	Supporting Information	Potential Outcomes
Cargo loading Hull Girder Vertical Bending Hull Girder Lateral Bending Hull Girder Torsion	Main deck LBSGs or SBSGs, port & starboard	Section properties Operational profile Structural analysis Post-voyage analysis	Overload alarms Hull girder load history Hull girder fatigue indicator
	Bilge keel strain gauges	Limit state analysis (FEA)	Improved overload alarm (buckling risk) and hull girder fatigue
Temperature	Themocouple or fiber-optic temperature sensor	Thermal coefficients	Temperature compensation Thermal history
Slamming Green Seas over Bow Whipping	Accelerometers, pressure transducer High speed data acquisition		Slam avoidance warning and event history Improved hull girder fatigue indicator
Hot-spot stress Cross deck structures stress Side frame loads Hatch Corners stress	Local strain gauges (SBSG)	Structural analysis (FEA)	Local stress / overload monitoring Detailed structural load history (e.g. multihull spreading loads) and fatigue indicator
Wet deck slamming (multihull)	Local accelerometers and strain gauges (SBSG)		Wet deck slam warning and slam event history Improved fatigue indicator
Navigation data	Ship systems	Sea keeping analysis Weather forecasts	Weather routing Economic routing
Wave Environment	Wave radar Motions sensors	Launch and recovery safe to operate limits	Operator guidance for off-board systems Improved routing Improved load / fatigue assessment

For the hybrid prototype system, a total of 20 Narada wireless units were installed throughout the ship and interfaced to single or tri-axial accelerometers and foil strain gauges; a total of 28 sensor channels (8 strain, 20 acceleration) were added. These are sampled at high rates of 100 to 1000 Hz to capture slamming events and the wireless monitoring system had to be divided into three separate networks to avoid wireless bandwidth issues. Result of the wi-fi sensors installation on the vessel were quite successful and efficient: the data lost by wireless communication were few and moreover compensated by the greater advantage of reduced time and cost of installation with respect to wired systems.

As reported by Department of Defence (2013) , in spite of its rapid expansion in different engineering applications, wireless data transmission is still not considered a proven technology for navy application as the long term reliability of the wireless data acquisition and control units in this environment has not been established. Bennett et al. (2014a) document the application of multiple wi-fi sensors with synchronized video for measuring the loads and motions of a multi-segmented ship model tested in a wave tank versus traditional wired sensors. The same accuracy of results is achieved, but the practical installation advantages and flexibility make the wi-fi systems very attractive for future full-scale installations.

Interesting opportunities will come in the future from the combination of MEMS technology with wireless data transmission. One of the first applications has been recently documented by Xiong et al. (2013) and it is related to the measurement of atmospheric pressure in harsh environment (high temperature pressure vessels). The use of various types of MEMS sensors is expected to expand in the future also on board of ships. A singular example of recent application on board of a fishing vessel is shortly described by Chen et al. (2013).

Acoustic emission sensors

The use of Acoustic Emission Testing (AET) systems targeted at potential fatigue 'hot spots' areas has been recently suggested as a viable approach for active detection of structural failures. The principle behind these sensors is the measurement of the acoustic energy emission released during plastic deformations of metals, providing a method to detect crack and monitor fatigue damage also in marine structures (Rogers & Carlton 2010). These sensors have been successfully used to detect flaws in offshore structures (Ternowchek 2012, Wang et al. 2010, Anastasopoulos et al. 2009) and are expected to rapidly expand in ship HSMS, especially if combined with fiber-optic multiplexed data transmission or wireless data transmission (to avoid the large number of wire cables otherwise needed).

Lee, A.K. et al. (2014) report results obtained from a joint development project between ABS, MISTRAS and a global container transportation company. This pilot project positively verified the viability of acoustic emission technology as a screening tool for surveys and inspection planning. Specifically, in-service AET data were collected from container ships during voyages through the Pacific and Atlantic Oceans and provided useful information on the more critical structural details of the ship. The paper also establishes a standard AET procedure, as 1) test plan, 2) AET system installation and checks, 3) data acquisition and analysis, 4) reporting documentation, and 5) follow-up inspection. A problem encountered by the authors during the monitoring operation is the filtering of the background noise; the identification and elimination of the noise made by water slamming was particularly difficult and in some cases impossible to eliminate.

Rogers & Stambaugh (2014) describe the application of in-service Acoustic Emission (AE) and strain monitoring for locating stable propagating fatigue cracks in ship hull structures. A new fracture mechanics approach to fatigue damage assessment and crack life prediction is introduced as the basis for the interpretation of results. Provisional results for potential fatigue sensitive structural details are reported as obtained during a measuring campaign performed on board of the USCG Bertholf cutter. The authors underlie the physics of stable fatigue crack growth in metals and the acoustic emission produced by the associated micro-fracture events. New numerical models to simulate the fatigue crack growth and the associated acoustic emission, incorporating the latest developments in our understanding of the mechanics of fracture on an atomic scale, are described. Examples are given of in-service global AE surveillance of ship hull structural details. When combined with strain monitoring at suitable locations in the same structural area, the estimated crack growth from the AE measurements can be modelled as a function of the strain energy input to the platform (cumulative cyclic loading) to predict the crack propagation life.

2.7.3 New full scale monitoring campaigns and related studies

Applications of HSMS on board of merchant ships have increased and studies of long operating periods offer interesting insights in particular about the relevance of high frequency loads on fatigue life of ship structures and on the response of the ship hull girder to different environmental conditions in general. Often, results derived from sea measurement campaigns, are compared with theoretical predictions based on different level of fidelity, ranging from the rules empirical formulations on the lower end, to seakeeping predictions including slamming induced whipping on the other end. In exceptional cases of larger research projects, grouping classification societies, ship hydromechanics labs and industry, model scale test are also performed and results obtained in model scale are verified with the measurements taken by the HSMS at sea.

Frangopol et al. (2013) propose an integrated life-cycle framework to address maintenance of reliability of naval ships structures, in which they envisage the use of structural health monitoring to provide a powerful and necessary mechanism to reduce uncertainty, calibrate, and improve structural assessment and performance prediction models. Various applications are worked out with their method integrated with HSMS data, among which a US Navy high speed catamaran and a tanker. Their analysis framework is aimed ultimately to serve the US Navy to optimize inspection planning.

Storhaug & Hareide (2013) report an interesting analysis of a three year long measuring campaign of deck strains acquired on a blunt merchant ship. The characteristics of the ship have not been released for confidential reason, not even the size, but possibly the so called blunt ship which has been measured in ballast and cargo conditions should be generally representative of tankers or bulk carriers. The ship was recently designed and built for a longer target life than usual in unrestricted service and consequently strengthened beyond the minimum industry standards. A basic HSMS system compliant with DNV hull monitoring rules was installed onboard to collect and process data from: GPS for position, course and speed; gyro for ship heading; wind sensor for wind speed and heading; two strains sensors on the deck amidships, one on port, one on starboard side. Data were collected in a period of three years. The measured fatigue life based on a stress concentration factor of 2.0 has been estimated to be well below the design life. It is found that whipping and springing loads contribution to the fatigue life is about 42%, highlight the importance of these high frequencies dynamic responses for the lifecycle design of blunt ships. No particular difference was noted in between the cargo and ballast conditions, in terms of vibration contribution to the total fatigue damage. The stresses measured during three extreme weather events encountered by the ship (in Northern Pacific) have been generally higher than the IACS rule wave bending stress level. In the worst storm, actually the structure of the vessel could have collapsed without the extra-margins on strength used for the design to allow for the unknown whipping contribution.

The conclusions of this study in terms on the effect of whipping and springing on the fatigue life of ships are completely opposite to those drawn in the monitoring study of USCG cutters, later on described. The reasons have to do principally with the different extreme weather conditions encountered by the two vessels during their operation, but also to the different hull shape (very slender with deep-V sections at bow as opposed to blunt hull with presumably flat bottom also at the bow) as it is expected to have a considerable influence on slamming events and loads.

These conclusions are confirmed by another analysis study of HSMS measurements made by Storhaug et al. (2013) on a LNG carrier. Although the considered ship is less blunt than the previous one (with a slenderness midway between tankers and container carriers), the relative importance of whipping and springing on the total accumulated fatigue damage is still around 40% (32% in ballast and 45% in cargo conditions). The analysed data refer to a period of 5 years of unrestricted service on worldwide trade routes (40% time in the North Atlantic) and information from wind (simple anemometer) and waves (radar) was also included. As for the previous vessel, head and bow quartering seas are responsible for the most part of the fatigue damage. The measured stresses in Beaufort 6, corresponding to sea state 3-4, contribute the most to the fatigue damage. The information about the encountered sea states permit the comparison between numerical and measured wave damage which in this case is surprisingly good: only 3% deviation. This confirms that the measurement of the incoming sea state is very useful information for through life cycle and maintenance planning.

Kahl et al. (2013) report the results of a monitoring campaign performed on two container carriers: a 4600 TEU Panamax ($L = 275$m, $B = 32.25$m, $T = 12$m, $C_B = 0.672$, $V = 23$ knots) and a post-Panamax ($L = 356$m, $B = 51.2$, $T = 13.5$m, $V = 26$ knots). The period of observation is shorter, corresponding to a single round the world route. Weather conditions encountered by the Panamax included severe weather, while the post-Panamax sailed in milder sea states. For this reason prediction of the fatigue life of ship structure was also repeated superimposing the high frequency load contribution derived from the measurement on the long term linear seakeeping predictions (frequency domain, 3D panel method) of rigid body motions and hull bending moment in waves.

On both ships, global loads were monitored by strain gauges placed on three different stations along the ship. Also, additional strain gauges were arranged in the same sections in such a way to enable the separation of vertical and horizontal bending moment and torsion. The strain data were complemented by ship motion measurements obtained from an inertial platform installed in the deck house and accelerometers at the bow and stern and by measurement of the directional sea state via an X-band radar scanner mounted on the foremast.

Also in this case, by means of spectral analysis of the monitored stresses and a standard rain flow counting method, the accumulated fatigue damage was quantified from the data collected on the two ships. Low pass filters were applied to distinguish the effect of high frequency loads (whipping and springing) on the overall fatigue accumulated damage. On the Panamax ship, the measured high-frequency loads contributed 32% to the total fatigue damage on the route in the North Atlantic and 41% on the PAX route that excluded the North Atlantic and the North Pacific. To represent typical world-wide service routes, these measured high-frequency contributions of the Panamax ship were utilized to extrapolate the high-frequency response of the post-Panamax ship operating in severe seaways. For the PAX route, this resulted in a high-frequency contribution of 51%. Indeed this estimate of the quantitative contribution of high frequency response to the total fatigue budget of the ship obtained by Kahl et al. (2013) is significant and in the same order of magnitude of those found by Storhaug & Hareide (2013) for the blunt ship or by Storhaug et al. (2013) for the LNG carrier. The fatigue life prediction of the two ships was estimated by an empirical method based on the linear seakeeping predictions based on zero speed green functions with forward speed corrections (Papanikolaou & Schellin 1992). According to this method, the high frequency hull girder response contribution derived from full-scale measurements is added on top of the rigid moment to derive the fatigue life for the total long term response on the basis of a GWS (Global Wave Statistics) annual directional scatter diagrams relative to the areas touched by the ship route weighted with their probability of occurrence over the whole ship life. According to this semi-empirical method, for the Panamax ship the contribution of high-frequency loads was found to go down to 35% of total damage (instead of 41% straightly derived from the relatively short time measurements at sea), while for the post-Panamax ship the contribution goes up to 57% (instead of the 51%).

The long term seakeeping predictions on wave scatter diagrams have been used also to predict the maximum wave bending moment encountered by both ships in their lives. In both cases the predicted values exceed the envelope curve representing the average rule-based value of the hogging and sagging wave-induced VBM (Germanischer Lloyd 2012) applied for fatigue strength checks. For the Panamax ship the rule curve is exceeded by 30%; for the post-Panamax ship, by 20%.

At this point, it is worth noting that there is neither common recognized procedure nor even a recommendation at regulatory level to include high frequency dynamic response loads on the fatigue life prediction of ships for design. The research in this field is still trying to quantify the uncertainties level behind different theoretical or semi-empirical procedures, i.e. different seakeeping predictions methods, different sea state statistical characterizations, different hull structural models, etc.

The panoramic given on recent studies about HSMS application and data elaboration ends on fast military vessels. In this case, the first results of large campaign monitoring structural response initiated by the United States Coast Guard (USCG) have been recently presented at the Symposium of the Ship Structural Committee. Some years ago, USCG initiated a project to assess fatigue design approaches for its new National Security Cutters (NSC). The results reported by Drummen et al. (2014) have been obtained from the long term monitoring campaign on NSC USCGC Bertholf: a 120 meters long, 4500 ton full load, cutter. The unit was instrumented with a rich combination of sensors and tested along almost 9 months. Sensors included: 24 LBSGs whose locations on the ship is given in Figure 3, 73 unidirectional strain gauges, 26 accelerometers, 28 fatigue damage sensors, and a wave radar.

The full scale measurements were complemented by numerical calculations and model tests in waves on a self-propelled self-steering segmented hull built in scale 1:25 at MARIN. The model was composed of six segmented rigid segments connected by a flexible backbone. Very good correlations (maximum error in the order of 10%) are shown between the results of the measured bending moments in model tests and at sea. Based on results from the model tests, it was concluded that weakly nonlinear effects do not contribute significantly to fatigue damage.

For sea states with a significant wave height smaller than about 4m, whipping loads have a limited contribution to the fatigue budget consumption. This result is completely opposite to what found on the merchant ships previously mentioned. This may be due to the different type of ship (deep-V bow sections), different structural dimensioning philosophy and particular severity of the wave climate experienced.

Using the same data acquired at sea on the same ship, another study presented by Hageman et al. (2014) was just dedicated to the comparison between theoretical/numerical methods for the prediction of the fatigue life of a naval unit with respect to the measurements. The scatter of the results obtained from four different seakeeping codes presented in the study of Hageman et al. (2014) well express this concept.

As also remarked in the previously mentioned paper of Drummen et al. (2014), the first perhaps biggest uncertainty affecting long term predictions of maximum stress levels on ship hulls and in parallel the ship structure fatigue life, is the statistics of the sea state in the operational area of the vessel: data acquired by monitored ships at sea often show deviations from the GWS, which seems to be the main source of sea state statistics taken in the design phase. The noted deviation could be due to a general change of environmental conditions or to the pro-active decision of captains that try to avoid extreme sea states by changing the route. The relevance of this human factor is addressed in the study of Stambaugh et al. (2014), which presents a detailed analysis of the uncertainty deriving from various factors in the assessment of the fatigue life of a ship. First principle considerations formulated in this work are general and can serve as a guideline also for other studies based on HSMS data; their quantitative validity though only applies to the particular case of the USC cutter on which measurement data were collected. The relative weight of various factors influencing the uncertainty level in the prediction procedure of the ship fatigue life, found by Stambaugh et al. (2014) on the USCG Bertholf cutter, is given as follows:

- wave environment: 50%
- wave spreading: 20%
- number of days at sea: 18%
- loads prediction: 8%
- fatigue calculation (rainflow counting, stress definition): 4%.

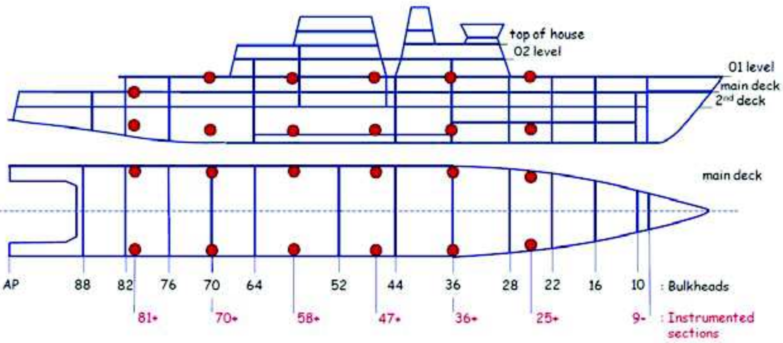

Figure 3. Locations (indicated with dots) of the LBSGs installed on USCGC Bertholf cutter (Drummen et al. 2014).

They encourage the use of the method proposed by Sikora et al. (1983) and Sieve et al. (2000) or similar spectral fatigue approaches in the early design since they may produce significant returns of investment when compared to modifications required late in the design process, unplanned ship repairs and sustainment cost. By comparison with values derived from the measurement campaign, they also conclude once again that improvements are recommended for the Sikora et al. (1983) approach to fatigue damage from impact loading and whipping response. Their conclusion appears very well supported by all the other studies referenced in this section.

2.8 Uncertainties

In structural dynamic systems, there are various sources of uncertainty. The sources of the uncertainties include but not limited to (a) parametric uncertainty - e.g., uncertainty in geometric parameters, manufacturing tolerance, damping coefficient, strength of the materials involved; (b) model inadequacy arising from the lack of knowledge about the model which is a-priori unknown; (c) experimental uncertainty and unknown error percolate into the model when they are calibrated against experimental results; (d) computational uncertainty e.g. machine precession, error tolerance in finite element analysis, and (e) model uncertainty genuine randomness in the model.

Uncertainties generally appear to be random phenomena. Some of them such as material property variations may be modelled in terms of probabilities, and others such as geometry variations are difficult to quantify. There are two basic approaches to introduce uncertainties into structural dynamic analyses. The parametric approach identifies model parameters individually and treats them as random variables within the structural models. The nonparametric approach considers the overall effects of all the uncertainties on the structural dynamical behaviours without specific analyses of individual uncertainties. Characterizing dynamic properties of structures with uncertainty is an important task that provides critical predictive information for structural design, assessment, and control.

Various methods are developed and applied for vibration analysis with uncertainties. The book entitled “Probabilistic Methods for Structural Design” edited by Guedes Soares (2012) covered the recent advances on modelling of uncertainty, prediction of the strength of components, load modelling and combination, assessment of structural systems, stochastic finite elements and design consideration. Considering ship operational and environmental uncertainties, procedures for the short term and the long term prediction of wave-induced and whipping bending moments are developed by Ćorak (2013).The problem was formulated in the frequency domain using standard engineering tools for the load computation: a seakeeping code for the rigid-body response and a beam finite element model for the transient vibratory response.

DiazDelaO et al. (2013) applied Gaussian process emulators to alleviate the cost of characterizing the random response of a structure subjected to vibration. The effectiveness of the method was demonstrated by performing uncertainty analysis of the frequency response of a non-proportionally damped plate made of a carbon fibre/epoxy composite material. Xia & Tang (2013) presented Gaussian process regression as an efficient approach to analyse structural dynamics, especially characterizing structural responses under uncertainty. This method uses only relatively small samples to make predictions about the collective response characteristics, and computational costs thus can be saved remarkably. A two-stage hierarchical modelling strategy has been adopted for Gaussian processes to bypass the difficulty in numerical integration involved in a full Bayesian framework.

Regarding the vibration of a structure with uncertain properties a novel method, referred to as the Stochastic Reduced Order Model (SROM) method, is proposed by Grigoriu (2013) for finding statistics of the state of linear dynamic systems with random properties subjected to random noise. The method is conceptually simple, computationally efficient and non-intrusive in the sense that it uses existing solvers for deterministic differential equations to find state properties. Choi et al. (2014) investigated the sound radiation from a vibrating plate having uncertain dynamic properties. Estimates are developed for the reverberant vibration field in the uncertain plate subjected to a point-excitation, and for the ensemble average of pressure from the direct field and from the reverberant field, leading to an estimate of the average sound intensity.

Accurate prediction of the vibro-acoustic response of a structural system with uncertain properties is an important issue in the design of engineering structures which are sensitive to manufacturing imperfections. The difficulty of the problem is mainly embodied in two aspects, i.e. modelling approach and uncertainty description. Existing literature provides two typical approaches including Finite Element (FE) method and Statistical Energy Analysis (SEA) to model the system. In general, FE is the most common technique in engineering practice with low frequency vibration while conversely SEA is especially developed to deal with high frequency vibration. However, the “mid-frequency” problems are not avoidable for the two methods.

As far as the description of system uncertainties is concerned, either parametric or non-parametric models can be employed. Specific physical properties of the system are considered to be uncertain in the parametric model, whereas the non-parametric model concentrates on the effects of uncertainty at a higher level by using some form of random matrix theories.

Cicirello & Langley (2013) proposed a hybrid FE-SEA method, in which some components are assumed to be deterministic, modelled by FE and other components to be highly random modelled by SEA employing a non-parametric model of uncertainty. The coupling between the FE and SEA components is affected by using the “diffuse field reciprocity relation”, and the resulting method can adopted to yield both the ensemble mean and the variance of the response.

However, the division of the system into “deterministic” and “random” components is not always appropriate in the case that some components may contain a degree of randomness, even though they cannot be appropriately modelled as SEA subsystems. In order to address the problem, Cicirello & Langley (2014) extended the hybrid method by applying parametric uncertainty models to components that are not highly random, thus allowing an enhanced description of these components in the mid-frequency range.

In nonlinear domain, the stochastic multi-dimensional harmonic balance method is proposed by Didier et al. (2013) in order to solve dynamical problems with non-regular non-linearities in presence of uncertainties. The quasi-periodic stochastic dynamic response is evaluated considering uncertainties in linear and nonlinear parts of the mechanical system. The problem of optimal sampled-data vibration control for nonlinear systems with time delays and uncertainties is considered by Lei (2013). The time-domain response of a randomly parameterized structural dynamic system is investigated by Kundu & Adhikari (2014) with a polynomial chaos expansion approach and a stochastic Krylov subspace projection, which has been proposed here. The simulations have been performed for different degrees of variability of the input randomness and different dimensions of the input stochastic space and compared with the direct Monte-Carlo simulations for accuracy and computational efficiency.

To control vibrations for structures with uncertainty, Seigler & Hoagg (2013) presented a controller for uncertain structures that are minimum phase and potentially subjected to unknown-and-unmeasured disturbances. The controller is applied to structures modelled by finite-dimensional vector second-order systems with unknown and arbitrarily large order. With the purpose of simplifying the Nonlinear Optimal Vibration Control (NOVC) design, the original time-delay sampled-data system is converted into a discrete-time non-delayed system first, as well as the nonlinear and uncertain terms is treated as external excitations. A new procedure on random uncertainty modelling is presented by Gan et al. (2014) for vibration analysis of a straight pipe conveying fluid when the pipe is fixed at both ends based on the stochastically nonlinear dynamic theory and the Galerkin method.

For practical application in ships, a special issue themed in "Uncertainty Modelling for Ships and Offshore Structures (UMSOS)" is published in Ocean Engineering 2014 based on the context of the joint ISSC-ITTC UMSOS. Papanikolaou et al. (2014), Kim & Hermansky (2014) and Qiu et al. (2014) reported recent advances in modelling the combined hydrodynamic responses of ship structures using cross-spectral combination methods and in implementing uncertainty models used for the development of modern decision support systems as guidance to ship's master. Kim & Hermansky (2014) discussed uncertainties in seakeeping analysis and the related ITTC procedures for loads and responses in waves. The inherent variability and epistemic uncertainties associated with wind and wave data, including model tests, are discussed and their consequences on specification of design criteria are illustrated by examples. The authors conclude that following a well-established verification and validation process is important in order to understand the error sources and the degrees of uncertainty and accuracy of both computational predictions and model tests.

Ship structures are subjected to various deteriorating mechanisms throughout their service life. This deterioration is highly uncertain and can adversely affect the performance and safety of the vessel. Deteriorating mechanisms affecting ship structures and their prediction models under uncertainty are reported by Frangopol & Soliman (2014) in the Handbook: Damage to Ship Structures under Uncertainty: Evaluation and Prediction (2014).

Ćorak et al. (2014) give an outline on how to derive wave time traces from a given sea state, which can be used for such response calculations. The crux of their approach lies in explicitly addressing the correlation between the wave bending moments and the whipping induced bending moments through a probabilistic approach. It may be worthwhile to investigate whether the approach followed by the authors can be used to deal with uncertainty of dynamic structural response as well.

2.9 Standards and acceptance criteria

This section focuses on noise, vibration, and shock acceptance criteria and procedures for their measurement. International standards with regard to habitability, underwater noise radiation, and shock test for ships are reviewed.

2.9.1 Habitability

IMO recognized the need to establish mandatory noise level limits for on board living and working spaces. In 2012 the Maritime Safety Committee (MSC) adopted resolution MSC.337 (91) which contains a new code with mandatory and recommendatory provisions to prevent seafarers from hazardous noise levels and to provide standards for an acceptable environment (IMO 2012a) . Newly adopted SOLAS regulation II–1/13-2 as contained in resolution MSC.338(91), IMO (2012b), will apply the Code to ships of 1,600 GT and above

- with a building contract placed on or after 1 July 2014; or
- in the absence of a building contract, the keel of which is laid or which is at a similar stage of construction on or after 1 January 2015; or
- delivered on or after 1 July 2018.

For applicable ships smaller 10,000 GT the limits remain the same as specified in IMO Resolution A.468 (XII) , whereas for ships greater or equal 10,000 GT noise level limits in accommodation areas are decreased by 5 dB. Also stricter requirements are settled for the measurement companies and instrumentation. Measurements shall be conducted under simulated port conditions and at normal service speed at no less than 80% of the Maximum Continuous Rating (MCR). For thrusters, measurements shall be made at 40% thruster power.

On the 20^{th} August 2013 the ILO MLC (2006) came into force setting minimum standards, for the health, safety, and welfare of seafarers. The regulations are subject to the implementation into national laws. The convention specifies requirements with respect to preventing the risk of exposure to hazardous levels of noise and vibration and is calling for a decent ambient. The limits for noise levels defined in IMO Resolution A.468 (XII) (1982) are commonly understood as satisfactory for compliance with the noise aspects of the convention. Because MLC 2006 does not define limit values for vibration exposure, this should be addressed by the national legislations. Most of the flag states that ratified the convention so far did not concretise the convention in this respect. Recently the Flag of Antigua and Barbuda encouraged both existing and new vessels joining the registry to comply with guidance such as that contained in GL Guidelines for Compliance with MLC 2006 Noise and Vibration Requirements and also the MSC.337(91).

GL's guidelines (2013) specify quantitative vibration and noise levels and define the process and requirements for the approval of the corresponding service suppliers. Since some competent authorities especially in the EU define vibration limits in way of daily exposure action and limit values acceleration to ISO 2631–1, a simplified procedure to determine the daily vibration exposure based on a state of the art sea trial measurement acceleration ISO 6954 is introduced.

Guidance for complying with the convention's requirements is also provided in the Guidance Notes of ABS (2010) and BV Guidance Note (2012). Both give assessment criteria and measurement methodology for obtaining a voluntary class notation.

IACS (2013) published its human element recommendations for structural design of lighting, ventilation, vibration, noise, access and egress arrangements. The objectives of this recommendation are to summarize information for human element and ergonomics during the structural design and arrangement of ships e.g. to reduce noise and vibration in manned spaces. All four standards IACS, ABS, BV and GL refer to the IMO Resolution A.468 (XII) or MSC.337(91) with respect to the applicable noise limits and define a vibration acceptance criteria of 6mm/s maximum overall frequency-weighted r.m.s. velocity values.

One of the aims of the EU funded SILENV (2012) project was to define a set of new pre-normative requirements able to enforce a significant reduction of the noise and vibration impact of shipping activities. The requirements for internal noise were set on the basis of an analysis of existing requirements, a collection of existing and new data of noise measurements, and a correlation of noise measurement results with the human perception, acquired through a large number of questionnaires, distributed on board ships. Compared to MSC.337(91) the limits are significantly lower, e.g. for cabins a limit of 50dB(A) is proposed. The same is true for the proposed vibration limits compared to ISO 6954 with limit values of 1 to 3 mm/s maximum overall frequency-weighted r.m.s. velocity values.

Also requirements for noise emissions in air aiming at ensuring living conditions for inhabitants of the areas close to shipping activities were specified by the SILENV project. 75dB(A) at 25m was proposes as radiation limit from sailing ship and 70dB(A) at10±1m for moored ships at quay.

2.9.2 Underwater noise

IMO has published MEPC Circ. 833 "Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life" which sets out advice on design and operational solutions that may be adopted to reduce underwater radiated noise (IMO 2014).

ISO (2012a,b) has developed the ISO/PAS 17208–1 – Acoustics – Quantities and procedures for description and measurement of underwater sound from ships – Part 1: General requirements for measurements in deep water and ISO/DIS 16554.3 – Ship and marine technology – Measurement and reporting of underwater sound radiated from merchant ships – deep-water measurement.

Italian class society RINA has combined these standards into the DOLPHIN notation. The notation to be published in 2014 will give requirements on instrumentation, site and procedures to carry out the measurements, and will describe the information and post-processing activities necessary for reporting. Limits both for when the ship is underway and quiet ship operational modes are established. By this RINA is the second class beside DNV (Det Norske Veritas 2010) publishing underwater noise rules.

In a similar matter the SILENV (2012) project introduced pre-normative limits also aiming at reducing the impact of shipping on marine mammals. The limits are based on the present state of the art, represented by the most silent existing commercial vessels. Two curves are provided for commercial ships, corresponding to the design speed "transit", while the "quite" condition is related to a reduced speed, particular studied in order to minimize the acoustic impact e.g. of cruise ships in protected areas.

EU is funding two ongoing underwater noise projects, SONIC and AQUO. With respect to pre-normative standardization SONIC's objective is to develop test measurement techniques for determining the noise footprint at trial. Whereas AQUO's objective is to deliver practical guidelines for the ship design and shipping control and regulation.

2.9.3 Others

The common German Dutch shock standard BV 0230 / D5050-0599 was revised in 2013. The main alterations are

- the standard now contains ship type specific, operational status and shock zone dependent shock response spectra,
- four independent load cases shall be considered in shock analysis, one in each of the three ship's axes and one ellipsoid loading,

- for mast modules still individual loads shall be derived by full ship FEM calculations,
- for the propulsion system a dynamic shock calculation shall be conducted based on shock loads to be provided by the naval authorities. The simulation model needs to consist of the shaft, bearings, struts and propeller,
- for rigidly mounted equipment the NRL-Sum-Method is now also applicable,
- the permissible stresses were revised.

ISO published ISO 20283-4 (2012a) focusing on the measurement and evaluation of vibration of the ship propulsion machinery.

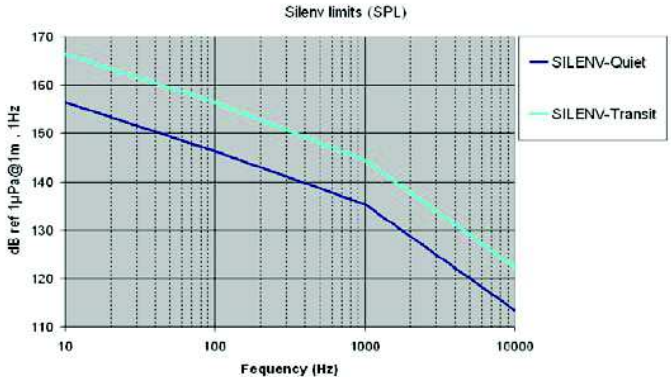

Figure 4. SILENV limits for the underwater noise radiated from commercial ships (SILENV 2012).

3. OFFSHORE STRUCTURES

3.1 Vibration

This section covers vibration in offshore structures due to several environmental sources such as wind (3.1.1), wave (3.1.2), ocean currents (vortex shedding, 3.1.3) and ice (3.1.5), as well as internal flow-induced vibration, which results from operational conditions (3.1.4). Even though they are treated herein as separate physical mechanisms, they are frequently concurrent, therefore should be treated altogether. The excitation mechanism phenomena are complex in nature and often the structure response exhibits nonlinearities. The current state of knowledge for the vibration assessment and analysis of offshore structures are discussed herein.

3.1.1 Wind-induced vibration

Owing to the characteristics of the jack-up drilling unit, the environment loads are important factors to the structure safety. According to the MODU rule, the projected area method is used to calculate wind load. In Hu et al. (2013) a 400ft jack-up is studied as an example. Considering the Reynolds number effects, the wind loads of jack-up both in normal drilling and severe storm conditions are obtained in the experiment. Compared with the results which are calculated according to MODU rule, it is found that the experimental results give lower response levels. The effect of aerodynamic interference between the different parts of the structure is hence believed to be important.

In Jameel et al. (2014) a spar platform which is subjected to both wave and wind loading is analysed, and the corresponding steady-state response behaviour is studied. The wind loading which is acting on the exposed part of the platform is decomposed into mean and fluctuating wind forces. The spar responses in surge, heave and pitch along with mooring top tension are computed. The spar platform is found to experience a significant lateral offset in the wave direction due to the wind loading. Inclusion of wind loading also leads to an increase of the standard deviations of the surge and heave responses, in particular for the latter. The mooring line tension increases for wind loading but the corresponding increase of the dynamic tension fluctuations is very modest.

For floating offshore wind turbines, the simultaneous action of waves and wind are usually considered. This applies both for model and full-scale testing as well as for numerical response analyses. Accordingly, it is not always easy to identify the wind-induced versus wave-induced components. Furthermore, it is not always possible to make a distinction between low-frequency versus high-frequency response components. In the following a brief review of model tests and numerical analysis of floating wind turbines is given.

Such floating platforms can be grouped into three categories: spar, semi-submersible and tension leg platforms. Each has its benefits and drawbacks. Turbine designs require that pitch angle during operation is below 10^o, and with the large mass and thrust loadings inherent to these devices these low motions can be difficult to achieve. A very informative review of different concepts for floating wind turbines is given by Nicholls–Lee et al. (2014).

Offshore wind turbines are designed and analysed using comprehensive simulation tools (or codes) that account for the coupled dynamics of the wind inflow, aerodynamics, elasticity, and controls of the turbine, along with the incident waves, sea current, hydrodynamics, mooring dynamics, and foundation dynamics of the support structure. Comparison of computed results obtained by application of different computer codes is hence important. This topic is addressed e.g. by Robertson et al. (2014) in relation to a 5-MW wind turbine installed on a floating semisubmersible in a water depth of 200m.

In a similar manner, verification of computed response with corresponding results from model tests and full-scale measurements is a very important issue; see e.g. Robertson et al. (2013) in relation to the test campaign which was performed for the DeepCwind Consortium. Model testing techniques are discussed e.g. by Kimball et al. (2014). An example of a comparison between the resulting DeepCwind test data and corresponding numerical calculations is provided by Koo et al. (2014).

Design verification of various floating wind turbine concepts by model testing is addressed in a number of recent papers; see e.g. Adam et al. (2014) for testing of the GICON concept which is based on a Tension Leg Platform (TLP) floater. Testing of the GustoMSC concept with a semi-submersible floater is presented in Huijs et al. (2014). Testing of the VolturnUS concept is described in Young et al. (2014). This turbine was installed in May 2013 and has a tower which is made of composite materials; see Lim et al. (2013). Comparative testing of different floater types (i.e. TLP, spar and semi-submersible) was described by Nihei et al. (2014).

A comparison between full-scale measurements and numerical analyses is provided by Utsunomiya et al. (2014). The floating foundation is of the spar type. It carries a 100kW wind turbine of the down-wind type, with a rotor diameter of 22m and a hub-height of 23.3m. The floating foundation consists of an upper part made of steel and a lower part which is made of prestressed concrete segments. The turbine was installed at a site about 1km offshore from Kabashima Island, Goto city in the Nagasaki prefecture in 2012. Since then, field measurement had been made until its removal in June 2013.

Full-scale measurements for the same turbine subjected to extreme wind excitation levels which were experienced during the typhoon Sanba (and other somewhat weaker typhoons) are reported by Utsunomiya et al. (2013).

Jia (2014) calculates wind-induced fatigue damage of offshore structures employing nonlinear time domain dynamic analysis. He investigates the role of drag coefficient, comparing Norsok and DNV specifications, showing that the former is more conservative. He also addresses the impact of time step and duration and flare boom connections' stiffness on the response. Results for static and dynamic analyses (non-structural elements' inertias are considered) are compared and he identifies that it is important to take into account the contribution of secondary components such as flare and vent lines when assessing the fatigue damage. He also investigates the role of the structure self-weight and discussed the non-Gaussian nature of the statistical distribution of the local responses. Finally he emphasizes that the fatigue methodology presented can be extended to other offshore tubular structures exposed to wind excitation.

3.1.2 Wave-induced vibration

Wave load is one of the important environmental loads to offshore platform design, dynamic action of waves on the ocean platform play a significant role in platform design to the deep regional development. Offshore structures are designed to resist continual wave loading which may lead to significant fatigue damage on individual structural members, and other types of loads due to severe storms, corrosion, fire and explosion etc. The associated pressure pulsations excite the piping and/or equipment, which may result in serious damage (Nakamura et al. 2014).

To date, the current design philosophy for the prediction of motions and wave-induced loads has been driven by empirical or first-principles calculation procedures based on well-proven applications such as ship motion prediction programs. Some of the recent advances in the assessment of loads for ships and offshore structures with the aim to draw the overall technological landscape available for further understanding, validation and implementation by the academic and industrial communities (Hirdaris et al. 2014). By artificially introducing a proper time-delay into control channel, a delayed H_∞ controller is designed to attenuate the wave-induced vibration of the offshore platform and thereby improve the control performance of the system (Zhang & Tang 2013).

Zhang et al. (2010) reviewed progress in the evaluation of wave forces on both slender and stocky offshore structures in detail, with emphasis on the correlation between analytical/theoretical solutions and full-scale measurements. Hydrodynamic impact and statistical aspects of wave-induced motions and loads are briefly considered.

Recently on a previously unknown phenomenon in wave-induced vibration of the flexible structures with large aspect ratio (length to diameter) was discovered in field experiments, which shows that traveling wave rather than standing wave dominates the response of wave-induced vibration (Wu et al. 2010).

The wave-induced pressure is termed the push-and-draw pressure. At present, this push-and-draw pressure is analysed using the potential theory developed for dissipative wave radiation problems (Anami et al. 2012).

In both the mono- and multi-frequency types of response, the flow excites the structural vibrations within the lock-in region and damps the structural motions in the non-lock-in region. The multi-frequency character of the response impacts both the lock-in phenomenon and the fluid–structure energy transfer (Bourguet et al. 2012).

A more practical approach entitled Modified Endurance Wave Analysis (MEWA) considering the random and probabilistic nature of wave loading and utilizing optimal time duration is introduced. MEWA can be a time-saving and also reliable method both in design and assessment of offshore platforms (Diznab et al. 2014). The quantification of uncertainties may be challenging in model tests and numerical simulations of ocean and offshore structures (Qiu et al. 2014). After considering more practical factors, it is expected to be more applicable in structural damage assessment (Wang 2013).

The stochastic dynamic analysis of structure with and without damper is first presented in frequency domain for parametric study on the performance of both the dampers to control wave induced vibration response. The optimum performance of Tuned Liquid Column Damper (TLCD) and Tuned Liquid Column Ball Damper (TLCBD) systems is further investigated to study the effectiveness of a particular damper system over the other (Chatterjee & Chakraborty 2014).

3.1.3 Vortex-induced motion

Floating offshore platforms which are subjected to a uniform current may oscillate laterally across the current if the vortex shedding frequency is in the vicinity of the natural surge and sway frequency. This phenomenon is called Vortex Induced Motion, or VIM. Understanding VIM is of utmost importance to the oil and gas industry, because especially spar platforms are very prone to it, with potential motion amplitudes being of the order of the spar diameter. These types of motions have a significant impact on both the mooring and the riser fatigue design. In particular, Steel Catenary Risers (SCRs) suspended from the floater can be sensitive to VIM-induced fatigue at their mud line touchdown points. Strakes are typically on the hull of the spar platform in order to mitigate or reduce the amplitude of motions to a more manageable level.

At present, it seems that a widely applied approach for spar platforms is to calibrate numerical calculations based on Computational Fluid Dynamics (CFD) analysis to experimental data obtained from laboratory testing. Subsequently, a large number of parametric studies can be performed purely by application of the numerical model. Benchmark studies have been performed in order to improve confidence in CFD, see e.g. Halkyard et al. (2005, 2006).

Simulations of spar geometries with increasing detail are typically performed starting from a hull with strakes, adding pipes and mooring components and also incorporating truss structures if such are present. The effects of each component can then be studied and the corresponding effect on VIM response can be quantified. It is generally found that quite accurate predictions are possible and that it is practical to incorporate CFD into the design process. Screening and the generation of response curves can be done during initial design and more targeted assessments during detail design, see Oakley & Constantinides (2013).

In Lefevre et al. (2013) a set of VIM CFD simulations for a spar hard tank with appurtenances is described together with comparison against a high quality scaled model test. The test data showed considerable sensitivity to heading angle relative to the incident flow as well as to the magnitude of the reduced velocity. The simulated VIM induced sway motion was compared against the model test data for different reduced velocities and spar headings. Agreement between CFD and model test (VIM-induced) sway motion was within 9% over the full range of parameters. Guidelines were provided for meshing and selection of time step/solver settings.

The time variation of the experimental added mass coefficient and also the natural frequency of a truss spar were investigated by Zhang, H. et al. (2012). The mean added mass coefficient as well as the time-variable added mass coefficient was calculated based on measurements obtained from model test.

In addition to spar platforms, it has also been observed that e.g. deep draft semisubmersibles are subjected to VIM motions; see e.g. Gonçalves et al. (2012a, b) and Zou et al. (2013). The impact is not as significant as for the spar design, because the column diameters are generally smaller, and the hull footprint larger. However, the understanding of the maximum motion characteristics is of critical importance. This applies in particular to semisubmersibles with dry tree applications.

Although the potential for VIM of multi-column floating platforms such as semi-submersibles and TLPs is well-acknowledged, the industry guidelines for design with respect to VIM are not comprehensive and more research effort seems to be required.

Application of model tests combined with CFD analysis is also found to be feasible methods to investigate VIM for the present type of platforms. Subsequent to the model tests and preliminary CFD simulations, further CFD analyses can be carried out using improved simulation techniques by means of commercial software. Good agreement between model test results and CFD calculations for VIM of a multi-column floating platform was reported by Tan et al. (2013). Sensitivity of CFD results to the modelling assumptions such as mesh size and density, time-step size and different turbulence models was also presented.

In Rijken (2014) the effect of the mass ratio and the effect of performing physical experiments at model scale are examined through CFD analyses for the hull of a semisubmersible platform. The objectives of the CFD analyses are to focus on the VIM phenomenon itself and to compare response magnitudes, while giving less importance to the hull details and absolute response magnitudes. Responses for various cross-sectional shapes of the columns are examined which comprise square, rectangular and five-sided geometries.

A comprehensive evaluation of the experimental investigations during the past decade on the VIM was performed by Fujarra et al. (2012). One of the observations was that the effect on VIM due to the coexistence of current and wave-excitation still deserves a better understanding. It was recommended to perform a comprehensive investigation with consideration of a wide variety of wave characteristics. The intention should be to propose better procedures on how to consider wave-excitation and VIM during the first stages of design. Hence, excessively conservative predictions can be avoided.

This issue of VIM in the presence of waves superposed on a stationary current was investigated for a large-volume semi-submersible platform by Gonçalves et al. (2012a); see also Gonçalves et al. (2012b). The VIM model tests were performed both with regular waves and also different irregular wave conditions which were characterized by spectral density functions. Significantly different behaviour was observed for regular versus irregular waves. For regular waves, motion amplitudes in the transverse direction were strongly reduced and no VIM was observed. However, for the case of irregular waves, the amplitudes decreased slightly (as compared to the case with only current being present) but a periodic motion which is characteristic for VIM was still observed.

VIM for other types of platforms than traditional semisubmersibles is also considered. In the already mentioned work by Zou et al. (2013), results for VIM towing tests of a Paired-Column Semisubmersible (PC Semi) platform are reported. The PC Semi configuration is different from a conventional Deep Draft Semi (DD Semi) in three aspects, 1) 8 columns versus the more traditional 4 columns; 2) rectangular column shape versus square column shape; 3) larger column slenderness ratio. The influence on VIM from key design parameters, such as gap distance between the inner column and the outer column, platform draft and mooring stiffness were investigated systemically.

Model testing and CFD simulation are used in order to investigate VIM behaviour of a TLP platform by Tan et al. (2014). A mono-column hull type was investigated by Saito et al. (2012).

3.1.4 Internal flow-induced vibration

Offshore floating production units contain a large number of pipes and equipment to process the oil and gas, however vibration due to internal flow has not been explicitly reported in applied publications.

A dynamic analysis of elastic cylindrical shells subjected to annular gas flow is developed by Bochkarev & Matveenko (2013). The rotating fluid is assumed compressible and described by a potential theory. A semi-analytical variant of the finite element method is employed and the shell stability is analysed for different boundary conditions, geometrical and physical parameters. The effect of the outer shell elasticity on the hydro-elastic stability is investigated.

Chang & Modarres-Sadeghi (2014) develop a numerical solution to investigate the Hopf bifurcation stability condition of a cantilevered pipe conveying fluid subject to small displacement periodic base excitation. The pipe may experience flow-induced planar or non-planar oscillations when flow exceeds the critical velocity. The cantilevered pipe may experience 2 and 3D quasi-periodic and chaotic oscillations at high velocities. The problem is governed by three-dimensional nonlinear equations which are discretized using Galerkin technique and the resulting set of algebraic equations is solved by a finite difference method. The authors advocate that the numerical predicted results qualitatively agree with previous experimental work.

3.1.5 Ice-induced vibration

This part of the review was divided into theoretical analysis, numerical simulation and model tests and field measurement.

Theoretical analysis:

Guo & Yue (2011) derived a criterion to predict the occurrence of ice induced self-excited vibration based on its physical mechanism. The criterion was expressed as a relationship among the structure's parameters (stiffness, damping ratio, and diameter etc.) and ice properties (thickness, moving speed, and compressive strength). Some measured data from full scale and model tests were used to validate the criterion. Meanwhile Guo (2012a), from the engineering perspective, analysed two ISO 19906 (2010b) standard criteria (damping criterion and velocity criterion) of Ice Induced Vibration (IIV) using data from two full scale structures, and found that the damping criterion was conservative and velocity criterion was reasonable. Guo (2012b) developed a simple spectral model to simulate continuous crushing ice loads based on ice load time series measured on the Norstromsgrund lighthouse. The model had only two input parameters and it was relatively easy to estimate ice-induced dynamic response of slender structures. A simulation example was also presented in the paper. Considering that the uncertainties of ISO 19906 standard of ice induced frequency lock-in vibration remained, Guo (2013) developed an approach to estimate the highest ice velocity causing frequency lock-in vibration. He predicted the possible range of dynamic ice load, and estimated the structural response if the dynamic portion of ice load was given.

Yue & Guo (2012) and Wang & Yue (2013), based on the observation on a prototype offshore structure, proposed a physical mechanism to explain the ice induced self-excited vibration where a single vibration cycle was divided into two phases: the loading phase and the unloading phase. It was assumed that the compressive strain rate in the ice sheet was close to ductile-brittle transition during the loading phase. An approximate quantitative analysis and verification was made for the proposed mechanism.

Yan (2013), based on the analysis of ice failure process observed in the field and ice load and structure response data, described the ice failure of lock-in vibration as a ductile damage – collapse failure process. A method of using an ice breaking length was presented to estimate the vibration magnitude.

The number of vibration cycles caused by frequency locked-in ice load is one of the key parameters for fatigue evaluation. Bjerkås et al. (2014) proposed a new method to estimate the number of vibration cycles and applied it to the Norstromsgrund lighthouse. Comparing with other methods, the authors showed that all available methods overestimate the number of vibration cycles significantly.

IIV can influence the crew members both physiologically and psychologically when working and living in a vibrating environment for long periods of time. Zhang, D. et al. (2012) conducted a study which was based on data monitored on the platforms. Human feeling and dynamic response of the pipeline on the platforms caused by deck vibration were evaluated. By comparing with the Chinese standard "Reduced Comfort Boundary and Evaluation Criteria for Human Exposure to Whole-body Vibration" evaluation results for the JZ20-2 platforms showed that serious IIV made work efficiency degrade, and conventional IIV exceeded comfort degradation boundary. IIV can also lead to the associated accidents to pipelines, such as fatigue fracture of the pipes and loosening of flanges.

Metrikine (2011) compared three induced vibrations: vortex-induced vibration of deep water riser, IIV of flexible offshore platform, and pedestrian-induced vibration of bridge. He attempted to analyse synchronization phenomenon in these three vibrations and tried to help cross-fertilize the research in the fields.

Numerical modelling:

Nandan et al. (2011) used Maattanen's model to predict Steady-State Ice Induced Vibration (SS-IIV) of the Norstromsgrund lighthouse. A closed-form stability contour based on eigenvalue analysis was developed to define a boundary for ice-structure conditions conductive to SS-IIV, which can be used to guide structure design away from SS-IIV at an early stage of the design process.

Hendrikse et al. (2011) investigated frequency lock-in vibration of a generalized beam with a modification of the Matlock-Sodhi-Huang strip model. The study was tried to answer three interesting questions: (i) can IIV occur at high ice sheet velocities? (ii) what are the conditions for IIV to occur at a higher natural frequency of the structure? (iii) can an initially aperiodic ice loading cause IIV? And further, as a part of Joint Industry Project (JIP), Hendrikse & Metrikine (2013) studied an effect of friction in ice-structure interaction and to answer a question: why were modelled ice loads off more than 100% from measured load for a slender cylindrical structure. A Coulomb friction law was implemented in the simulation and results showed the maximum increase in ice load was in the range of 15% when taking into account the friction.

Shkhinek et al. (2013) developed a 2-D numerical solution of IIV using the discrete element method. The modelling of the ice was based on PFC2D-Particle Flow Code. All the results were qualitatively and, in some cases, quantitatively consistent with data from model tests and field measurements.

Popko (2014) simulated the dynamic response of the Norstromsgrund lighthouse in ice. A 3D numerical model of the lighthouse was setup based on the solid elements in Abaqus software. And the eigen-frequency response of the numerical model was tuned to correspond with the structural response of the full-scale lighthouse.

Wind turbine dynamic behaviour in ice is also an interesting study. Hetmanczyk et al. (2011) simulated wind turbine dynamic behaviour in ice by using the OnWind simulation software where dynamic ice loads were calculated by an empirical ice model. Influences of ice velocity, ice thickness, and damping effects of ice-structure and air-structure interaction were taken into account. By using commercial software Abaqus, Jussila & Heinonen (2012) also predicted ice-structure interaction response in the time domain for a cylindrical substructure and a conical substructure of a wind turbine. Comparison of the results between cylindrical and conical structures showed that the conical structure can reduce IIV.

Model test and field measurement:

Currently model test and field measurement is still the most important tool and very active in the investigation of IIV even though a higher cost is needed.

Karna et al. (2013) introduced a JIP entitled "Ice Induced Vibration" sponsored by some offshore oil companies for development and validation of models of IIV. The background, progress and some validation findings were presented. The JIP activity includes workshop, reviewing experience from laboratory to full scale, model development into working software, and validation of the software. Results from the first phase of this project, completed in June 2012, were given in detail.

In 2011 NTNU also started a project "Deciphering Ice Induced Vibration" (DIIV). The objectives of the project were to design and manufacture an adaptable test set-up, to conduct scale-model test, and analyse results. The program included a series tests with ice properties, ice velocity, structure waterline, surface roughness, structure compliance, natural frequencies, etc. Three papers related this project were published in IAHR2012. Maattanen et al. (2012) introduced the measurement project, test rig design, instrumentation, experiment program, and an overall view of achieved results. Nord & Maattanen (2012) described an indirect approach, which was based on a frequency response function, to measure dynamic ice load. Hendrikse et al. (2012) presented the forced vibration experiments in order to identify the added mass and added damping in dynamic ice-structure interaction.

Yap (2011) and Yap & Palmer (2013) replicated various IIV modes in a model test from low to high indentation velocities in order to investigate the mechanics of the Steady-State Self-Excited vibration (SSSE). Analysis of the test results together with a collection of existing full-scale structure and model test data was made and used to formulate a hypothetical framework of the mechanics of dynamic level ice–structure interaction. A dimensionless parameter was proposed to predict the occurrence of SSSE. A suggestion was made to discard Froude scaling and to adopt Cauchy scaling and replica modelling in the simulation of SSSE.

Bjerkås et al. (2012) used Norstromsgrund lighthouse full-scale data from winter 2002 to 2003 to study a question: whether IIVs were more frequent in specific time periods? It was found that the IIV seemed to occur more frequently when the ice cover was warmer which corresponds with relative high air temperatures and significantly higher drift speed of the ice. Bjerkås et al. (2013) also analysed the Norstromsgrund lighthouse field test data, which occurred on 30 March 2003 and was one of the harshest vibrations during the entire measuring program 1999-2003. He concluded that spatial synchronization of local loads was the reason for triggering of frequency locked-in vibration.

Palmer & Bjerkas (2013) analysed the field record data on nine load panels of the Norstromsgrund lighthouse, and found synchronization phenomenon of the nine loads in frequency and phase when the IIV began. An idealized model was used to explain the synchronization.

Gagnon (2011) introduced a high-speed imaging method (up to 30,000 images/s) to observe ice crushing against a plate in laboratory-scale experiments. Lock-in vibration was observed at two different frequencies, which was a frequency of the pump/actuator system (350 Hz) and a flexural resonant frequency of the acrylic platen (900 Hz), by means of image analysis and ice load record. It also pointed out that these observations were relevant to large-scale ice-structure interaction. Focused on an ice-crushing induced vibration of Molikpaq (May 12, 1986), Gagnon (2012a, b) proposed a relationship between the spalling frequency and ice sheet speed, and the lock-in occurred when the spalling frequency was in the vicinity of the resonant frequency of the structure-ice system. He made an explanation for the event in terms of ice spalling frequency, spalling mode, and variation of the effective mass and effective spring of the structure-ice system.

Tian & Huang (2012) investigated a series of model tests on new compliant four-leg model where each leg of the model was installed as ice breaking cone. It was found that the ice sheet broke non-simultaneously before each single cone, and the structure was easy to be excited in nonlinear resonance.

Lan et al. (2011) introduced a measurement of IIV of the JZ9-3W HPB platform in Bohai Sea, China with a remotely controllable system. According to the field test data and vibration mode of the platform the effect of anti-ice induced vibration structures were analysed, and ice resistant proposals were presented also.

Wang & Yue (2012) conducted a field measurement of a fixed ice-breaking cone which was installed on the vertical riser of the JZ9-3E platform in the Bohai Sea, China in order to reduce IIV. The field measurements and observations showed that the fixed ice-breaking cone was successful to reduce the vibration.

Nord et al. (2013) investigated force identification methods in the frequency domain when a flexible structure was acted on by an ice sheet and its response was measured from a set of non-collocated measurement transducers. An example of the experimental result was discussed.

Huang et al. (2013a, b) conducted model tests to investigate the dynamic ice loads on two types of four-legged jacket platform (cylindrical and conical models). The comparison showed that ice load and structure response levels were significantly lowered by introducing a cone fixed to the platform legs, but amplifications of the foundation reactions were higher in the cone test than those in the pile test.

Ziemer & Evers (2014) conducted a series of model tests in ice for a compliant cylindrical structure. The IIVs were observed and were categorized into four different types of vibration according to their characteristics: random, straight, circular and periodic vibrations. It was found that the same ice conditions can lead to both periodic and straight vibrations, meanings that the loading frequency can be doubled or even multiplied by three without visible change of outer circumstances.

3.2 Very large floating structures

Very Large Floating Structures (VLFS) enable the creation of land from the sea without the need for a massive amount of fill materials. These kinds of structures have been gradually appearing in many parts of the world for applications such as floating bridges, floating piers, floating performance stages, floating airports, and floating storage facilities (Wang et al. 2008). Pontoon-type VLFS have large horizontal dimensions and a relatively small depth. Due to this small depth to length ratio, VLFS are often modelled as an elastic plate under wave action. Within the hydroelastic analysis, which can be carried out either in the frequency or time domain (Wang & Tay 2011), the interaction of the fluid and the structure is taken into account.

In Gao et al. (2011) the hydroelastic response of a VLFS is considered by modelling the structure as a thick Mindlin plate and the water as an inviscid and incompressible fluid with an irrotational flow. The modal expansion method proposed by Newman (1994) is applied to decouple the fluid-structure interaction problem and the hydroelastic analysis is carried out in the frequency domain. The Laplace equation is solved with the boundary element method and the finite element method is applied to compute the deformation of the floating plate. In this way the influence of flexible line connections on the hydroelastic response can be studied, demonstrating that hinge and semi-rigid line connections allow reducing the hydroelastic response and the corresponding stress resultants in the VLFS. In Yoon et al. (2014), a numerical procedure for the hydroelastic analysis of floating plates with hinges is presented and validated by experiments. The influence of the hinge connections on the maximum bending moment is studied for different structural and wave conditions. It is demonstrated that the hinge connection has a strong effect on the hydroelastic response of the VLFS.

Papaioannou et al. (2013) present a stochastic hydroelastic analysis approach for VLFS assuming that the surface waves can be described by a directional wave spectrum. The hydroelastic analysis is carried out in the frequency domain, taking advantage of the modal expansion method. The fluid potential is solved by the boundary element method and the Mindlin plate theory is discretized with the finite element method. Applying the linear random vibration theory, the stochastic hydroelastic analysis of VLFS is studied for multidirectional irregular waves. The influence of the mean wave angle on the standard deviation and extreme values of the deflection and stress resultants is found to be very strong.

The numerical and experimental analysis of a hydroelastic response of a VLFS edged with a pair of submerged horizontal plates in the time-domain is presented by Cheng et al. (2014). To this end, a direct time domain modal expansion method is applied to the fluid-structure interaction problem. Based on the numerical simulation and experiments the response-reduction efficiency of a VLFS equipped with submerged horizontal plates is studied. The measured data and the simulation results are found to agree well. Applying the simulation approach, different variants of submerged horizontal plates can be investigated and an improved design of the anti-motion plate can be suggested.

3.3 Noise

Noise and underwater sound due to exploration, construction, transport, drilling, and production is important for offshore activities. Identification of pertinent mechanisms, multiple potential noise sources, and noise paths from vessels and drilling platforms are necessary for implementation of effective treatments. Hence, the subject of noise can be divided into two major branches in which specific sources and noise makers are identified, and possible treatments for those sources, mechanisms, and paths are considered.

With the rising number of offshore activity, the noise emission into the sea, caused by pile driving for the foundations of the wind turbines and offshore structures, becomes an issue of great importance. Considering the immense costs and high logistic complexity of offshore tests, there is a strong demand for numerical models, which are able to calculate the resulting underwater sound of pile driving activities. Consequently, study for noise mitigation measures such as bubble curtain was carried out.

3.3.1 Analysis of underwater noise by pile-driving

Numerical study for underwater noise by pile-driving for wind turbines was studied by Lippert et al. (2012) and Tsouvalas & Metrikine (2013, 2014). In the study of Lippert et al. (2012), a 2D modelling approach for the acoustic near field based on the finite element method is able to correctly reproduce the general characteristics of the underwater sound pressure field due to pile driving. Besides a qualitatively proper representation of the developing pressure wave at the pile and the corresponding reflections at both seabed and water surface, also a feasible magnitude for the absolute peak values of the sound pressure could be achieved.

Tsouvalas & Metrikine (2013, 2014) studied a linear semi-analytical formulation of the coupled vibro-acoustics of a complete pile–water–soil interaction model. The pile is described by a high order thin shell theory whereas both water and soil are modelled as three-dimensional continua. Results indicate that the near-field response in the water column consists mainly of pressure conical waves generated by the supersonic compression waves in the pile excited by the impact hammer. The soil response is dominated by shear waves. The Scholte waves are also generated at the water–sea bed interface which can produce pressure fluctuations in the water column that are particularly significant close to the sea floor. The effects of soil elasticity and pile size are thoroughly investigated and their influence on the generated pressure levels is highlighted.

3.3.2 Measurement and mitigation of underwater noise

Marine impact piling is a significant source of low-frequency impulsive noise and Robinson et al. (2012) described methodologies developed for measurement of marine piling including estimation of the energy source level. Measurement was made during construction of an offshore wind farm involving piles of typically 5 m in diameter driven by hammers with typical strike energies of around 1000 kJ. Acoustic data were recorded using hydrophones deployed from a vessel, allowing the transmission loss to be confirmed empirically.

In order to effectively measure the underwater noise by offshore oil production vessels, Erbe et al. (2013) performed the underwater acoustic recordings of six Floating Production Storage and Offloading (FPSO) vessels. Monopole source spectra were computed for use in environmental impact assessments of underwater noise. Given that operations on the FPSOs varied over the period of recording, and were sometimes unknown, the authors present a statistical approach to noise level estimation. No significant or consistent aspect dependence was found for the six FPSOs. Noise levels did not scale with FPSO size or power.

Kuhn et al. (2012) have developed a new underwater piling noise mitigation system, Hydro Sound Dampers (HSD). The HSD is based on the theories of dispersion, dissipation and resonance effects for elastic balloons. One of the main advantages of the HSD is that the mitigation can be pre-adjusted to a pre-defined frequency range, as marine mammals are sensitive only for a certain sound frequency range. The results of a small scale tests and a full scale test were promising a reduction of 12 dB up to 20 dB. The research findings concerning the shape and the material of the HSD were also presented.

Bohne et al. (2014) have performed numerical modelling of a bubble curtain to reduce the underwater radiated noise from pile driving and Wochner et al. (2014) developed a new prototype open-ended resonator design and tested for the purpose of incorporating arrays of the resonators into an underwater noise abatement system. Individual resonators were designed to have a resonance frequency near 100 Hz in order to reduce the low frequency noise by pile driving and drilling.

3.3.3 Equipment noise

Decoupling between vibrating machinery and ship & offshore structures produces both a significant reduction in the vibration power transmitted to the hull and a reflection of some vibration energy back to the machinery. Moro & Biot (2013) carried out the experimental test of ISO 10846–1~5 standards that has been applied in order to achieve the dynamic response of a very large resilient mounting specifically designed for a medium-speed marine diesel engine. The results obtained by the experiment show that experiments are able to give useful information which, without complex data manipulation, clearly identify dynamic behaviour of the resilient elements in both the vertical and horizontal direction.

Wang & Shen (2014) developed the active vibration isolating system which can effectively reduce the low-frequency noise transmission of the diesel engine. The technical problems are discussed to meet the engineering application requirements when the active vibration plant is used for ships and offshore structures, such as the control of installation size and weight, engineering reliability, the configuration of active and passive vibration isolation components, anti-shock measures, electromagnetic shielding measures and external interfaces.

Machinery resiliently supported by rubber or metal isolators constitutes a most common mounting system. But at high frequencies, standing wave resonances occur in isolators and isolation effect would be diminished. Xu et al. (2014) carried out the experimental study for engine mounting system that about 30 dB attenuation of vibration acceleration can be obtained at most of frequencies above 1 kHz especially for the modern variable speed electric motor. The study applied the two-stage mounting system with an intermediate mass which is smaller and lighter than conventional mass. The experimental results showed that over 45 dB isolation effects can be obtained at the switching and harmonic frequencies.

Pipe or duct elements like orifices and constrictions are widely used in pipe or HVAC system and are often responsible of turbulent flow noise and whistling. The characterization requires the development of new techniques to describe the dynamics of the noise sources and the flow-acoustic interaction. Sovardi et al. (2014) studied the identification of noise sources in internal ducted flows using LES (Large Eddy Simulation) and SI (System Identification) in order to characterize simultaneously both the acoustic passive scattering and the active noise generation of an orifice placed in a duct or pipe.

3.4 Blast

The topsides of offshore platforms are the most likely areas to be exposed to hazards such as hydrocarbon explosions. Profiled barriers are being increasingly used as blast walls in offshore topside modules to provide a safety barrier for personnel and critical equipment. The corrugated blast walls are one of the common passive protection systems. Most existing stainless steel blast walls are rated to a pressure of approximately 1 bar. However, some joint industry projects have shown the possibility of blast-induced overpressures as high as 4 bars. The blast walls can be designed using the Single Degree Of Freedom (SDOF) method as recommended in the design guidance and a time-domain finite element commercial software should be used for predicting the response of blast wall panel by the Technical Note 5 (TN5) issued by the Fire and Blast Information Group (FABIG 1999, Fischer & Häring 2009).

Sohn et al. (2013) conducted the structural response analysis of FPSO topside blast wall under explosion loads, in which the computed based time-domain nonlinear finite element analysis and single degree of freedom method based on resistance function were adopted. The results show that both methods have more similar results at larger deflection domain than smaller deflection domain and results of the SDOF method are less conservative than the finite element analysis results. Nwankwo et al. (2013) examined a blast wall partially-retrofitted by Carbon Fiber Reinforced Plastic (CFRP) patches in the central region for understanding the effect of a composite patch on the blast resistance of profiled blast walls. The analysis results show that the strengthened scheme was able to absorb more blast energy than the un-strengthened scheme and an average reduction of 33% in the maximum displacement was observed in the inelastic response.

Sandwich panels are widely used in various fields because such panels have lower density, easier fabrication method and higher strength and blast resistance compared with monolithic plates. The dynamic response of a sandwich structure depend upon many parameters, including the properties of the skins, the compressive/shear moduli of the core, the strength of the core, as well as the strength of the bond between the skin and core. In many cases, the strength of the sandwich structure is controlled by the failure characteristics of the core material and the skin-core interface.

Balkan & Mecitoğlu (2014) investigated the dynamic behaviour of a viscoelastic sandwich composite plate subjected to the non-uniform blast load by theoretical and experimental study. Parametric studies show that increasing the thickness of the core layer is more effective than the increase of face layer thickness. In order to observe a good structural vibration damping, increasing the thickness of the core layer is recommended. Guan et al. (2014) conducted the comparison of the stitched and unstitched sandwich panels suggested that for a given impulse, the stitched laminates exhibited a slightly superior blast resistance. Results show that the through-thickness stitching does not play a significant role in enhancing the blast response of the sandwich panels.

Li et al. (2014) investigated dynamic response of corrugated aluminum sandwich panels under air blast loadings experimentally and numerically. Parametric studies show that the residual deflections of the face sheets can be effectively reduced by increasing the thickness, the yield stress and the contact area of face sheets and core. Jing et al. (2014) experimentally investigated the deformation/failure modes and blast resistance of cylindrical sandwich shells comprising two aluminum face-sheets and an aluminum foam core, subjected to air blast loading. Various failure modes - indentation or tearing of the front face-sheet, collapse of the core, severe inelastic deformation or tearing of the rear face-sheet, and failure between the face-sheets and foam core, were observed. The findings are useful for validating theoretical predictions, as well as to guide application of cellular metal sandwich structures for blast protection purposes.

3.5 Damping and countermeasures

Methods for vibration control of structures can generally be classified into three main categories: (i) passive control, (ii) semi-active control (i.e. tunable over time) and (iii) active control. While some of the methods that can be applied for this purpose are the same for land-based and offshore structures, additional options naturally arise for offshore structures. This is e.g. due to presence of thrusters for many floating vessels and the possibility of increasing the hydrodynamic damping and not only the structural (and possibly the aerodynamic) damping as for land-based structures. At the same time, the additional sources of hydrodynamic excitation clearly also represent challenges.

This is exemplified by the struggle to mitigate vortex-induced vibrations for offshore structures. Passive control methods are frequently used to control vortex shedding or the flow around the structure. They are used widely for VIV suppression (see e.g. Zdravkovich 1981, 1997, 2003, Bearman & Branković 2004, Assi et al. 2009, 2010). Passive control of aerodynamic and hydrodynamic devices are according to the classical text by Zdravkovich (1981) divided into three categories: (i) surface protrusion, (ii) shrouds, (iii) wake stabilizers. The passive control devices in the first two categories disrupt the boundary layer on the surface of the structure. The wake stabilizers hinder the two shear layers, thus weakening the vortex shedding process.

Helical strakes represent a much applied option for category (i) devices, i.e. surface protrusions. In Resvanis et al. (2014) the effects of strake coverage and marine growth on flexible cylinder VIV was investigated. The results show that even small bare sections (missing strakes) can lead to significant VIV response.

Results from two testing programs on long cylinders towed at high Reynolds numbers to assess the performance of helical strakes with differing conditions along the cylinder length are given by Allen & Liapis (2014b). Similarly, the performance of fairings was studied by Allen & Liapis (2014a). The results show that the coverage length, density, and location of the helical strakes or fairings have a substantial effect on both the local and global response of the tubular.

Ng et al. (2014) considered the effect of fairings for VIV suppression in relation to tandem risers by means of scaled model tests. Application of parallel and oblique plates for suppression of VIV was considered by Assi & Franco (2013).

Although helical strakes tend to reduce the VIV amplitudes, there are also cases with interaction between several cylinders where the opposite may occur. Freire et al. (2013) performed a study on how an upstream cylinder fitted with helical strakes can induce higher vibrations than bare cylinders in relation to a second cylinder mounted downstream.

Park et al. (2013a) investigated Passive Turbulence Control (PTC) in relation to flow-induced motions of a circular cylinder. The efficiency of different layouts of partial surface covering by means of longitudinal strips was compared. Furthermore, in Park et al. (2013b) suppression of flow-induced motions of two cylinders in tandem using surface roughness is studied experimentally.

Numerical studies are frequently employed as a supplement to experimental methods. Corson et al. (2014) studied the application of CFD to predict the hydrodynamic performance of different fairing designs. The VIV suppression effect for a finned cylinder was investigated by means of CFD in Wang, Y. et al. (2014). The numerical results show that the cylinder with fins can significantly modify the vortex shedding and synchronization process implying reduced vibration levels. Through numerical simulations, the flow past a circular section cylinder with a conic disturbance is investigated at subcritical Reynolds numbers by Lin et al. (2014).

Passive control of the vortex shedding process is also the basic mechanism underlying increase of roll damping for floating vessels by introduction of bilge keels. This is a widely applied scheme for floating production systems, and recent papers dealing with this subject are e.g. those by De Oliveira & Fernandes (2012), Minnick et al. (2012), Tom et al. (2012). The possibility of applying U-tanks for increase of roll damping was considered by E Silva et al. (2012).

Different methods for passive control of various types' offshore structures are considered in a number of studies. Bottom-fixed platforms are addressed e.g. by Lee, C.H. et al. (2014), TLPs by Chandrasekaran et al. (2014) and Very Large Scale Structures (VLSFs) by Wang, C.M. et al. (2012). Barges for support of floating wind turbines were studied by Shadman & Akbarpour (2012a, b).

Active control schemes implemented as Dynamic Positioning (DP) systems are much applied for floating vessels. These are based on the application of counteracting forces (that sometimes can be represented as additional stiffness and damping) for floating vessels by means of thrusters. This is in order to control the motion levels, primarily those associated with slow-drift motions, see e.g. the classical texts by Balchen et al. (1980) and Saelid et al. (1983). Here, just a brief summary is given of some of the recent developments of such control algorithms.

Sliding mode control algorithms are investigated by De Sousa & Tannuri (2013). Two robust control techniques were applied and compared: first order Sliding Mode Control (SMC) and Higher Order Sliding Mode control (HOSM). To validate the simulated controller, experimental tests were performed considering a small-scale model of a DP tanker.

Different algorithms for DP heading control were compared by Miyazaki et al. (2013). The paper addresses the analysis of the final equilibrium heading of several published weathervane control strategies for two different DP vessels. The computed headings are also compared to the exact minimum power heading.

DP thrust allocation algorithms which also take into account the physical limitations of each thruster such as the maximum thrust (saturation), the maximum rate of turn (azimuth) and the maximum rate of change of RPM were addressed by Arditti et al. (2014).

The very few full-scale DP operations in the Arctic have demonstrated the need for improvements in DP systems for ice-covered waters. An example of a controller which is addressing ice-related challenges is presented by Kerkeni et al. (2013).

3.6 Uncertainties

The uncertainties depend on the phenomenon that is studied and on the time and spatial scales of interest. Obisesan (2012) divided the uncertainty of offshore structures into the following two major categories:

- Epistemic: The uncertainty induced by the lack of knowledge, and it is predictable.
- Aleatory: The system has an intrinsic random or stochastic nature and it is not predictable.

The epistemic systems have uncertainty that may be reduced upon additional information. Uncertainty in a structural member may be reduced by measurement of the element behaviour. Aleatory uncertainty assumes that an underlying Probability Density Function (PDF) exists and is the square of the wave function in quantum mechanics and also, the PDF is a fundamental property of the system. In most engineering systems, the PDF is obtained from historic data and represents both epistemic and aleatory uncertainties. Thus, the precise form of a PDF can only be assumed. On the other hand, interval methods play an important role in quantifying epistemic uncertainty.

During the modelling data obtained from oceanographic instruments it is necessary to identify uncertainties. The condition assessment of offshore structures is very challenging due to the presence of various uncertainties in the geometric properties and material and load characteristics. Complex interactions do exist between different uncertainties and the significance of extreme value effects in the reliability analysis. The model of these uncertainties is used in limit states formulated to meet design criteria for structural members.

The results of reliability and uncertainty analysis provide rational assertion on how more attention should be given to the ultimate capacity of structural members and the representation of least sensitive random variables with deterministic values. The uncertainty quantification and also structural dynamic analysis help in identifying structural components that could lead to collapse of offshore structures and also revealing the true state of structures. This information eventually contributes knowledge to risk assessment and improve on the safety of personnel and properties operating on offshore structures.

In Wang & Li (2013) the wave-induced vibration of offshore platform with Magneto-Rheological (MR) damper is presented. The model of the platform coupled with MR damper is established where the external wave force is approximated with a white noise via a designed filter. A lot of control strategies have been investigated and illustrated to be effective for structural vibration mitigation. The authors considers that full state feedback is required for an effective control which need a lot of sensors, and uncertainty in measuring state variables can’t be considered.

In Rezanejad & Guedes Soares (2013) the performance of floating oscillating water column in finite water depth is analysed based on the linearized water wave theory in the two dimensional Cartesian coordinate systems. It is assumed that the floating oscillating water column is very large and has negligible motions and is therefore considered as fixed. The free surface inside the chambers is modelled as a non-plane wave surface. The boundary integral equation method is employed to solve the associated boundary value problem and the multi region concept is used to overcome the numerical errors due to the assumption of thin barriers. The numerical results are compared with the existing experimental results and analytical results and the accuracy of the numerical model is evaluated. The effects of the geometrical dimensions of the floating oscillating water column and harbour attached to the device are investigated.

3.7 Standards and acceptance criteria

Revision works for dynamic ice action and responses

Dynamic ice actions are addressed in ISO 19906 Clause A8.2.6. However, the ISO provisions are not enough to conduct a fully dynamic design of an offshore structure under ice action. Especially, information on floating structures is limited and only generalities are offered in the normative part A8 or A13 involving check lists and general recommendations for design, but no guidance on induced ice actions, including ice scenarios is offered. In addition, ISO 19906 does not provide implicit or explicit guidance for the design and operation of arctic pipelines.

Therefore, through Barents 2020 project (Det Norske Veritas 2012), which was supported by Russian, Norwegian authorities, and international oil and gas industry, an additional guidance document was developed for design against ice loads on stationary floating structures. With respect to dynamic response, these were focused on a consistent methodology for application of the recommended analytical ISO formulas to derive the global ice load as a function of the floater's response and table over calculation methods for ice loads with original references and applicability ranges.

Furthermore, by Joint Industry Project (JIP), Det Norske Veritas (DNV) is developing DnV-RP-C209 (2009) which is a new recommended practice for arctic structures and pipelines. The focus of this rule is on describing methodologies for qualifying assessment tools and in generating rational characteristic values to describe the governing ice regime during the life time of the pipeline system. Particular attention is being paid to ice gouging and optimized pipeline burial depth, where assessment methodologies and tools are very much at the cutting edge of technological development. However, DNV had not published this recommended practice and it is expected to be released in the near future.

Revision of comfort and health notation

BV notation of comfort and health on board (Bureau Veritas 2013) for noise and vibration was revised to enhance its practicability, which is applicable to all offshore units. In the notation, the procedures for measurement of airborne sound insulation index between rooms and calculation of reverberation time in space was more specifically described.

4. CONCLUSION

An overview of the technical literature related to dynamic response of ship structures over the past three years clearly indicates continuation of concern for environment-induced vibrations, which was also an important issue in the previous reporting period. This is the true not only for springing and whipping, but for ice-induced vibrations too. Springing and whipping remain to be important topic, which is particularly consequence of increased number of very large ships having benefit of economies of scales. A large number of full-scale measurement campaigns, mostly related to large container ships, have been reported. Reasonably, the same vessel types are mostly considered in a number of reported model tests and numerical calculations. Hence, it is obvious that all available methods i.e. full-scale measurements, model tests and numerical methods were combined to assess wave effects on ship structures. Most of full-scale measurements offered information on the influence of high-frequency vibrations on fatigue. Also, some interesting observations on total structural damping are reported. Model tests mainly concern segmented models with an elastic backbone (BB), or with flexible hinges, while the use of fully flexible models has not been reported. Since mostly container ship models were investigated, challenges related to torsional response assessment as a consequence of shear center below the keel arise irrespective on the segmented model type selection. From the references related to numerical calculations, slamming and whipping are recognized as important subjects. In whipping calculations boundary methods and field methods are distinguished. Still, the most common method for calculation of the slamming forces has been the von Karman momentum approach, while recently Generalized Wagner Method (GWM) has become very attractive, or Modified Logvinovich Model (MLM) as its simplification for blunt sections.

In case of ice-induced vibrations, both ship hull and propeller interactions were investigated. Important topics like pressure distribution and structural response in ship-ice interaction are dealt with by model tests and numerically. Some estimation methods for excitation forces and vibration levels are offered based on records from icebreakers and ice-going ships. However, general conclusion on this topic is that additional effort is necessary to improve numerical techniques and related methodologies for reliable prediction of ice-induced vibrations. Hence, it is expected that this topic will attract many studies in near future.

Different aspects of propeller-induced vibrations are considered in the reporting period in rather low number of publications: application of transfer matrix method for shafting line dynamic response assessment, prediction of hull pressure fluctuation induced by propeller sheet cavitation, performance analysis of a periodic isolator to reduce the vibration and noise radiation influenced by propeller forces, etc. Also, application of Computational Fluid Dynamics (CFD) tools for some particular problems is noted. In spite of new developments of engines with ultra-long stroke and low revolution rate, which are recognized to have better efficiency but at the same time having increased external forces and moments transmitted to the ship hull, there is lack of references related to the machinery-induced vibrations in the reporting period. However, some references related to testing of widely used friction connection and hydraulic type top bracings to control H-mode resonance and to reduce the vibration of the engine itself are reported.

In the context of numerical and analytical vibration studies, limited time and resources are recognized as drawbacks of finite elements, and therefore some simplified and approximate solutions are offered for vibration and buckling problems of isotropic and orthotropic plate structures as constitutive members of a ship structure, aiming at both modelling facilitation and simplification of finite element formulations.

A set of interior noise regulations is being put under discussion to check its compliance with actual technological developments. A-weighted sound pressure levels are confirmed to reliably indicate noise situation on board, although there were several studies aiming to develop more sophisticated indicators. However, it seems that some improvements of IMO A.468 (XII) are necessary. Alternative numerical methods to FEA/SEA based approaches are considered, but still correct modelling of nature of the coupling between structural elements remains to be the biggest limit of the available methods. Improvement of acoustic behaviour of insulation panels and partitioned walls is recognized as a trend, and extensive studies, mainly experimental ones, were conducted to enhance insulation performance by varying materials, panel constitutions, etc. Within the air radiated noise, which is relative new field of investigation, a big lack of normative regarding the protection of coastal inhabited areas and harbours is recognized. In that field most of publications originated from the findings achieved EU project SILENV. Many of the most recent studies in the field of underwater radiated noise are focused to establish its correct limit to be taken into account and in finding a correlation between such limit and the behaviour of the marine fauna. Still, underwater noise for military and civil applications is necessary to be distinguished. As expected, within the former one there are no references due to confidentiality issues, but within the latter one there are many studies particularly considering propeller's behaviours as a major source. Underwater radiated noise measurements are reported from several places worldwide, considering influence of different ship types on marine life. Also, within the ongoing EU project AQUO a description of the oceans environment as noise mapping is proposed in order to establish the effect of the anthropogenic sound on marine life.

Sloshing induced impacts are very important in the design of a ship tank and the CCS. Many physical effects have to be considered at the same time: gas cushion, liquid compressibility, boiling of liquid cargoes, aeration, thermal exchange, hydroelasticity. When analysing sloshing impacts, one must always have the structural response in mind. This implies that the fluid (liquid, gas) flow must be solved simultaneously with the dynamic elastic structural reaction.

It is common in tank design to do model experiments for sloshing-induced impact effects by means of forced oscillation tests. However, the scaling of the model-test results represents a challenge due to the many physical effects that may matter. This concerns not only the maximum values of the pressure but also their time evolution. The relationship between the temporal characteristics of the load and the structural response is nonlinear and dependent on the impact characteristics related to the natural periods of the structure. Therefore, the effect of scaling the pressure time histories may only be assessed by analysing the dynamic response of the containment system.

On numerical side, it appears that the correct numerical modelling of hydro-structure interactions during the sloshing impacts inside the LNG tanks is still beyond the state of the art and there is still no rational direct calculation procedure to be used for design verification of the CCS. The quasi full scale model tests and intermediate scale model tests are believed to bring more light into this difficult problem. In particular they could be used for detailed validation of the hybrid approach discussed in Section 2.4.2, which, once validated, could be put into the rational design methodology based on direct calculation approach. The full scale measurements and monitoring of the real LNG ships would be extremely helpful for better understanding of the way how the CCS is "suffering" in reality. How to perform these full scale measurements is another complex question. In any case, the actual situation is that, for the design verification of CCS, we still rely on the so called comparative approach. However, it is very important to mention that, in spite of all the imperfections of the comparative approach, the overall safety record of LNG floating units is excellent and only few incidents were experienced.

A benchmark study for shock response of panels to the blast loading is provided by the previous ISSC committee V.I report (2012), and in the reporting period several numerical investigations are reported on different issues as for instance dynamic failure of ship structure steel plate under near-field air-blast loading, effects of blast loading on response of corroded plates, weapons attack on ship structures (investigated also numerically), etc. Response of ship structures to the underwater explosions was mainly investigated utilizing finite element method in combination with different techniques. Shock resistance performance of different materials like composites, rubber coated plates and sandwich structures with core, is investigated both numerically and experimentally. Numerical studies dealing with the effect of bottom reflection of the shockwave in shallow water require further investigation to achieve general conclusion.

In the forced vibration analysis of ship structures, damping is still mainly accounted for in a simplified way, i.e. by lumping all its components together through a constant damping coefficient specified as a percentage of critical damping.

Hull structural monitoring systems for ships and offshore structures are basically the same. Advancements in new sensors technologies, large data handling and wireless communication networks are recognized in the reporting period. A general trend is to replace classical communication between the peripheral and main processing units with wireless or fiber-optic cables. Extensive review of new sensors technology and application particularly and related to optic-based, wireless and acoustic emission sensors is provided.

Among different sources of uncertainties, special attention was paid to ship operational and environmental uncertainty assessment.

Concern for ship habitability improvement is evident in the reporting period not only from the needs to establish mandatory noise level limits initiated by IMO, but also from guidelines and standards issued by IACS and related classification societies, referring to relevant IMO resolutions. Two ongoing EU underwater noise related projects (SONIC and AQUO) are expected to enhance standardization in measurement techniques for the noise footprint at trials and to deliver practical guidelines for the ship design and shipping control and regulation.

Vibration in offshore structures due to environmental and operational loads continues to be a major concern for design. Often several physical mechanisms occur simultaneously and cannot be treated separately. The excitation mechanisms are complex and the structural response frequently exhibits nonlinearities.

Wind-induced loads impact the safety of jack-up drilling units. The aerodynamic coupling between parts of the structure may be significant. For spar platforms, wind loading amplifies the standard deviations for surge and heave motions. The mooring line tension increases with wind loading but the dynamic tension fluctuations are modest.

Floating offshore wind turbines can be grouped into three major categories: spar, semi-submersible and tension leg platforms. Comprehensive simulation tools account for the coupled dynamics considering all relevant loading components: wind inflow, aerodynamics, elasticity and controls of the turbine, along with incident waves, marine currents, mooring and foundation dynamics of the support structure. For such complex analyses it is important to compare and validate numerical results from different codes with small and full scale tests.

Dynamic action from waves is important for offshore platform design. Emphasis has been placed on correlating results from analytical/theoretical solutions with small and full-scale measurements. However, in the motion prediction and wave induced loads assessment, still ship motion prediction programs are mainly used.

Vortex-induced motion occurs in floating offshore platforms subjected to uniform currents if the vortex shedding frequency and natural surge and sway frequencies are close. These motions particularly affect spar platforms, having also impact on mooring and riser fatigue design. It is important to calibrate numerical results from CFD with experimental laboratory data. Benchmark studies have improved confidence in CFD analysis. Deep draft semisubmersibles may also be subjected to VIM, however with lower impact on the design as compared to spar platforms. VIM in multi-column floating platforms is recognized, but industry guidelines are not comprehensive.

Although offshore floating production units contain a large number of pipes and equipment to process the oil and gas, it is difficult to find references explicitly reporting internal flow induced vibration.

Ice-induced self-excited vibrations depend on the parameters that characterize the structure as well as the ice properties. Relatively large number of measured data from full scale and model tests has been documented. Ice-induced vibrations can influence the crew both physiologically and psychologically.

Model test and field measurement are very important in order to complement and validate numerical analyses. Dynamic ice actions addressed in ISO 19906 are not sufficient for a full dynamic design of an offshore platform and arctic pipelines. DNV is working on a recommended practice to cover this deficiency.

Very Large Floating Structures (VLFS) have been considered for applications such as floating bridges, piers, airports and storage facilities. Pontoon-type VLFS have small depth as compared to their horizontal dimensions, therefore they may be modelled as an elastic plate under wave action. Bearing in mind their large dimensions, and consequently lower natural frequencies that can fall into the range of ordinary sea spectrum, hydroelastic analysis is recommended to be carried out both in the frequency and time domain.

Noise is important for offshore exploration and production activities. Identification of mechanisms, potential sources and paths are required. Numerical simulation of underwater noise by pile-driving for wind turbines reproduces the general characteristics of the sound pressure field. Marine impact piling is a significant source of low-frequency impulsive noise. Methodologies have been developed for estimation of the energy source level. Underwater noise has been measured in six Floating Production Storage and Offloading (FPSO) vessels.

Decoupling between vibrating machinery and the hull of ocean structures produces reduction in the transmitted and reflected vibration power. Active vibration isolating systems can effectively reduce low-frequency noise transmission in diesel engines.

In the context of blast loading, it is worthy to mention that offshore platforms topsides are the most exposed areas for hydrocarbon explosions. Barriers are being increasingly used in topside modules to safeguard personnel and critical equipment. Corrugated blast walls are commonly employed in passive protection systems. Sandwich panels are light, easy to fabricate and offer high strength and blast resistance.

Vibration control methods can be classified into passive, semi-active and active. Hydrodynamic excitation mechanisms represent challenges to offshore structures. To reduce vortex-induced vibrations passive control methods are used to control vortex shedding.

Sources of uncertainties generally need to be taken into account during the design process. These will typically be strongly dependent on time and spatial scales of interest. Uncertainties can in general be classified as (i) Epistemic: induced by lack of knowledge and (ii) Aleatory: intrinsically random or stochastic in nature. In practical assessment both uncertainty types are represented by probability density functions, with assumed form originating from historic data.

Within the contribution to standard and acceptance criteria improvement, some new guidances for design against ice loads and notations of comfort and health onboard are already offered in the reporting period, and also some recommended practices are expected to be released by the relevant subjects in the near future.

Generally, a significant contribution is achieved both in understanding of physical phenomena related to dynamic response of ships and offshore structures and their numerical and experimental modelling and monitoring. However, it is reasonable to expect that the trends in shipping and offshore industry mentioned in the Introduction will continue in the near future. Therefore, additional efforts of all relevant subjects are necessary to increase reliability and accuracy of available dynamic response analysis techniques.

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