Ship Stability, Dynamics and Safety: Status and Perspectives

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ABSTRACT

With the aim of analysing the current status and possible future perspectives of research in the field of ship stability, dynamics and safety, this paper deals with an extensive review of the research work presented at the International Conferences on Stability of Ships and Ocean Vehicles (STAB Conferences) and the International Ship Stability Workshops (ISSW) held during the period 2009-2014. The reviewed material is organised in different sections, corresponding to a set of identified main typical focal macro-topics of research. On the basis of the reviewed material, consolidated research topics are highlighted together with emerging topics, and ideas for possible future research and its needs and focus are provided. Discussion is also provided regarding the link between research and educational aspects.

Keywords: *ship stability; ship dynamics; ship safety; STAB; ISSW; review*

1. INTRODUCTION

Ship stability is undoubtedly a subject of paramount importance in the field of Naval Architecture, its fundamentals having wider implications for the design and operation of ships and floating units. Moreover, "stability" is a concept which, in Naval Architecture, has a very wide meaning, embracing ship stability fundamentals with ship dynamics and ultimately ship safety. In this respect, research in the field has received considerable attention within the whole maritime community, resulting in the contemporary evolution of the subject to the integrated notion of "ship stability, dynamics and safety" as it is being currently appreciated.

Although, due to its wide implications for the design, regulatory development and operation of ships, the subject receives attention in almost all the Naval Architecture scientific forums, the series of the International Conferences on Stability of Ships and Ocean Vehicles (STAB Conferences) and the International Ship Stability Workshops (ISSW) are certainly the venues where expertise and contemporary developments tend to be collected and thoroughly debated. Therefore, a review of the status and perspectives of research and contemporary developments in "ship stability, dynamics and safety", the subject of this paper, can certainly be considered as representative of the field when based on work presented in these series of international conferences and workshops. Following these considerations, herein a review has been carried out considering the series of the International Conferences on Stability of Ships and Ocean Vehicles (STAB Conferences) and the International Ship Stability Workshops (ISSW) organised during the period 2009-2014. This period was chosen since some of the contributions from earlier events have been reported in the "Contemporary Ideas on Ship Stability" series of two books [1.1, 1.11], in special issues of International Shipbuilding Progress [1.4, 1.9] and in some issues of Marine Technology [1.3, 1.5, 1.6]. It should be noted, however, that the work carried out in this review is to a very large extent exhaustive of the research included in the two STAB and four ISSW events covered in the review period (2009-2014), as compared to the selective earlier reporting, and this approach is in line with some reviews carried out in the past regarding single STAB events [1.2, 1.7, 1.8, 1.10]. For completeness of the review, some linked references presented elsewhere have also been included.

In order to provide an organised review, firstly, a set of main typical focal macro-topics of research related to the subject of ship stability, dynamics and safety have been identified. The paper has been organised in a series of sections corresponding to such topics, namely:

- Intact stability
- Damage stability
- Stability for specific types of vessels and floating objects (fishing vessels, naval vessels, inland vessels, other types of vessels and floating objects)
- Roll damping & anti-rolling devices, CFD for ship stability, and modelling of granular materials
- Ship stability in operation
- Modelling of environment

As a result, for each topic, a structured review is herein provided of the research carried out, organised in the appropriate sub-topics constituting the macro-topic covered in each section of the paper. The review is then followed by an elaboration of ideas for possible future research and its needs and focus.

Furthermore, the additional topic of "education" is also considered. In this context, some considerations are provided on aspects related to the transferring of present evolution of knowledge in the field of ship stability, dynamics and safety, to future Naval Architects during their university education.

2. INTACT STABILITY

Nonlinear ship dynamics in intact condition is one of the fundamental research topics when dealing with ship safety. Indeed, when comfort or operability are of concern, linear (or weakly nonlinear) approaches are typically sufficient. Instead, when the goal is to address the safety of the vessel in adverse weather conditions, large amplitude motions (particularly roll) are to be taken into account, with the consequent need of properly accounting for, and modelling of, (often strongly) nonlinear effects. In the past, nonlinear ship dynamics was often considered as an almost purely-research topic. However, with the increase of the computing capabilities and the advances of the research, this topic has transferred knowledge and tools also to the design and operation of vessels, as well as to the regulatory framework.

In the period of time considered in this review, an important topic has grown and has attracted attention, i.e. the IMO development of so-called "Second Generation Intact Stability Criteria (SGISC)". In this framework, a specific set of failure modes associated with potentially dangerous dynamic stability phenomena in waves are considered, namely:

parametric roll, pure loss of stability, surf-riding and broaching and excessive accelerations. Such failure modes are strictly connected with nonlinear phenomena. As such, criteria aimed at guaranteeing sufficient safety with respect to these failure modes, need to embed the main features of the underlying nonlinear dynamics. Furthermore, the 3+1 tiers structure of SGISC allows accommodating methodologies at different levels of sophistication, from simple approaches up to the use of more complex nonlinear ship motions time domain tools. The development of SGISC has therefore represented a direct or indirect attractor for a significant amount of papers investigating the dynamics of the various failure modes and/or presenting possible methodologies for addressing such failure modes at design (or operational) stage.

With regard to SGISC, continuously updating overviews of development and general discussions have been provided over time [2.1, 2.2, 2.3, 2.23 2.62, 2.81, 2.85], showing the evolution of the framework. The more advanced status of development has been achieved, so far, with respect to Level 1 and Level 2 vulnerability criteria for the various failure modes. In this respect, in the observed time period, proposals have been put forward for addressing parametric roll [2.24, 2.37, 2.38], pure loss of stability [2.24], surf riding and broaching [2.25, 2.37], dead-ship condition [2.38], and excessive accelerations [2.40]. Also, test applications, sample calculations and consistency checks of the available Level 1&2 proposals have been presented [2.84, 2.101]. Some specific experiments have also been carried out to validate the mathematical models proposed for being implemented in Level 1 and Level 2 criteria [2.39, 2.59, 2.94], and importance was also given to a designers-oriented clarification of the underlying dynamics of surf-riding [2.92]. A more specific attention is yet to be given to the topic of regulatory application of direct stability assessment and associated development of operational guidance, although the interest is growing over time. A specific general discussion on tools and methodologies for regulatory direct stability assessment was presented in [2.64], while a discussion on the development of appropriate ship-specific operational guidance for increasing ship safety was given in [2.26]. Direct assessment procedures for surf-riding and broaching assessment have been proposed in [2.25].

In parallel to the implementation of concepts and methods from nonlinear dynamics into design through SGISC, research has of course progressed on fundamental aspects of nonlinear ship motions. In the following, an attempt is made to report the identified contributions by dividing them according to failure modes considered by SGISC. However, this sharp separation, although pragmatic, is clearly an oversimplified scheme for categorizing stability-related research in the field on nonlinear dynamics in intact condition. A number of contributions indeed span among different failure modes, or touches diverse topics. Therefore, other subjects will also be considered in the following.

The first nonlinear phenomenon to be addressed is surely parametric roll. Indeed, among various potentially dangerous dynamic stability phenomena in waves, parametric roll has clearly gathered the majority of the attention. Specific benchmark studies have been organised in order to assess the prediction capabilities of existing simulations tools [2.18, 2.47]. An evolution in addressing the phenomenon could clearly be noticed. Indeed, while in the past parametric roll was mostly studied by means of 1-DOF uncoupled roll models, more recent research has clearly shifted towards the use of more advanced mathematical models, where more degrees of freedom are taken into account, at different levels of sophistication. The 1-DOF modelling, with roll restoring variations calculated assuming quasi-static heave and pitch, can nowadays be considered as a consolidated tool for sufficiently simple applications at the (early) design stage. Such model has also been used, explicitly or implicitly, in developing parametric roll Level 1 & Level 2 vulnerability criteria in the framework of SGISC. For more advanced applications, models with more DOFs have been developed and used, i.e. 3-DOF [2.10, 2.12, 2.35, 2.66, 2.67, 2.97], 4-DOF [2.12], 6-DOF [2.11, 2.50, 2.67, 2.72]. With the increase in the complexity of the simulation tools, also the computational effort tends to increase. In view of this, simple indications for identifying potentially dangerous conditions of speed/heading have been presented in [2.11], with the intention of providing means for reducing the computational efforts in determining the inception and amplitude of parametric roll. Regarding the convergence of modelling techniques, it is to be noted that still there exists a significant variety of modelling when more than 1-DOF is considered: single time scale vs double (slow-manoeuvring and fast-seakeeping) time scale, consideration of memory effects or constant hydrodynamic coefficients, modelling details of damping, modelling of manoeuvring forces, etc. From the point of view of the peculiar nonlinear characteristics of parametric rolling, detailed studies have been carried out in some cases. The extent and shape of instability regions in regular waves, as well as the amplitude of roll within the instability regions was numerically studied in [2.10] through time domain simulations of a 3-DOF model, while a semi-analytical approach based on direct application of Floquet theory was used in [2.16] for the identification of instability regions in longitudinal regular waves. Results from such studies also relate with the observation that parametric roll can have a non-monotonic relation between amplitude of forcing and amplitude of roll motion [2.15, 2.51]. Although the majority of studies regarding parametric roll have dealt with conventional vessels, some studies have also been presented for unconventional hull forms, such as trimarans [2.13, 2.16]. Some attention has also been given to roll reduction means, intended to mitigate parametrically excited roll, such as passive anti-rolling tanks [2.34, 2.77] and active rudder stabilization [2.67, 2.90]. In the context of parametric roll, it is also worth mentioning the book in [2.82], where different authors have dealt with some of the mentioned topics, and also with other aspects of parametric roll resonance.

Studies on the dynamics of loss of stability have, instead, been more limited in number. In [2.36] a probabilistic approach was presented for dealing with pure loss of stability in irregular longitudinal waves. Comparisons between experimental results and numerical simulations have been instead reported in [2.39, 2.94].

In parallel to the already mentioned contributions regarding the development of SGISC, additional fundamental research studies have also been carried out with respect to surf-riding and broaching. In [2.5], a 6-DOF blended code (LAMP) was used to study the ship behaviour in following/quartering waves and an approach based on continuation analysis was also implemented which allows tracing equilibria and periodic motions. With the same goal, a continuation analysis approach was also used in [2.75]. A detailed investigation of yaw motion and low-speed-broaching in following/quartering waves was instead presented in [2.9], where rudder control was used in order to reduce undesired yaw motions. In [2.76] an approach based on an extended Melnikov method was presented for improving the semi-analytical determination of the (second) surf-riding threshold. While most of the studies are based on regular waves, research progressed also on two open points: the issue of providing a proper definition of surf-riding in case of irregular waves and the problem of providing proper tools for the identification of surf-riding occurrence from simulated time series. To this end, ideas and proposals have been provided in [2.39, 2.74, 2.91, 2.102].

Fundamental aspects of nonlinear roll dynamics in beam waves have also been subject of specific investigation, also in this case in parallel to the already mentioned contributions specifically targeting SGISC. In [2.68] the inception of sub-harmonic roll motion was studied experimentally and also numerically with 1-DOF and 6-DOF models in the particular cases of bi-chromatic waves. Sub-harmonic motions in irregular beam waves have been experimentally observed and numerically simulated in [2.89]. In [2.73] the Melnikov method was used for determining the critical wave forcing leading to capsize using a 1-DOF approach, while in [2.41] the extended Melnikov method was used for the same purpose considering a 3-DOF mathematical model. An interesting and uncommon set of experiments and comparison with numerical simulations (1-DOF and 4-DOF) of roll motion in irregular beam waves and fluctuating wind have been carried out and reported in [2.59]. In [2.4] the beam sea condition was instead addressed from a more regulatory perspective, by proposing a procedure combining model tests and numerical simulations for the determination of a Weather Criterion GM limit curve.

A notable amount of research efforts was also observed regarding the development, tuning and use of blended codes for the simulation of large amplitude ship motions and manoeuvring in waves. Herein, the wording blended (or hybrid) codes is intended to identify advanced systems-based tools having the necessary characteristics for efficient time domain simulation of nonlinear large amplitude ship motions in waves. Due to the high level of semi-empiricism which is present in such codes, a variety of blended codes exist, in a variety of different “flavours”. However, in general, blended codes are typically embedding (or at least are expected to embed) nonlinear rigid body dynamics, Froude-Krylov pressure calculation on the instantaneous wetted surface of the hull, radiation and diffraction effects based on linear (or partially nonlinear) hydrodynamics, and, when necessary, appropriate models for manoeuvring forces, steering means, propulsors, mooring lines, wind effects, etc. Such codes can also be considered, in most cases, as suitable tools for direct stability assessment in the framework of SGISC. In this respect, some general considerations have been provided in [2.70] regarding the characteristics of codes intended to be used for direct stability assessment in the framework of SGISC. In [2.86] an approximate technique was presented for speeding up the calculation of Froude-Krylov forces in blended codes. In [2.17] a blended 6-DOF code for the simulation of ship motions and manoeuvring in waves was presented, designed to determine, in addition to ship motions, also instantaneous loads on the vessel, and discussion was provided regarding the difficulties involved in creating a consistent and still numerically efficient model. A methodology was presented in [2.32] for improving the capabilities of the 6-DOF blended code FREDYN of taking into account water on deck by improving the estimation of the free surface elevation around the vessel. In [2.33] the main theoretical aspects at the basis of the development of the 6-DOF blended code TEMPEST have been described, and some comparison between numerically computed and experimentally measured forces have been reported. A detailed description of the modelling of hull lift and cross flow drag forces used in TEMPEST, together with some sample calculations, has been presented in [2.54]. The blended code NLOAD3D was used in [2.69] and an interesting conceptual link with EEDI related issues has been provided together with a series of useful information regarding the process of software tuning. In [2.71] simulations in following quartering long crested irregular waves were carried out using the blended code LAIDYN in conditions characterised by strong narrowing of the spectrum due to Doppler effect, leading to large rolling, and simulations in following quartering waves were also carried out in [2.100] using a two-time-scales mathematical model. In [2.14] the blended code NLOAD3D was used for the simulation of parametrically excited rolling motion in irregular sea, and a methodology, based on the use of coherence function, has been proposed for trying to discriminate between parametrically excited roll and 1:1 direct roll resonance on the basis of the analysis of time histories from numerical simulation. Such methodology has later been used also in [2.52]. Other examples of use of blended 6-DOF codes can be found in, e.g.: [2.12] (NMRIW, phenomenon: parametric roll), [2.5] (LAMP, phenomenon: surf-riding & broaching), [2.68] (SHIXDOF, phenomenon: nonlinear roll in beam sea), [2.79] (phenomena: parametric roll, surf-riding and broaching).

With the increased possibility of using advanced nonlinear ship motions simulation tools for the assessment of safety in intact condition, and with the foreseeable possibility that such tool can be used within the approval process (e.g. through Direct Assessment in SGISC, or through SOLAS provisions for alternative design) or for defining ship-specific operational guidance, the issue of a proper validation has become of significant practical importance. However, the validation process (or actually, the verification, validation and accreditation process) of such complex, usually modular and partially semi-empirical, tools is not a straightforward task. This is especially true when considering strongly nonlinear behaviours (coexisting solutions, strong dependence on initial conditions, possibility of chaotic motions, etc.) and/or nonlinear motions in irregular waves (convergence of statistical estimates, non-Gaussian distributions, etc.). Proposal of general procedures and/or frameworks for the validation of modular codes for the purpose of large amplitude ship motions simulation have been described in [2.7, 2.42], while attention to metrics and acceptance criteria was given in [2.63, 2.65, 2.93]. Connected with the process of validation, is also the problem of uncertainty assessment/propagation in experiments and simulations, and of sensitivity analysis. Such topics have, unfortunately, received limited attention in the field of nonlinear ship dynamics. In this context, an uncertainty propagation study in case of simplified mathematical models for parametric roll was carried out in [2.53] and a sensitivity analysis was carried out in [2.35] with respect to damping coefficient in a 3-DOF nonlinear mathematical model for parametric roll prediction.

In addition to the above, other specific topics related with nonlinear ship dynamics in intact condition have been addressed by a more limited number of contributions. Measurement and modelling of forces due to deck in water was the subject of the study in [2.6]. The use of artificial neural networks, as physics-free adaptable models, has received some attention as a tool for the very short term prediction of motions [2.78] and for parameter identification in physics-based mathematical models [2.8]. A database of experimental results from (semi-)captive model tests carried out on a fishing vessel in following waves has been described in [2.96], with the intention of providing reference data for the tuning of blended 6-DOF codes. Experimental equipment and techniques for ship motions tests in following waves, targeting specifically the case of small models were described in [2.95]. In [2.87], the problem of yaw instability of a turret moored FSRU in waves was addressed experimentally and numerically.

Ship intact stability has been well studied within a deterministic context, due to the nonlinear character that spans the extreme ship motions, especially the rolling motion, which could jeopardize ship safety. Nevertheless, the weather environment a ship operates is actually a random field. At the same time uncertainty covers other operational parameters. Therefore, a issue that stability researchers had to consider was the incorporation of random sea and wind in the nonlinear ship motion problem, something that it is not straightforward due to the nonlinear relation between excitation and response. Moreover, the next step was the integration of the associated hazards into a risk-based framework. Studies related to the abovementioned context are reviewed in the following.

Using numerical simulations to predict extreme events is often a popular choice to directly attack to the problem, however the are some issues related with the statistical treatment of the results, the, hopefully, rare character of capsize events and the respective validation of the models and methods of prediction. In [2.29] the "Envelope Peaks over Threshold" (EPOT) was used, comprised by a statistical extrapolation, allowing explicit account of influence of nonlinearity of GZ curve on roll distribution. From a similar viewpoint in [2.56] the EPOT method was used, combined with the FREDYN code, in order to produce the targeted Generalised Pareto Distribution. The authors suggest that the EPOT method requires the least number of simulations for reliable results of a rare event. A discussion on the EPOT method can also be found in [2.80]. Moreover direct counting and Poisson distribution fitting techniques have been examined in [2.43]. In this context, dangerous wave conditions that produce rare events through hydrodynamic simulations were defined. In addition, direct counting was used in [2.91] for the statistical analysis of surf-riding realisations observed as high-runs. A high-run was defined as the time segment in which ship's speed is maintained higher than her expected one, and mean time durations of high-runs were calculated. An approach to generate the distribution of extreme values of parametric roll was presented in [2.44], by using a Design Load Generator (DLG), a process to approximate the extreme value distribution of a Gaussian random variable. Moreover, in [2.48] several alternatives were examined for the modelling the distribution of parametric roll including a Gram-Charlier series, the Pearson type IV distribution, and an approximation based on a moving average. It is also worth mentioning that probabilistic methods for the assessment of parametric rolling can also be found in some of the contributions in [2.82].

As mentioned before, the problem of rarity represents a challenge to be addressed. One possible method to deal with it is the statistical extrapolation. In such method one aims to use data where the targeted event (e.g. a specified, large, roll amplitude) has not occurred and then appropriately extrapolate the data for carrying out predicting regarding the target event. In [2.99], features of the modelling of the tail of the distribution of peaks as a Generalized Pareto Distribution (GPD), which can be derived from the Generalized Extreme Value distribution, have been examined. The key issue of this method is the appropriate selection of the threshold limit. Moreover, in [2.98] a multi-tier validation study for the statistical extrapolation method based on the Generalised Pareto Distribution was presented. The comparison was carried out considering the "true" values derived from numerical simulations by a direct counting method. The determination of confidence intervals for estimates of mean and variance from a time series, taking into account the correlation structure of the process, was examined in [2.88], with particular emphasis on simulations of roll motion. Another approach to the rarity issue of capsize is the so-called split time method [2.80]. For example, in [2.45] the split-time method for the evaluation of the time-dependent probability of broaching-to has been implemented, describing the development of a simple model of nonlinear surging and surf-riding response in following irregular seas. Furthermore, in [2.83], the split-time method has been utilised for the evaluation of the probability of capsizing for the case of variation of righting arm in waves, as in case of pure loss of stability. The threshold in roll angle was fixed and then the critical roll rate at the instant of up-crossing was calculated. On the other hand, the problem of nonlinearity has been attempted to be treated by the piece-wise method. In [2.19], capsizing has been considered as a sequence of two random events, up-crossing through a certain threshold and capsizing after up-crossing. A critical roll rate was introduced as a stochastic process defined at any instant of time. From a similar viewpoint, in [2.20], the capsizing probability of a Ro-Pax in dead-ship condition has been calculated by using the piece-wise linear approach, and the correlation between winds and waves on the capsizing probability has been examined.

The concept of wave groups has been also utilised as they can constitute the critical wave episodes for the assessment of dynamic stability. In [2.22] experiments were described which have been performed in a model basin to generate groups of large-amplitude waves in irregular seas. Generation of asymmetric wave groups is the first step in the development of an experimental test technique that ensures a model will be exposed to multiple realistic extreme wave events. Furthermore, in [2.27], a method using wave groups to evaluate ship response in heavy seas was presented. Wave groups critical to ship response were defined, separating the complexity of the nonlinear dynamics of ship response from the complexities of a probabilistic description for the response. Finally, in [2.57] a comparison of two different methodologies for the calculation of exceedance rates utilising the same seakeeping code for the modelling of ship motion was presented. The first method refers to the critical wave groups approach and the second to direct Monte Carlo simulations. A discussion on the method of critical wave groups can also be found in [2.80].

Using stochastic differential equations represents another approach for the probabilistic treatment of nonlinear rolling motion. However closed-form solutions cannot always be derived in manageable form. In [2.21], new equations were derived governing the joint, response-excitation, pdf of roll motion, roll velocity and excitation, without any simplifying assumptions concerning the correlation and probabilistic structure of the excitation. Furthermore, in [2.61], the probabilistic characteristics of the long-time steady-state response of a half oscillator, subject to a coloured, asymptotically stationary, Gaussian or non-Gaussian (cubic Gaussian) excitation, are derived by means of the Response-Excitation theory. On the other hand, in [2.46], Gaussian and non-Gaussian response of nonlinear ship rolling in random beam waves has been studied by moment equations. An automatic neglect tool was developed to handle the complex and untraceable higher order cumulant neglect method and capture the non-Gaussian effect of the nonlinear rolling phenomena. The developed tool was also used in [2.58], where dynamical systems forced by filtered Gaussian coloured noise were studied using Gaussian and non-Gaussian cumulant neglect methods, and, numerically, using the path integral method.

Finally, as mentioned previously, risk-based frameworks for the assessment of intact stability have been developed. For example, in [2.28], inland container vessel rolling due to the influence of beam gusting winds was investigated, and a critical analysis was given of the requirements of the European Directive for Technical Requirements for Inland Waterway Vessels. In [2.60], an overview and a critical analysis of the regulations for river-sea ships were given, and some of the existing regulations were evaluated from the probabilistic point of view. Moreover, in [2.30] a discussion was provided on the tolerable risk associated with the loss of a naval vessel due to the weather conditions. A review of tolerable risk and potential methodologies for calculating an annual probability of loss of the vessel using time domain simulations and statistics of observed weather conditions aboard naval ships was also presented. On the other hand, in [2.31], different intact dynamic stability methodologies that can be employed to naval ship design addressing dynamic stability in such a way as to minimize technical and safety risks in an economical manner have been discussed. Finally, in [2.55], a proper risk analysis and management framework was presented that can be brought into the process of stability control of naval ships by quantifying uncertainties, identifying and calculating consequences, and by developing status metrics that are based on risk-based calculations.

Based on the observed status, some directions could be suggested for future research. In case of research in the field of SGISC, two topics are likely to become of significant importance and require further research: direct stability assessment on one side, and associated development of ship-specific operational guidance on the other side. These two topics require development: of appropriate mathematical models, of verification, validation and accreditation procedures, and of appropriate application guidance. So far, most of the available experience regarding ship dynamics is based on the use of linear seakeeping tools, which are however not typically intended for being used in a regulatory framework. Bringing nonlinear time domain simulations of ship motions into the regulatory framework is going to be a challenging activity. With respect to parametric roll, nowadays it seems that the fundamental aspects of such phenomenon in regular longitudinal waves are quite well established. However, research is still needed in following/bow quartering waves and in irregular waves. In case of parametric roll in irregular waves, research is still necessary on more accurate estimations of the inception threshold, and on how to effectively model and handle the strong non-Gaussianity of the motion. In case of loss of stability in following waves, not much research efforts have been noticed in the analysed period. However, research would be useful regarding loss of stability in following waves, particularly in terms of characterization of roll motion in irregular sea. In case of surf-riding and broaching, two main topics could benefit from further research, namely: control/mitigation of the phenomenon, and description/definition of the phenomenon in irregular sea. In case of roll dynamics in dead-ship condition, it seems that a lack of information is present regarding the vessel behaviour in non-beam waves, since the beam-sea case is often considered as a reference condition for experiments and simulations. As a result, additional research on the topic of nonlinear rolling in quartering waves (where direct excitation and parametric excitation combine) would be useful. For all these phenomena, and, in addition, for the increasingly important topic of assessment of ship motions and manoeuvring in adverse weather conditions, blended 6-DOF codes will likely show their usefulness. However, for a proper application of such tools, it would be useful to more thoroughly investigate uncertainty and error propagation, and to perform sensitivity analyses. Indeed, estimation of confidence on predictions, and identification of the most sensible parameters could help in identifying those blocks of the experimental/simulation chain where efforts are to be put to reduce uncertainty. In this respect, it is expectable that, roll damping modelling will play a key role. These aspects seem to have been given limited attention so far. Regarding the modelling of environment, in practice, most of the reviewed research has been carried out considering either regular waves or irregular long crested waves. Short crested irregular waves have been very seldom considered. This is understandable in case of experiments, due to intrinsic limitations of most facilities. However, this also reflects in most of the presented numerical investigations, since they are often compared with experimental data. As a result, information associated with short crested waves is rarely available. Also, detailed information associated with nonlinear ship motions in sea states characterised by non-idealised, more realistic sea spectra are largely missing. It is therefore useful that additional research efforts are put in the experimental and numerical assessment of nonlinear ship motions in more realistic sea conditions. This also means improving, when necessary, the modelling of wind actions, in addition to the modelling of action of waves. With reference to probabilistic approaches in intact stability, possible forthcoming studies could be envisioned. For example, one concerns the incorporation of CFD models into probabilistic methods and how the massive incurred computational cost could be appropriately decreased. Thus, the utilisation of critical realistic wave groups could be introduced in such assessments. On the other hand, the work related with statistical extrapolation could pave the way in order to properly minimise the required data for the prediction of rare events within reasonable confidence intervals, keeping in mind that these models should appropriately reproduce the governing physics of the targeted problem. Furthermore, stochastic differential mathematical models that capture the nonlinear behaviour of rolling motions is also another worthwhile direction, however it should be reminded that up to now only primitive models of rolling motion have been used, thus questioning the practicality of this approach when advanced models are needed. Finally, one of the goals of the research in the field of nonlinear ship dynamics should always be to better understand the complex phenomena associated with the motions of a vessel at sea. However, in addition to this, one of the goals should also be to eventually transfer knowledge and tools from the level of research to the level of application (design/operation). According to the observed status of research and development, this goal is definitely achievable.

3. DAMAGE STABILITY

The subject of damage stability has arguably been in the forefront of developments relating to stability and safety research for the period of the last 30 years, with concerted large-scale initiatives taking place involving the research community, regulatory authorities and industry. During the review period considered in this paper research on damage stability has evolved in a number of diverse but interrelated directions, including direct simulations of motions in the damaged condition, research on the prediction of ship behaviour following progressive flooding and on experimental techniques, development of rules and regulations, probabilistic and risk-based methods and frameworks, integration of damage stability into ship design, research on safe return to port as well as on the importance of active operational measures for damage mitigation and containment, and last but not least, accident investigations.

A number of studies for validation of codes for the direct simulation of ship motions in the damaged condition, including in most cases experimental validation, were carried out during the review period.

Numerical simulations and benchmarking against data from physical experiments of a generic RoPax ship have been performed, investigating how parametric variations can lead to establishing of survival limits outside which capsize will not occur or certainly occur and addressing ship's survival as a time-independent problem, [3.16]. In order to validate a dynamical model accounting for coupling in ship motions and floodwater dynamics (coupling of flooding module with MARIN's software FREDYN), model tests were carried out on a generic destroyer model (1:40) with floodable internal compartments, [3.19]. The study reported in [3.20] focused on the validation of results of numerical simulations using the software tool (Shipsurv) which calculates motions, internal loads and survivability of damaged naval ships in seaways. Validation results for flooding case of a barge and cross-flooding case of a RoPax ship as reported during ITTC benchmark study were also presented. Numerical and scale model tests of a damaged cruise vessel were presented in [3.21]. Simulations and model tests were performed in calm seas and in regular and irregular waves whereas experiments were conducted at MOERI's ocean engineering basin. The numerical studies were performed with use of a quasi-dynamic CFD code. In [3.22] an application of the DoE (Design of Experiments) methodology in building a model for transient flooding was presented, which was tested through physical experiments on a model of damaged ship section (PRR02) subjected to 6-DOF forced oscillations. In [3.29] a methodology for coupling of a seakeeping solver (PROTEUS3) with a volume-of-fluid (VOF) solver was presented in assessing the behaviour of a damaged ship in waves. Flooding and internal water dynamics was simulated by the VOF solver, while the seakeeping solver addressed the external fluid-structure interaction. Numerical simulations were then compared with experiments (originating from ITTC tests) in case of a Ro-Ro ferry in regular beam waves. The presence of floodwater onboard a vessel was simulated within the LAIDYN software using the lump-mass method [3.30]. The time varying mass of floodwater was pre-calculated through the NAPA Flooding Simulation tool in calm water. An example application for a passenger vessel was considered in the simulations carried out in calm water and in irregular waves. In [3.36] an investigation on the time to capsize for a RoPax vessel (M.S. Estonia) using both physical model experiments and computer based time domain simulations was presented. The computer model also included a two-dimensional multi-model sloshing model, composed by a non-linear near-resonance pendulum model and an acceleration ratio model at non-resonance used for calculating the transverse centre of gravity of ingresses water in the damaged compartment and on car deck. In [3.37] a study on the evaluation of the performance of cross-flooding arrangements using Computational Fluid Dynamics (CFD) was reported. Computations for a simple arrangement including scaling effects were first carried out with model experiments performed for the validation of the computational results. Comparisons with the factors evaluated by the IMO simplified regression formulae were carried out. Computations for a complex arrangement was also carried out and compared with results from existing studies. A flooding extent prediction decision-support method including the intermediate phases of flooding was presented in [3.38]. The simplified, but reasonably accurate, algorithm was evaluated on the basis of test cases featuring comparisons to experimental data and time accurate flooding simulation results. In [3.39] simulation results addressing the probability to capsize and the flooding of ships in collision damages were presented. The results were discussed in the context of the IMO regulatory concept for orderly abandonment for damaged passenger ships (in addition to the safe return to port regulatory provisions). Timely identification of the damage and the enhancement of survivability requirements were suggested as rational measures for improved survivability and safety of people onboard passenger ships. In [3.40] a numerical model for progressive flooding simulation was presented. The model utilises a direct approach in which the flow between the compartments is computed based on the Bernoulli equation and the current pressure heads at each intermediate step. The implemented approach makes use of graph theory in modelling the flooding paths. The developed method was validated by investigating the accident of the S.S. Heraklion occurred in 1966 and the results of the simulation method were compared with model tests of a barge performed at the Helsinki University of Technology in 2006. In [3.41] a CFD study for the flooding process of a fully constrained damaged compartment was presented, which was then extended to the flooding scenario of a damaged cruiser in calm water with 6-DOF motions. In [3.59], the Stability in Waves Committee of the 27th ITTC reported their investigation on how to deal with the ship inertia contributions due to floodwater mass from three points of view: (1) floodwater domain, (2) floodwater inertia itself, (3) floodwater entering the ship. The Committee suggested three criteria for accounting on floodwater dynamics in damage stability.

In many cases, progressive flooding is the determinant factor of ship capsizing or sinking. A number of investigations and research initiatives were reported on the subject of progressive flooding, including verification through experiments. In [3.5], the application of the pressure-correction technique for analysis of progressive flooding in a damaged large passenger ship was studied through a case study focusing on the efficient convergence of the pressure-correction iterations. In addition, a simple method for estimation of increased flooding due to waves and implementation of pumping and closing of open doors into the pressure-correction equation were discussed. A numerical method capable of describing the progressive flooding of ships, accounting for complex subdivision arrangements, was presented in [3.6]. Numerical results were shown for the progressive flooding of the ITTC box-shaped barge. Comparison was made with experimental results aiming at validating the numerical simulation method and conclusions are drawn. In [3.7] the flooding phenomena with emphasis on transient and progressive flooding stages of damaged Ro-Ro ships were analysed and recommendations were proposed for an alternative assessment of the flooding process.

Research has also been reported on the use of experimental data for damage stability and survivability performance verification. A direct link of the s-factor with the time to capsize was discussed in [3.4] showing how to utilise experimental data from 30-minute test runs for the s-factor based on longer duration of tests. In [3.11] a series of experiments performed in calm water and in waves in order to study the motions and flooding process of a damaged cruise vessel were reported. The in-waves effects of inflow and outflow through opening and internal water motion were investigated in [3.12]. In [3.59] the work carried out by "The Stability in Waves" Committee of the 27th ITTC was presented, concerning the investigation of the significance of scale effects related to air pressure on flooding model tests under atmospheric conditions. Particular attention was given to effects associated with trapped air. The results were employed to update ITTC model test procedure for damage stability experiments.

Research on probabilistic and risk-based methods for the development of rules and regulations, and comparisons between different regulatory provisions has received great attention during the review period. A review and historical background of damage stability regulations with respect to Ro-Ro passenger ships was presented in [3.14]. Some vulnerabilities of the probabilistic framework based on HARDER EU-funded project were highlighted in terms of specific modes of flooding and modes of loss typical to RoPax ships (low residual freeboard, flooding to car deck and presence of long-lower holds). The EU-funded project GOALDS was presented in [3.15] which is considered as the next step forward following HARDER project. Inconsistencies in predicting survivability of large and small passenger vessels, issues related to accumulation of water on deck (RoPax) and omission of grounding in the probabilistic framework were pointed out in this particular research work. In [3.24] issues related to evaluating probability of collision and subsequent hull breach leading to flooding of internal spaces of the ship were addressed. From this perspective, discussion focused on aspects of models used in evaluating risk from ship to ship collision. A comparison on the survivability assessment between SOLAS's s-factor and Static Equivalent Method (SEM) was presented in [3.17] by two case studies of a RoPax ship Polonia and a box-shaped barge, identifying large discrepancies between SOLAS and SEM. In [3.18], middle-sized RoPax vessels were considered and comparisons were carried out regarding the level of safety achieved by SOLAS 2009 compliant vessels and ships compliant with SOLAS 90+SA (Stockholm Agreement). To this end limiting GM curves were compared. Limiting GM was also sought by means of model test. In [3.23] concepts related to capsize band were addressed and simple regression models were presented allowing for linking probability of capsize with sea state. In [3.25], a probabilistic model was presented for grounding damage characteristics (separately for full, non-full and all vessels) based on an updated accidents database proposed by the EU-funded GOALDS project. Also, an analysis was reported regarding the probability of breaching double bottom shells designed in marginal compliance with SOLAS Reg. 9 requirements. In [3.26] the importance of wave statistics in the survivability assessment through "s-factor" within SOLAS2009 was assessed. The concept of "critical significant wave height" was discussed with particular attention to its dispersion for a given set of residual stability parameters as well as the importance of considering the "operational wave profile" of the vessel for obtaining more appropriate measures of survivability. The IMO work on SOLAS2009 requirements in the context of RoPax vessels was analysed in [3.27]. Open issues in SOLAS2009 regarding the accounting for water on deck were reported. The need for specific requirements for RoPax vessels, which could be vulnerable to fast capsize in case of water accumulated on large undivided spaces was also discussed there. A historical overview regarding SOLAS regulations associated with watertight doors and discussed whether this regulatory treatment is still appropriate for passenger ships of the future was provided in [3.28].

Research on the development of probabilistic and risk-based methods for new regulatory and design frameworks extending the capabilities of current provisions was also a focal area during the review period. In [3.31], the sequence of ship collision, flooding and loss of stability within given time has been investigated on the basis of an interdisciplinary calculation procedure. The method looked at the interaction between structural and damage stability computations and has been used to study the significance of various parameters, such as significant wave height and size of damage. A direct comparison of probabilistic and deterministic regulatory frameworks for damage stability on a selection of Ro-Ro passenger vessels of various sizes has been undertaken in [3.32]. Both numerical and analytical performance-based assessment methods were utilised, highlighting inherent inconsistency in each framework. The study constituted an attempt to present state-of-the-art methodology for damage stability assessment appropriate even for non-standard designs. In [3.34], the development of an alternative formulation for the assessment of the survivability of a damaged ship in waves was presented. The authors discussed briefly concerns related to the current survivability model and present the process of development that led to the re-engineered formulation. The proposed formula based on simple and rational model accounted well for size of the ship and floodwater dynamics. In [3.35], established numerical methods for the measurement of performance-based survivability have been utilized and used as benchmark against available analytical methods in an attempt to define a rational requirement for the level of survivability. Survivability analysis results on representative cruise and Ro-Pax ships were related to design and operational parameters with a view to define and quantify the relationships between damage survivability characteristics following a collision and time available for evacuation with potential outcomes in terms of people potentially at risk. In [3.42], a new methodology for probabilistic bottom damage stability requirements following grounding has been developed, which takes into account also the probability of safe beaching. The analysis of the probability of safe beaching was based on historical data (indicating about 80%) and a specifically developed methodology, also indicating large values. An alternative formulation for the probability of a compartment flooding following grounding (the p factor) based on the GOALDS database on grounding damage was proposed in [3.43]. To this end, original GOALDS formulations for the probability density functions of damage characteristics, which employed rational functions, were substituted by alternative ones based on exponential or triangular distributions, and this made it possible to arrive at a closed form for the p factor. In [3.47] the results of a study about the influence of the longitudinal subdivision in the lower cargo hold of a Ro-Pax vessel on the attained subdivision index calculated according to MSC.216(82) were presented.

Developments on the use, implications and application of probabilistic and risk-based frameworks for design and operational purposes also received attention. A way forward for establishing a stronger foundation to safety assurance in the maritime sector and for future developments on the subject of damage stability of passenger ships was proposed in [3.48]. In [3.49], the implications of the GOALDS revision of the regulatory requirements for the damage stability of passenger ships upon ship design were investigated. In particular, the study addressed impact of differences between the SOLAS 2009 and GOALDS formulations of the s-factor. In [3.52], the impact of the SOLAS 2009 formulation on the design and operational characteristics of ROPAX vessels was investigated. An in-depth review of the adopted formulation were analysed and applied within a multi-objective optimisation procedure developed and tested on RoPax ships. The practical design implications of SOLAS 2009 were discussed from a shipyard perspective in [3.54], where attention was given to the problem of rules' interpretation on the attained A-indices and the consequent perception of the safety level, and attention was also given to the importance of a true safety culture during the design phase. In [3.62] a historical overview of regulatory framework from HARDER project up to SOLAS 2009 was given. The research work proposed a re-assessment of existing large passenger vessels, with retrospective application for vessels with attained index A significantly lower than the required index R. Furthermore, some interesting considerations were provided regarding the impact of the new regulations on the safety level of certain types of vessels. The safety level of pre-SOLAS90 and SOLAS90 vessels was examined in [3.60]. In this study, SOLAS2009 vessels were assumed to have the same safety level with vessels complying with the deterministic SOLAS90 standards. The study focussed on Cruise ships and RoPax vessels of 1,000GT and above. Casualties and associated data regarding fatalities were extracted from IHSF database. Potential Loss of Life (PLL) values were calculated for both categories. F-N curves were also determined and assessed against the ALARP region.

A final area of developments of probabilistic and risk-based methods can be found in the development and testing of contemporary approaches for advanced tools for risk-based assessment. A systematic approach in constructing risk models using Bayesian Networks was presented in [3.3]. An approach also based on Bayes Networks was presented in [3.53], where a risk model for assessing risk associated with the occurrence of a collision accident was described. In [3.33] a data mining framework for ship safety management was presented. The approach utilised Bayesian Networks as a risk modelling technique, and provides means for systematic extraction of information stored in available data. Particular emphasis was placed on the integration of aspects of damage stability into such a framework for an overall management of ship lifecycle safety. The Goal Based Design, as an alternative to Risk-Based Design, was discussed in [3.9]. A case study was presented in order to demonstrate integration and advantages of Goal Based Design within the design process. In [3.10] the SAFEDOR design platform, a stand-alone multi-disciplinary design tool, was presented. In addition to the feature of regular optimisation platforms, the tool brought in an innovative functionally allowing for capturing the dynamics of the design process. As a result, incremental improvements through design optimisation became a secondary purpose of the platform, while the primary one was design from scratch towards trade-offs and cost-effective concepts. Experimental tests and numerical studies, carried out in relation to the progress of flooding, were described in [3.51] in the framework of FLOODSTAND project. A new approach to flooding simulation for onboard use has been developed. The authors discussed application of stochastic modelling to ship capsizes and uncertainties related to the "time-to-capsize" have been analysed. In [3.55] a benchmarking study addressing survivability assessment of a small RoPax ship was performed according to three different probabilistic frameworks – SOLAS 2009, GOALDS and SLF 55. The results showed that all three regulations results in comparable values of A-index and that there was considerable room for cost-effective design solutions resulting in attained safety levels well above the requirements for damage stability. In [3.56] the notion of vulnerability was used to present a concept of emergency response and crisis management in flooding casualties. Based on real catastrophic accidents (e.g. M.S. Estonia) they discussed inherent vulnerabilities in ship design and operation. This led to the concept of vulnerability management (identification, screening, reducing, mitigation and emergency responses).

Implications of contemporary issues such as safe return to port and the need for operational and emergency response measures has received great attention during the review period. A classification society's perspective on the Safe Return to Port requirements was discussed in [3.13], addressing residual operability of safety-critical systems onboard passenger vessels. The philosophy that the "ship is its best lifeboat" was highlighted by referring to potential issues relating to interpretation of the regulations, presenting relevant information to the master and its harmonization with the damage stability framework. In [3.50] the survivability assessment of damaged ships with respect to the coupled effects of structural degradation and damage stability in the context of the Safe Return to Port (SRtP) framework for passenger ship safety was assessed. The survivability was evaluated in the time domain with varying wave loads. An approach to safety in damaged condition for RoPax vessels was described in [3.61], embracing the full spectrum of measures (regulatory, design, operational and emergency response). A thorough and detailed discussion was presented regarding possible means and methodologies for the increase of safety of the vessels, using an holistic perspective, going from design to operation and, if necessary, emergency response.

Accident investigations are intended to determine the main and root cause of an incident, to identify possible unsafe conditions and recommend actions to mitigate or ideally eliminate similar cases in the future. In this context, the capsize of a 12,000 DWT bulk carrier which suffered heavy storm weather, when sailing in South-West Black Sea, was presented in [3.1]. The analysis focused on the circumstances of the accident as well as the sequence of events leading to loss of stability, capsize and sinking. The catastrophic loss of Ro-Ro passenger ship M.S. Estonia who sank rapidly between Estonia and Finland was presented in [3.2]. The analysis focused on the use of a combined simulation and model test approach for analysing ship's sinking sequence. An accident investigation of the dredger Rozgwiazda which capsized and sank while being towed was discussed in [3.44]. The reason of the capsizing was sea water inflow to one hold and locker through opening of the hawse hole which had not been closed and properly secured on departure. The study presented most probable sequence of events and was accompanied with stability calculations performed for each major stage. In [3.46] the results of the accident investigation for S.S. Heraklion was presented including the reconstruction of the accident data available from a variety of original investigation reports, ship files and legal evidence. Ship's loading and post-damage behaviour was re-investigated and the flooding/ sinking of the ship were simulated in time domain. The same accident was investigated in [3.45]. The loss sequence was studied with use of an advanced numerical method. The study revealed interesting aspects of the earlier phase of the accident (before and during the flooding of the main garage deck). In [3.58], the capsizing of the French pre-dreadnought Bouvet during World War One (WWI) was investigated. The aim was to clarify hypotheses associated with the accident and to test modern tools against the well documented event. For that purpose both numerical computations and experiments were carried out. The investigation pointed to the presence of longitudinal bulkheads which, in case of breach in the compartment, allow off-centre flooding to induce a large heel angle and the correctness of a recommendation for the installation of cross-flooding ducts, which was not followed during construction.

Following the review of the current status of research on the topics relating to damage stability as addressed above, some insight and suggestions can be provided for directions future research could take.

Regarding the assessment of damage stability, direct simulations of the flooding process is a topic which will continue to receive attention. Benchmarking studies of the various codes developed is still required as well as research on progressive flooding and the development of experimental techniques and procedures. Research on the development of simplified methods suitable for design and regulatory purposes, e.g. p-factors and s-factors, would eventually evolve to the development of integrated methods, for example, to include treatment of consequences from collision and grounding incidents. With the increase of computational capabilities, and with the dissemination of information for in-house development of tools for dynamic flooding simulations, it seems there is space for advances in this respect, moving little by little the use simulations from research to design, or some detailed aspects of design. Also, it is worth noticing that the introduction of SOLAS 2009, and subsequent current research, has changed the perspective regarding damage stability assessment from a design and a regulatory perspective.

On the associated topic of development of rules for damage stability, the research of project HARDER and other initiatives world-wide, lead to the introduction of SOLAS 2009 and subsequent developments at IMO. Recent developments in project GOALDS and projects led by EMSA will lead the way for possible future regulatory developments. Research has progressed regarding the possibility of improving the s-factor. Furthermore, research is ongoing regarding the introduction of a probabilistic regulatory framework dealing with grounding damages. It is therefore likely that some attention will be given, in the near-medium future, to this topic. Furthermore, the introduction of the requirements for safe return to port by IMO, is directing additional research focus in the area of post-damage availability of essential ship systems.

The development of probabilistic and risk-based methods for damage stability and safety has received considerable attention. Risk assessment is extensively used for rule development purposes, cost-effectiveness analysis and the proposal of adequate safety thresholds. Simplified tools are developed for capturing the time-domain behaviour of the ship by means of simplified formulae (simplified time-to-capsize approaches). Different approaches are used for risk analysis, for example, fault and event trees, Bayesian networks, etc. There is a variety of research issues still to be adequately addressed, namely the availability and representativeness of the selected accident datasets used, integration of considerations of the effects of the human element, research on formal data mining methods to achieve proper filtering and clustering of the dataset used, the integration of simplified probabilistic models of the flooding process within current practice in developing risk models, the consideration of the full chain of events starting from pro-active measures aiming to reduce the frequency of collision or grounding incidents occurring, to the direct association with structural degradation leading to flooding and the assessment of mitigating the consequences of flooding, the treatment of uncertainties in the data used and uncertainty propagation within the chain of events considered, and finally, the assumptions made and parameters considered in developing representative frameworks for cost-effectiveness assessment which should include costs and benefits expected from the reduction of the frequency and consequences of the accidents to the society and the environment.

The area of design implications due to advancements in damage stability research is set to receive considerable attention in the future. Current contributions relate to the development of design concepts and methodologies and multi-objective and multi-criteria optimisation techniques. This trend is to continue developing, particularly as research on design parameterisation and concept development and their integration within contemporary design practices. Associated areas of research which will definitely play a significant role are developments in post-damage availability of essential ship systems, and the consideration of active design and operational measures for accident prevention and mitigation of consequences.

Finally, regarding accident investigation, even though being pro-active is the appropriate approach for ensuring safety, it is a fact that, unfortunately, accidents still happen and will likely still happen in the future. Therefore best use should be made of the process of learning from accidents, for increasing the level of safety of the relevant engineering field in general, and the field ship stability in this particular context. Accidents data can therefore provide valuable information for software development, application and for a better understanding of the physical phenomena. The research carried out in this area during the reporting period, highlights the further need for use of advanced scientific methods for accident investigations. In addition, further efforts should be spent in promoting a better reporting of stability-related data (loading conditions, damage characteristics, openings, etc.) in all those accidents reports associated with stability-related accidents. Such data are indeed very important for a technical assessment of the accident and, possibly, for having at disposal quantitative information for historical data analysis.

4. STABILITY FOR SPECIFIC TYPES OF VESSELS AND FLOATING OBJECTS

4.1 Fishing Vessels

From the stability point of view, fishing vessels may be treated as special due to a number of design features related to their operational requirements. Fishing vessels are also specific because of a well-known regulatory paradox: despite the fact that fishing is recognized as one of the most hazardous occupations, the major international regulations addressing various aspects of stability and safety are not mandatory for this type of ships.

The problem is particularly evident in case of small fishing vessels whose length does not exceed 24 m. A group of papers dealing with practical measures on how to tackle the safety of such vessels could be distinguished. The safety of small fishing vessels is the subject of [4.1.10] where the Safety Recommendations for decked fishing vessels of less than 12 metres in length and undecked fishing vessels, jointly developed by IMO, ILO and FAO, have been presented. In [4.1.4] a government-supported educational and advisory program was presented, that does not directly deal with the stability, but primarily addresses the safety-related habits of the crew (the Safest Catch program). On the other hand, the contribution [4.1.7] presented a cost-efficient iOS-based solution (an app) SCraMP, that supplies the fishing boat crew with a “safety index” (calculated upon measured roll, heave and pitch motions), roll period and metacentric height and warns of risks associated with large amplitude motions.

Another group of papers concerns the model tests performed either to investigate the accidents of fishing vessels or to gain a better insight into dynamic behaviour of vessels in seaway. The results of investigations into three accidents that occurred in Spanish waters were given in [4.1.1]. Again, the stability of the small vessels is addressed: all the examined ships (two purse seiners that capsized in following/quartering waves and a trawler that capsized in – most probably – beam seas) were below 24 m in length. The paper deals with a number of practical aspects of model testing. Experimental analysis of foundering of two Japanese fishing vessels was the subject of [4.1.9]. A purse seiner capsized in head waves and foundered due to a combination of improper loading and inadequate drainage of green water from the exposed deck. The examined stern trawler sank in matter of minutes in adverse weather conditions, after flooding of the engine room through watertight doors that were supposed to be closed. Both accidents pointed out the importance of proper stability management that seems to be often lacking on fishing vessels.

Model experiments are also used to validate mathematical models and numerical tools used in simulation of fishing vessel dynamics. In [4.1.3, 4.1.5] experiments with both physical and numerical models were used in order to test the decision-support system, based on artificial neural networks (ANN), that warns the skipper of the parametric roll resonance risk. Further research on this topic was presented in [4.1.8], where model tests were used for validation of a mathematical model that was later used in training of ANN for parametric roll prediction. The contribution in [4.1.6] reported on an in-depth research campaign, that made use of both model tests and sea trials carried out on a 23 m long trawler in order to validate a numerical simulator, developed within the scope of the study with an ultimate goal to gain understanding of the small fishing vessels behaviour in extreme seas.

In some papers, fishing vessels were not of the primary concern of the research carried out but were used in case studies or as sample ships. In [4.1.2] several capsizing accidents associated with freak waves were investigated, three of which involved fishing vessels.

Based on the reported papers it may be concluded that, presently, the research advances towards short- and mid-term solutions that would enable crew to gain an insight into dynamic behaviour of the vessel and take a more active role in risk avoidance. Small craft (below 24 m in length) were in the focus of the most of the studies. If some trend can be established, it appears that the research in this area moves away from the studies done in the past which mostly dealt with, conditionally speaking, a long-term approach to the safety of fishing vessels (e.g. development of the regulations).

It also seems that not many studies focus on specific design and operational features that pose a source of hazards for fishing vessels safety. In that respect, the dynamics of a vessel in case of the fishing gear malfunction or the loss of a paravane could be interesting topics. Similarly, the risks associated with the operation in ice conditions have not received any attention in the reviewed period. In past, some studies concerned with the effects of water trapped on deck were presented as well; it seems that this topic is not exhausted either. Finally, another valuable research direction was already reported in the section dedicated to the Nonlinear Dynamics: the stability of fishing vessels in light of the present framework of the Second Generation of Intact Stability Criteria [4.1.11].

4.2 Naval Vessels

Naval ships can also be considered as a special type of ships. At STAB 2009, Arthur Reed gave a keynote [4.2.1] about a naval perspective on ship stability and wrote: *"A navy has the same concerns relative to stability failures that all ship owners, designers and operators have. The significant differences arise from the fact that a navy is not governed by IMO regulations ; that the naval vessel is often much more costly than a commercial vessel; and that the naval vessel may not have the luxury of avoiding dangerous weather* *conditions when performing its missions, while a commercial vessel may be able to choose an alternate route. In addition to these differences, a navy often has access to more research and development funds to investigate these issues than the commercial builder and operator"*. Since this date there was a naval session during every STAB or ISSW. About four papers were presented each year, with the exception of ISWW2011 when there was no naval session, but nevertheless still some papers were presented addressing naval vessels.

As mentioned in [4.2.1], naval ships are governed by different rules than commercial vessel. Many regulations for naval vessels (e.g. those from United States, United Kingdom, Canada, Australia and France) are coming from the original studies of Sarchin and Goldberg in 1962, as mentioned in [4.2.9]. Suggested criteria were based on the experience of two destroyers who sank during COBRA typhoon in December 1944. The two mentioned papers demonstrated the need for improvements in stability assessment methodologies, connected with the appearance of modern hull forms and the need for a higher level of safety. Several navies work on this subject by participating to the NSWG (Naval Stability Standards Working Group). The methodology described in [4.2.9] was based on two main parts: determination ship hydrostatics, on one side, and estimation of probability of capsizing through direct simulation, on the other side. Then an analysis was carried to find a correlation between the two, concluding that parameters related to GZ curve are more correlated with the simulated probability of capsize than form parameters, and that stronger results are obtained when considering GZ curves in waves. The last step for such an analysis would be to define a "tolerable risk level", and a justified choice for it was discussed in [4.2.8]. From setting the tolerable risk level, it could then be possible to set the corresponding limiting values of the stability parameters. Such a methodology is defined in [4.2.10] as "rules based on probabilistic dynamic approaches". Furthermore, in [4.2.10], other possible approaches for rule-development are also described, that can be employed to naval ship design and that address dynamic stability in such a way as to minimize technical and safety risks in an economical manner, namely: empirically based rules, direct probabilistic assessment and relative probabilistic assessment. A global view of risk assessment method for naval ship design is presented in [4.2.18]. After a definition of risk (the etymology of the word "risk" is complex and, among various possible origins, it includes also a link with the concept of collision with rocks at sea) the paper introduces the Naval Ship Code (NSC) prepared by NATO with the objective to provide rules for naval ship design. Similarly to the process undergone at IMO, also NATO has followed the "Goal Based Standards" (GBS) approach, but taking into account the specific aspects associated with naval ships. In [4.2.19] an approach is described which is meant to include risk into the overall weight and stability control process, taking into account the uncertainty in weights and position of centre of gravity. Within this framework, it is proposed to add error bands on ship KG values, and to add multiple (colour coded) KG limit curves associated with known consequences (e.g. increase of heeling angles, margin line immersion, etc.).

Studies performed on a series of French frigates have been reported in [4.2.20, 4.2.26]. In [4.2.20] parameters related with the GZ curve are correlated to annual probability to capsize calculated by direct simulations using FREDYN. In [4.2.26], instead, results from direct simulations are compared with approaches based on simplified mathematical modelling. In this context, Melnikov method and measurement of the erosion of the attraction basin are used as tools for the analysis.

Dedicated numerical codes for simulation of ships in severe sea states are nowadays used for, and in some cases are necessary for quantifying the level of safety of naval vessels in intact condition. The US Navy has embarked upon the development of a new blended (hybrid) computational tool, named TEMPEST, for simulating the nonlinear response of a ship in severe sea states, and the theoretical background of TEMPEST has been described in [4.2.15]. Another numerical code which has been used for investigating large amplitude motions for naval ship is FREDYN, developed by the CRNAV. With reference to FREDYN, in [4.2.13] an improvement of the code was described which was aimed at introducing the possibility of taking into account water on deck in an efficient way. Model experiments have been used to validate the code. A more comprehensive validation study of the code against experimental data is also presented in [4.2.21]. The validation was carried out by deterministically reproducing ship motions in experimentally measured wave trains. Also the progressive flooding module of FREDYN has been subject to validation, as reported in [4.2.14]. In particular, in [4.2.14] the simulation methodology was described (fluid considered with horizontal free surface at each time step and Bernoulli equation used for determining the flow through compartments), and simulations have been compared with dedicated model experiments. FREDYN was also used in [4.2.27], where results from a large number of direct simulations have been analysed using different techniques, and attention was given on how to report the outcomes using relatively simple and easily understandable visual indications.

As for commercial ships, operator guidance and training using shiphandling simulators are more and more used by navies and have encouraging potential for the future, as mentioned in [4.2.17]. Indeed, according to [4.2.17], the use of simulators for training in heavy weather can compensate the fact that mariners historically receive minimal initial formation on the topic of shiphandling in heavy weather (mostly relying on mentoring and hands on experience), and the fact that, in many present cases, the time actually spent at sea may represent a smaller portion of the mariner’s career in comparison with the past. In [4.2.16], a description was given regarding the interfacing of a state-of-the-art bridge simulator with the state-of-the-art numerical code FREDYN for the evaluation in real time of ship motions. A series of Naval Operator Ship Handling Workshops were held at the Royal Netherlands Naval College bridge simulator facility considering different simulation scenarios, and the feedback from different officers of the watch was clearly positive. Essential and desirable additional improvements for the simulator have also been identified.

An important subtype of naval ships is represented by landing craft. These ships are relatively small and they could be subject to stability-related problems, in particular due to the open vehicles deck. Moreover, as pointed out in [4.2.12], these ships present different characteristics compared with those more standard warships around which naval stability standards have been originally designed. As a result of this difference, specific rules for landing craft have to be designed, and progress made by Royal Navy in this direction have been described in [4.2.12] in accordance with the performance requirements of the Naval Ship Code. Similarly, a study by the Royal Australian Navy regarding motions and stability of landing craft was presented in [4.2.24]. Ship motions were investigated with and without water on deck using FREDYN. Also, the authors stressed the importance of a proper prediction of the roll damping, which is a critical factor for properly predicting ship motions and, for landing craft, it cannot be determined by usual tools. In [4.2.11] an example of instrumentation installed on a French mine hunter was described. The system was intended to help the crew in checking the stability of the ship, by using a traditional loads calculator but also a sea states estimator and a roll period measurement.

The tumblehome special naval ship hull form proposed by ONR has been the subject of several investigations. Although it constitutes a typology of scarce interest for commercial shipping, this special hull form has been proposed, in some cases, to validate the IMO Second Generation Intact Stability Criteria, due to its possible vulnerability to certain failure modes. For the ONR tumblehome vessel, parametric roll was investigated in [4.2.25], while dead-ship condition was investigated in [4.2.22, 4.2.29]. For these papers, the approach was the same: development of numerical tools, comparison with Second Generation Intact Stability Criteria and, finally, determination of safe zone (KG and/or speed) and suggestion of improvement on numerical codes. CFD calculations, system-based prediction methods and experiments have been instead presented in [4.2.6]. Then, in [4.2.28] the tumblehome hull form was used to present an approach where few CFD calculations are carried out in order to tune a manoeuvrability model. Use of the ONR tumblehome hull form for addressing the following sea condition can be found in [4.2.7, 4.2.30].

Also in damaged condition approaches are used for naval ships which are different in comparison with commercial vessels. In [4.2.5] a very useful database of Polish naval ship accidents was referenced. A simplified approach was also proposed for the on board estimation of the time to sink due to flooding. This approach was validated against model test and indications were given regarding the need of tuning of permeability. Although there could debate on whether historical damage data from commercial ships can also be used for naval ships, in [4.2.3] data from the HARDER database have been used to derive deterministic damage extent for naval vessels. The proposed solution was to set the deterministic damage extent that naval ships should be capable of withstanding on the basis of the 50th, 80th and 95th percentile of damage extents as obtained from the available historical data, depending on a specified category of damage severity (limited/moderate/severe). In [4.2.32] the determination of the optimum number of watertight compartments was instead addressed from an original cost-benefit analysis point of view. The more usual approach for intact stability analysis, based on comparison of rule's criteria with the risk evaluated by a direct time domain numerical code, has been used in [4.2.2] but for the more complex case of a damaged ship. The evaluation of ship performance was based on the use of an innovative index, referred to as the Relative Damage Loss Index (RDLI). In the contributions [4.2.4, 4.2.31] an interesting experience on the evolution of rules was proposed. As mentioned before, most of naval rules came from Sarchin & Goldberg studies in 1962. This is the case of Royal Navy rules, and in particular for damage stability criteria. One criterion in particular includes a dynamic allowance for heave and roll in waves. This aspect is taken into account by the so-called V-lines criterion. In [4.2.4, 4.2.31] an alternative methodology was proposed where numerical estimation of motions in waves was used in order to possibly extend the original approach to vessels of different type compared with those used by Sarchin and Goldberg.

With the exception of the previously mentioned Polish naval ships accident database, well documented naval ship accidents are rarely published. One very old event, namely the dramatic capsizing of the pre dreadnought ironclad Bouvet during World War One, has however been reported and discussed in [4.2.33].

In the considered review period, only one paper [4.2.23] was dedicated to submarines. In particular, the contribution in [4.2.23] dealt with the very special topic of Mathieu instability of surfacing submarines.

Some comments can then be provided regarding possible topics for further research. Behaviour of submarines, including the surfacing time, seems to be a complex problem which has unfortunately not very much investigated (or published). Therefore, further published analysis on this topic would be welcome. Then, as naval rules are based on quite old standards based on old hull forms, work is required in order to check if some modifications are needed in order to take into account new hull form (including, for instance, tumblehome vessels or even multihulls). In this context, it would also be worth to collect and critically re-analyse the justification which was originally given for existing (old) rules. In the process of updating stability regulations, there is a need for determining the tolerable risk associated with rules, and to this aim it would be preferable to use advanced numerical codes. In this context, existing general codes could therefore need to be improved or adapted in order to deal with the particular features of naval ships. With respect to nonlinear ship motions in waves, one important mode of stability failure for naval ships is broaching. Research in this domain is therefore needed for naval ships, which could be required to safely operate at high speed in very severe sea states.

4.3 Inland Vessels

Although research in the field of inland navigation is active within various conferences and journals, the safety and stability of inland vessels has so far not received much attention in the STAB conferences and workshops. In recent years, only two papers dealing with the stability of inland vessels were presented in STAB/ISSW events. In [4.3.1] a probabilistic safety assessment of inland container vessels exposed to gusting beam wind was presented (see [4.3.2] also). A review and a probabilistic analysis of the ship stability regulations intended for the river-sea ships was given in [4.3.3].

What makes inland vessels special from the stability point of view? Even though the wind-generated waves, due to a limited fetch, could be disregarded in the analysis of dynamic stability of ships in inland waterways, there are other, quite specific environmental loads and potential hazards that ought to be taken into account. The strong, gusting winds, in particular in combination with other heeling moments and effects may induce both partial and total stability failures. On the other hand, shallow-water sectors and periods of low water levels may cause grounding and contact. Some typical features of inland vessels, such as exceptionally low freeboards (some rules allow navigation with practically no freeboard) and carriage of non-fixed containers, are particularly important from the stability viewpoint. The river-sea navigation implies basically inland vessels (with few modifications) that operate in the coastal maritime stretches. Clearly, in such cases, the stability in waves should be assessed as well, having in mind the specific form and design features of river-sea ships.

Focusing on Europe only, perhaps the most important task of the future research is the improvement and harmonization of stability regulations. Both intact and damage stability rules intended for inland vessels are deterministic. In addition, the regulations imposed by the Directive 2006/87/EC (stemming from the Rhine Commission rules and valid on most of the waterways of European Union) are merely static stability requirements. Moreover, unlike in maritime transport, there is no common set of safety rules applicable to inland ships worldwide.

To carry out the aforementioned task efficiently, proper mathematical modelling of safety phenomena typical for inland vessels is required. Recent accidents on inland waterways in Europe warn against the oversimplified treatment of stability. The understanding and accurate modelling of weather phenomena (wind in particular) is of equal importance.

The notion of risk in inland navigation is a challenging topic too. Besides human casualties, environmental damage, loss of cargo and ship damage, accidents in inland navigation often yield an additional consequence: the suspension of navigation due to the waterway blockage. For instance, the tanker Waldhof that capsized in intact condition disrupted the navigation on the Rhine for 32 days in 2011, causing financial loss that amounted to EUR 50 million.

Finally, it is interesting to point out that the first practical implementation of the probabilistic approach to intact stability was realized in innovative rules for river-sea navigation, applied in Belgium and France. This seems to be a very promising track.

4.4 Other Types of Vessels and Floating Objects

Some contributions have also addressed some specific topics related with floating offshore structures. From a geometrical point of view, floating offshore structures are often characterised by shapes which are not elongated, as in the case of conventional vessels. This marked three-dimensionality can require reconsideration of, and/or elaboration on, concepts and calculation techniques for static stability and dynamics which are instead well consolidated for the case of conventional vessels. Contributions concerning static stability of floating offshore structures can be found in [4.4.2, 4.4.4, 4.4.13], where the issue of a proper calculation of the calm water righting lever for floating structures of generic shape has been discussed. More specifically, the potential energy of the floating structure was used in [4.4.2, 4.4.4, 4.4.13] as a fundamental tool to directly or indirectly determine the most critical ship restoring, and calculation methodologies have been proposed. Floating offshore structures have also been addressed from the point of view of nonlinear dynamics, since their shape and their possible mooring configurations can lead to the inception of ship motions governed by nonlinear phenomena. The behaviour of a long vertical cylindrical structure, representative of a spar platform, has been numerically investigated in [4.4.8] by means of an analytical nonlinear 3-DOF (heave/roll/pitch) mathematical model, indicating the potential occurrence of sub-harmonic roll motions for certain wave periods and height in regular waves. A long vertical cylindrical structure (mono-column), with different mooring configurations, has later been studied experimentally and numerically in [4.4.14]. Sub-harmonic motions (pitch and roll) have been observed, both in regular and in irregular waves, with different response patterns depending on the mooring arrangement. Still remaining in the field of nonlinear motions, in [4.4.9] large amplitude sub-harmonic yaw motions have been observed, both experimentally and by using a 7-DOF nonlinear mathematical model, in regular waves for a system comprising a TLWP (Tension Leg Wellhead Platform) connected to a nearby moored FPSO (Floating Production Storage and Offloading vessel). The study presented in [4.4.1] was instead more related with design and rules assessment, presenting an analysis of the effect of uncertainty of some parameters (most notably the position of centre of gravity) on the overall assessment of static stability criteria for an FPSO.

Nonlinear ship dynamics in the particular case of multi-hull vessels has also been considered. Roll restoring variations and parametric roll in case of trimaran vessels have been addressed experimentally in [4.4.6], by measuring roll restoring in waves and identifying conditions of occurrence of parametrically excited roll motion. The topic of parametric roll for a trimaran vessel was also investigated in [4.4.7], where instability regions and roll response curves were experimentally determined and compared with predictions based on a 1-DOF mathematical model. Another type of multi-hull, a semi-SWATH, was considered in [4.4.11] in case of following waves. In the study, a 3-DOF (heave/pitch/surge) mathematical model was developed and used to investigate the occurrence of the phenomenon of bow-diving and to assess the possibility of its reduction through active or fixed fin stabilizers.

Phenomena specifically relevant to mono-hull high-speed craft have also been subject of some contributions. In [4.4.12], the roll restoring moment of a planning craft operating at planning speeds was investigated experimentally and by means of two different mathematical models. In [4.4.19] an experimental investigation has been reported regarding the occurrence of the spinout phenomenon for a radio controlled high-speed craft model.

Furthermore, specific aspects of other special vessels/units have been addressed. A discussion has been provided in [4.4.12] regarding operational aspects and specific static stability issues of float on/float off (FLO/FLO) heavy-lift semi-submersible vessels during the de-ballasting phases. In [4.4.15] a numerical study was presented regarding second order forces for a series of variants of a semi-submersible floating structure. The second order drift roll moment was investigated because it was considered relevant to the observed possible occurrence, for this type of floating objects, of steady heel angles in head sea. In [4.4.18] the same phenomenon was investigated experimentally by considering three configurations of a semi-submersible (bare hull, with vertical barriers, and with sponge damping layers) in head waves. A weathervane turret moored floating storage and regasification unit (FSRU) was instead the subject of the study presented in [4.4.16]. The study provided an experimental investigation on the behaviour of yaw motion in regular and irregular waves, identifying regions of wave periods associated with the inception of yaw motions with large non-zero mean. Such regions have been linked with regions of instability of low-frequency yaw under second order forces, and numerical/analytical calculations have been carried out to predict such regions. Interestingly, the observed behaviour shows similarities with yaw instability during towing operations as presented in [4.4.17, 4.4.21].

Sailing yachts have been considered in [4.4.5]. The effects of size on the stability and safety of very large sailing yachts have been discussed from a design perspective, also in view of a reported series of wind tunnel experiments addressing wind heeling moment.

In addition to floating objects, also helicopters and Wing-In-Ground (WIG) craft have been given some attention. In [4.4.3], a study has been presented on anti-capsize floatation devices fitted on a helicopter. Two technical solutions have been considered, and results of static stability calculations and capsize model tests in irregular waves have been presented to assess the effectiveness of the solutions. The topic of WIG craft has instead been addressed in [4.4.20], where the take-off phase of a WIG craft has been numerically studied by means of a 3-DOF mathematical model (surge/heave/pitch).

Particular static and dynamic characteristics of floating offshore structures undoubtedly represent an opportunity for continuous research. However, the observed quantity of contributions within STAB/ISSW indicates that this opportunity seems not to have been fully exploited in the observed period of time, and possibility for improvements is clearly available. The strong three-dimensionality of (most) floating offshore structures represents a challenge for research on the development of new specific approaches or for the extension of tools and concepts originally developed for static and dynamic analysis of conventional ships. In fact such concepts/tools/methodologies of analysis often embed, implicitly or explicitly, assumptions and/or simplifications based on the elongated shape of conventional vessels, and can therefore become unsuitable if naively used. Moreover, the frequent presence of mooring lines in the configuration/operation of offshore floating structures add a further degree of complexity (also for ship-shaped floating objects) which is typically not considered for conventional freely floating vessels. Multi-bodies interaction, with associated increased system complexity, is another distinctive feature of offshore applications which is not considered in the typical analysis of freely floating/free running vessels. These general aspects, combined with the reported evidence of specific stability-related issues pertinent to floating offshore structures, provide sufficient ground to suggest an increase of interest and efforts on this topic in the future. It should also be considered that floating offshore structures are, typically, high-budget designs. As a result, high-end technologies, tools and concepts can be more easily accommodated within the design flow compared with conventional vessels. This aspect could be seen as a facilitator in the process of transferring research outcomes to practice.

Somewhat similarly to offshore floating structures, multihull vessels would also be worth additional attention in the future, with the aim of addressing stability-related design aspects and developing and/or improving specific models for prediction of ship motions and manoeuvring in waves, which can better take into account the hydrodynamic interaction between hulls.

High-speed craft are also associated with specific technical issues and specific dynamic phenomena. High-speed craft have been traditionally handled, mostly, outside STAB/ISSW framework. However, the high speed of such vessels has consequences on many stability-related aspects: stability is no longer governed by hydrostatics and hydrodynamics plays a fundamental role also in calm water, damage stability safety is governed by damage dimensions not in line with conventional low-speed vessels, dynamic phenomena occurring on high-speed craft are often so specific that they cannot be observed in conventional low-speed vessels, methodologies for ship motions and manoeuvring in waves for high-speed craft require significant re-thinking and re-modelling compared with those used for low-speed conventional vessels, etc. , Therefore, it seems there could be justification for trying, in the future, to increase the attention on this topic from the perspective of stability and (nonlinear) dynamics also within STAB/ISSW.

In general, what is clear from the analysis of the available STAB/ISSW literature on special types of vessels/floating objects, within the considered time period, is that, as expectable, peculiarities of the design eventually reflect on peculiarities of associated issues and phenomena. This fact should therefore be seen, and exploited, as an opportunity stimulating curiosity, research and development.

5. ROLL DAMPING & ANTI-ROLLING DEVICES, CFD FOR SHIP STABILITY, AND MODELLING OF GRANULAR MATERIALS

An accurate prediction of roll motion is of fundamental importance when ship safety is assessed. In case of an intact ship, the accuracy in the prediction of roll motion is, for a large set of dynamic phenomena, strongly dependent on the accuracy in the prediction of roll damping. In parallel to this, the fact that roll damping is, for conventional ships, governed by viscous effects, makes accurate roll damping prediction a very difficult task. Roll damping estimation and modelling have therefore represented important topics of research in the field of ship stability. In the considered review period, the subject of roll damping has been addressed from different perspectives and using different approaches.

The most commonly used approach for the estimation of roll damping has been in the past, and still is, based on semi-empirical methods. In this context, a simplified version of the well-known Ikeda's method was presented in [5.5], where regression formulae, derived from systematic application of original Ikeda's method, were proposed for the estimation of the various roll damping components. The approach has also been implemented within the framework of IMO Second Generation Intact Stability Criteria. In [5.4], following application examples, warnings have been given regarding the application of Ikeda's method to vessels with characteristics not in line with the original sample used for the development of the method. Proposals for improvements in estimation of bilge keel roll damping in case of shallow draught vessels, large rolling amplitude and non-uniform flow can be found in [5.10], while proposals for improvement of bilge keels roll damping modelling within time domain simulations have been presented in [5.18, 5.34]. The issue of proper modelling of roll damping in time domain simulations, in particular in case of large amplitude roll motions, has also been addressed in [5.9]. In [5.9] it was proposed to use different roll damping models at different rolling amplitudes, i.e. for regions assumed to be associated with substantially different physical phenomena (e.g. bilge keels or deck in water/out of water). The necessity of improvements in the modelling of bilge keels effects was also claimed and discussed in [5.16], with particular attention to the application in time domain simulation of large amplitude ship motions in waves, with or without forward speed.

Although semi-empirical methods still remain a reference tool for the prediction of roll damping, in the considered review period a significant number of studies have been presented where CFD techniques have been used with the intention of analysing roll damping (herein the short wording "CFD" is intended to refer to computational fluid dynamics techniques aimed at solving Navier-Stokes equations including viscous effects). In [5.17], forced roll motions (1-DOF - fixed roll axis) in calm water and beam waves have been simulated with CFDShip-Iowa. Large amplitude rolling motions up to 35deg and forward speed have been considered, with attention given to forces acting on bilge keels. CFD simulations using the commercial code Fluent have been used in [5.33] to study possible interaction effects between bilge keels plates. Such effects were considered to be the possible source of disagreement between experimental results and semi-empirical predictions based on Ikeda's method for a vessel with round cross sections fitted with bilge keels. Comparisons between experiments, semi-empirical predictions based on Ikeda's method, and CFD simulations using Fluent, have also been reported in [5.38] in the study of shallow water effects on roll damping for 2D sections. 1-DOF roll decay and forced roll motion of DTMB5415 have been simulated in [5.39] using the code SURF, and an analysis of flow field and pressure distributions with and without bilge keels has been reported. The same hull form was also used in [5.26], where roll decays (see also [5.15]) and forced roll motions have been simulated using the commercial code Fluent. This study also showed some forced roll simulations which are reported to have been carried out at full scale. A numerical study on roll damping, with simulations reported to have been carried out at full scale using the commercial code STAR-CCM+, was presented in [5.31] for a twin-screw RoPax ship, allowed to rotate around a fixed axis through sliding meshes. The influence of roll amplitude (up to 35deg), ship speed, vertical position of the roll axis, presence of bilge keels (with possible emergence/re-entrance) and presence of rudder have been thoroughly investigated, and comparisons have been reported with semi-empirical predictions based on methods of Ikeda and of Blume. The influence of degrees of freedom (sway/heave/roll) left free in roll decay has been addressed in [5.19]. Numerical simulations have been carried out using the solver ICARE for DTMB5512 at model scale, and then compared with experiments. Results confirmed a known characteristic, i.e. the fact that roll decays with prescribed fixed axis are often not representative of the actual ship behaviour, due to lack of coupling of roll with, mainly, sway, which should then be left free.

For practical limitations, the large majority of data regarding roll damping are available from model scale experiments. CFD techniques have been used in some cases to try predicting full scale roll damping, although corresponding validation is typically missing. However, in [5.30] a unique set of results have been presented regarding roll decays with forward speed carried out at full scale (through rudder action) for a modern Panamax Pure Car and Truck Carrier (PCTC). Full scale data were then compared with experimental results at model scale and with predictions based on Ikeda's method. For the extraction of full scale roll damping coefficients, a method of analysis of full scale roll decays was also presented combining the classical 1-DOF model with a polynomial function aimed at removing low-frequency experimental disturbances. Different analysis methods for determining roll damping from roll-decay experiments have also been discussed in [5.11, 5.19, 5.20].

Anti-rolling tanks have also been given attention in a series of contributions, and they have been studied using analytical methods or by means of CFD approaches. In this latter case, preference was given to meshless methods such as MPS (Moving Particle Semi-implicit) and SPH (Smoothed Particle Hydrodynamics), thanks to their capabilities of handling violent sloshing flows which often occur in free surface anti-rolling tanks. An analytical model for a (passive/active) U-tube anti-rolling tank has been coupled in [5.12] with a nonlinear 3-DOF model (roll/heave/pitch) for parametric roll assessment. In [5.27], MPS has been used to simulate 2D flow and resulting forces in a U-tube tank and in a rectangular free surface tank, coupling the tank with a 1-DOF roll model for parametric roll, and comparing simulations with experiments. In [5.1], SPH has been used to simulate 2D flow and resulting forces in a free surface rectangular tank, free to rotate around a fixed axis, and forced by a sliding mass (an archetypal 1-DOF mechanical model for roll motion). Experimental results with fluids having different viscosity have been compared with simulations. The SPH approach has later been extended to 3D simulations, taking advantage of parallelization on graphical processing units (GPUs), see [5.28].

As an active anti-rolling means, rudder-roll stabilization has also been considered. The use of active rudder-roll stabilization to mitigate parametric rolling has been studied in [5.21] with a blended 6-DOF code (in 6-DOF and in 3-DOF configuration), and in [5.36] with a 4-DOF model. In [5.23], instead, an unusual active anti-rolling device, based on a controlled wing assumed to be placed beneath the hull, has been proposed and studied numerically. An extensive control-oriented review of the development of, and challenges associated with, some active anti-rolling means (fin stabilizers, rudder, gyrostabilisers) can be found in [5.32].

As described above, an increasing application of CFD techniques has been observed in the fields of roll damping prediction and anti-rolling tanks performance assessment. CFD techniques have increasingly been used also for more general purposes in various additional contributions. Direct CFD simulation of free running ship motions in waves are still a too time consuming task for systematic application. However, a series of contributions combining simulations using CFDShip-Iowa, experiments and systems-based simulations for the ONR Tumblehome, have shown that, on one side, CFD techniques are becoming a reliable surrogate for model experiments and, on the basis of this, CFD simulation can be used as reference data for tuning more classical system-based approaches. For example, in [5.3] free running and semi-captive conditions in waves have been considered, giving attention to following waves, and to the occurrence of surf-riding, broaching and periodic motions. Semi-captive conditions have also been addressed in [5.6] for the HTC container vessel in bow and head waves. Further, in [5.13] ship motions and manoeuvring in calm water and in waves (turning circle and zig-zag) have been considered and a 4-DOF system-based model has been tuned making use of CFD results. A similar approach was also used in [5.22], considering manoeuvrability in following waves (straight running, course keeping, zig-zag) (see also [5.35]).

CFD techniques have been used not only for the case of intact vessel, but also for the case of damaged vessel. In this case, together with the inherent complexity in simulating the fluid within the ship internal layout, one of the most challenging difficulties is the simulation of the fluid motion considering both internal and external hydrodynamics. In [5.2] a volume-of-fluid (VOF) approach was used, among other applications (dam break and tank sloshing), to simulate the progressive flooding of a compartment. The free flooding of a compartment, as well as the flooding of a freely floating 2D box and an internal sloshing problem, have been addressed in [5.7] by means of a 3D parallel SPH approach. The commercial code Fluent was instead used in [5.8] to simulate the progressive flooding due to side damage, and the consequent motions, of a freely floating 3D barge. Air compressibility was taken into account and dynamic meshing was used. CFD simulations of flooding process in calm water (with and without ship motions), roll decays (intact & damaged condition) and motions in regular beam waves (intact and damage), have been carried out in [5.25] with CFDShip-Iowa for the SSRC cruiser. In the simulations 6-DOF have been considered, and results have been compared with experimental data. Roll decays in damaged condition have also been simulated in [5.15] assessing also the influence of free or fixed sway. A mixed (blended) computational approach has instead been used in [5.14] to simulate ship roll motion in beam waves. In the proposed approach, external hydrodynamics has been addressed by the blended 6-DOF code PROTEUS3, while internal flooding has been addressed by means of a VOF approach. In [5.24], the SURF code has been used to simulate the flow behaviour through cross-flooding arrangements, and outcomes have been compared with experiments and with IMO guidelines as given in MSC.245(83).

An important aspect to be borne in mind when addressing ship stability, dynamics and safety, is that not all the cargoes onboard can be categorised as single rigid blocks, or as standard fluid cargoes. This is the case of granular materials, which are made of a huge number of interactive constituent small bodies, with their own specific behaviour and specific interaction characteristics, depending on the material. As a result, granular materials behave differently from both a single rigid body and from a Newtonian fluid. As such, they pose risk to the safety of the vessel, and require special treatment in simulations. In this respect, contributions have been given in [5.29] regarding the direct simulation of granular materials (see also [5.37] for an extension of the analysis). In [5.29, 5.37], different available simulation approaches have been described and a soft sphere molecular dynamics approach was eventually detailed and used in a series of example calculations.

Considering the observed status of the research in the addressed topics, it is eventually possible to provide some comments and suggestions for possible directions of future research.

Roll damping is clearly a fundamental subject in the field of ship motions and stability. Indeed, an inaccurate prediction of roll damping can render useless even the most accurate ship motions model, if this is intended for roll motion prediction and ship safety assessment. Despite this is a very well known situation, it is evident that semi-empirical methodologies, i.e. the type of methods which are more likely to have a more widespread use, are still today showing difficulties in providing predictions systematically agreeing with experimental data. It is therefore of utmost importance that such methodologies are improved and/or updated, in order to give to designers and researchers, more precise, and still fast and easy to use, tools for roll damping prediction. Accurate predictions of roll damping are not only relevant when direct ship motions simulations are carried out. They are also relevant when roll damping becomes a factor within intact stability regulations (as it is the case, for instance, of the Weather Criterion and in some methodologies within the Second Generation Intact Stability Criteria). In this context imprecise roll damping estimations can lead, eventually, to uneven levels of safety for vessels complying with the criteria. More accurate prediction tools could also promote a virtuous design practice aimed at increasing the ship roll damping. Improvement of roll damping estimation should also be pursued at the level of modelling. While the concept of amplitude/frequency dependent linear equivalent roll damping as a substitute for nonlinear roll damping is suitable for frequency domain approaches, this is not the case when time domain large amplitude simulations are to be carried out. In this case, reliable time domain models need to be used. There is space, in this context, for improving present modelling of roll damping moment (which is mostly based on a nonlinear roll damping depending on roll velocity) in order to better account for phenomena occurring at large rolling amplitudes. Also, efforts should be spent in improving the modelling of roll damping when the ship is at forward speed and when the vessel is free running in waves, and in order to better understand to what extent information from roll decays in calm water can be considered appropriate for large amplitude ship motions in waves. Such type of improvements would largely benefit the accuracy of prediction of blended large amplitude ship motions codes. Scale effects in roll damping represent another topic which would benefit from further elaboration. Full scale experiments have been limited, and considering the associated difficulties, this is understandable. However, examples have been shown that carrying out full scale experiments is feasible not only for naval ships, but also for civil vessels. Additional, possibly systematic (e.g. at sea trials), efforts in this respect could therefore be recommended, with the aim of considering cargo, and possibly passenger, vessels. Together with the improvement in the predictions of roll damping, also prediction method for rolling period should be improved. Indeed, the rolling period represents a key aspect governing the dynamics of the vessel. Inaccurate predictions of such quantity inevitably lead to imprecise dynamic simulations. Since the added mass/inertia affecting the actual roll period is typically well predicted by nowadays standard linear seakeeping codes, it means that efforts should be spent in improving the methodologies for predicting dry radii of inertia.

Direct CFD approaches have gained increasing attention, especially thanks to the more widespread availability of suitable computational resources. Although some research has been carried out on using CFD approaches for directly simulating the motions of an intact free running ship in waves, the associated computational time is still prohibitive. However, such tools can be used in a virtuous combination with existing systems-based approaches (which are typical of blended ship motions codes). Useful research could therefore be directed into a more extensive validation of CFD tools, and on the use of such tools for tuning, or developing, appropriate, simpler and faster, mathematical models. This could typically include roll damping from decays, manoeuvring forces, forces due to appendages, wind effects, etc. Some use of direct CFD computations has been reported also for the damaged ship condition. Also in this context complete direct simulations are still prohibitively time consuming. However, similarly to the case of intact vessels, direct CFD simulations could be used to better tune semi-empirical progressive flooding tools (e.g. tuning of discharge coefficients). CFD approaches, in both intact and damaged condition, after proper validation, could be used not only for tuning, but also for producing surrogate (with respect to experiments) validation data for checking more simplified, semi-empirical, approaches.

With reference to anti-rolling devices, contributions have been provided for different types of system. Anti-rolling tanks (U-tube and free surface) continue, as in the past, to be a topic of interest. Additional interest was given to rudder-roll stabilization. With the increased availability of computational resources, anti-rolling tanks could be targeted for more in depth studies on the, possibly nonlinear, characteristics of the coupled tank-ship system. This could help in providing better tools at the design stage, and better information to the masters for operating vessels with such devices. Also, interest should be given to understanding whether, for passive devices, present knowledge and calculation and experimentation capabilities could allow to take such systems into account within intact stability regulations dealing with ship dynamics. Going to rudder-roll stabilization, the observed interest could benefit from a virtuous link with the field of controls, combining existing knowledge in such field, with more advanced dynamical models typical of the field of ship stability. In terms of active systems, it would be beneficial to dedicate more efforts to the modelling and assessment of active anti-rolling tanks, especially in case of large amplitude nonlinear motions.

A limited number of contributions have been provided on the interesting emerging topic of granular materials, which is relevant to certain types of cargo. Being such materials different from a perfectly solid or a perfectly Newtonian fluid cargo, a better understanding is necessary regarding the impact of granular cargoes in dynamic conditions. Also, this topic of research could be linked with the issues associated with the inception of liquefaction. Considering the limited availability of research in this specific context, the interest and complexity of the phenomenon, and its importance for the safety of certain types of vessels, it is expectable, and desirable, that further experimental and numerical studies will be carried out in the future.

6. SHIP STABILITY IN OPERATION

Enhancing the stability of ships during their operation could be a challenging task considering the uncertainty that spans the various operational parameters such as the weather and loading conditions as well as the human reactions in critical situations. On the other hand, the large amplitude response of a ship in random seas and the various instabilities that may appear have been well studied, while probabilistic methods and numerical simulation tools have been already incorporated in the design process. Moreover, it should not be disregarded that operational guidance is also considered as an important element in the second generation intact stability criteria. However, stability failures, either affecting ship's safety or cargo's integrity still occurring, and thus, it becomes obvious how all the knowledge gained from the above fields could be appropriately utilised in the operation of a ship.

One of the available methods is through the operational guidance to ship's master based on numerical simulation tools. A respective study was presented in [6.1], where polar diagrams of maximum acceptable significant wave height versus the seaway period and wave direction for different speeds and load cases were shown for the cases of excessive motions and accelerations for containerships in heavy seaways. In [6.8, 6.12] another approach was considered where stability limits for pure loss of stability and parametric rolling were derived from GM variation spectra calculated from stability variation RAO's and arbitrary seaway spectra based on linear response theory. The approach was evaluated in comparison to real stability incidents and time-domain simulations, and the importance of proper representation of the wave environment was highlighted.

From another viewpoint, one could take advantage of the direct measurements of ship motions in order to predict, and subsequently advice on stability in order to avoid possible forthcoming undesiring events. In [6.6], an approach for assessing parametric roll resonance based on roll motion time series was presented. The approach utilized the time varying autoregressive modelling procedure and parametric roll was detected by studying the characteristic roots of the time varying autoregressive operator. Additionally, in [6.14] an alternative autoregressive modelling procedure for parametric roll detection based on time series analysis was examined in order to decrease the required computational cost. In this case, an exponential autoregressive modelling procedure was applied. On the other hand, in [6.10] it was demonstrated that influential parameters of the encountered wave pattern, such as peak frequency and amplitude, can be detected through the monitoring of heave and pitch motions, which were considered as signals with time-dependent spectral content. In [6.9] an application was described for implementation in mobile phones and similar devices. Utilizing built-in accelerometers and gyroscopes, the application can provide low budget operators, like fishermen, with ship motion recordings, information about natural roll period and GM, and a safety index reflecting the severity of the motions.

In a similar manner, on-board tools can be utilised in order to optimise, in real time stability and provide the appropriate guidance to the crew. In [6.7] a 1-DOF simulation model was proposed as a candidate to use for generation of real time on-board guidance in terms of parametric rolling. Typical results were in the form of polar plots of roll amplitudes that could be presented to the crew to indicate dangerous zones with respect to parametric rolling. Furthermore in [6.13] a description was given of the practical implementation methodology of an artificial neural network (ANN) system for parametric roll prediction, which can be integrated in a fishing vessel for onboard stability guidance. A 1-DOF mathematical rolling model was used instead of expensive and time consuming towing tank tests for the training of the ANN.

On-board safety assessments can significantly enhance operational guidance to the crew also in critical conditions. From the viewpoint of damage stability, the contribution in [6.4] highlighted the challenges in real-time simulations of complex physical processes and/or evaluation of random scenarios by presenting real flooding scenarios leading to significant loss of life. The importance of time in crises management and consequences mitigation was therefore illustrated.

Various methodologies have been presented for the accurate prediction of sea conditions. In [6.5] a method for on-board sea state estimation was explored and validated. Based on the wave buoy analogy the method builds on comparison between measured and calculated ship motion response spectra and minimization of the error to obtain the parameters of a sea state spectrum formulation. Besides, in [6.11] computational issues associated with the identification process of the wave spectrum on the basis of indirect dynamic measurements of oscillation motion of the dynamic object in a seaway were examined, specifically the parametric identification based on the adaptive model that can be carried out in the on-board intelligent system.

Providing the right information to the crew will not ensure safe operation if crew’s training in critical weather conditions is not sufficient. A discussion was offered in [6.3] on the growing trend of turning to new technologies in heavy weather ship-handling training, which complements the traditional education relying on mentoring and experience. The importance of fidelity (virtual reality) in simulators was mentioned, in terms of real time 6-DOF large amplitude motions. This issue was also discussed in [6.2] where a benchmark study for the coupling between a bridge simulator with a nonlinear blended sea-keeping code (FREDYN) was presented. The incorporation of advanced numerical tools in bridge simulator could enhance the training of the heavy weather ship-handling.

Operational guidance has revealed, without doubt, its importance in preventing ship accidents associated with stability failures. Polar plots based on extensive time-domain simulations for all sea states and loading conditions stand as one of the strategies, so the validation and the capability of the numerical tools to capture the related phenomena are necessary. Real time on-board guidance based on the measurement of ship motions is a also a promising direction but the implemented mathematical modelling can adequately and promptly predict the forthcoming events keeping in mind the short time window that is available after the initiation of an instability. The techniques of artificial neural network could help on this direction. Besides, safety assessments aiming at the capturing of the basic stability failures could improve route planning given that the prevailing weather conditions could be sufficiently predicted. Last, but not least, crew performance in safety critical conditions should be enhanced, either by utilising crisis management on-board tools or by training in advanced bridge simulators capable of reproducing extreme ship response in rough weather.

7. MODELLING OF ENVIRONMENT

A proper modelling of the environment (typically waves and, in some cases, wind) is fundamental in obtaining accurate estimations of ship motions. Therefore, the modelling of the environment plays a crucial role in the evaluation of ship safety. In this context, in [7.1], analytical expressions of typical sea spectra used in Naval Architecture were analysed, showing that, with proper renormalization, such shapes can be approximated by families of functions usually used for describing probability density functions. The topic of extreme (freak) waves has instead been the subject of investigation in [7.2], where non-Gaussian behaviours in case of generation of short crested waves were reported, and a series of accidents are reviewed in view of the possible occurrence of freak waves, considering weather forecasting/hindcasting information. The experimental modelling of extreme waves was investigated in [7.4], where different approaches were described for experimental modelling of extreme waves and nonlinear effects on wave crests distributions have been investigated, showing that, for a given sea state steepness, the directional wave spreading reduces the probability of occurrence of extreme wave crest heights. A direct specific link between environmental modelling and nonlinear ship motions assessment was instead provided in [7.3]. In [7.3], idealised spectra and spectra coming from forecasting/hindcasting were both used together with simplified semi-analytical spectral methods for assessing risk of pure loss of stability and parametric rolling, showing that spectral representation can have a significant influence on the final assessment.

Considering the mentioned importance of environment modelling for ship motions predictions, it is evident that future developments in this context should aim at guaranteeing that more realistic environmental models are used in the field of ship stability. Although detailed information on realistic environment are nowadays potentially available (thanks to wave measurements through buoys and/or wave radars, numerical wind&waves forecasting/hindcasting tools, etc.), their use within the ship stability framework is still limited and requires developments and/or transferring of information from other fields. The availability of area specific probabilistic models of directional sea and associated wind spectra could provide an important resource for improving the accuracy of ship safety assessment compared with the presently common use of standard reference environmental conditions. Also, virtuous links could be created between nonlinear ship motions assessment tools and onboard measurement of environmental conditions (wind and waves), in order to provide accurate and relevant real-time measures of ship safety.

8. EDUCATION

Beyond doubt, four decades of ship stability conferences and workshops brought numerous scientific achievements and considerably increased the level of knowledge and the understanding of phenomena related to the ship safety in real operational conditions. Even if limited to a much shorter time window, the present paper clearly demonstrates this fact. From the educational point of view, the questions is, however, to what extent this "newly" acquired knowledge can be/is actually transferred to the present generations of undergraduate naval architecture students, or, more importantly, to what extent this knowledge is supposed to be transferred.

Although the concept of the university education varies across the globe, the objective of the engineering studies is principally the same: to nurture an individual capable of coping with daily tasks and challenges of a particular engineering field. From the naval architecture perspective, the question arises whether this goal is still attainable with the present state of teaching on ship stability, based on classical, mostly deterministic approach that was common in the past. Maintaining its historic role as one of the most important generators of progress, the maritime trade keeps on evolving. New ships, unconventional in terms of size, hull form and powering represent the milestones in this evolutionary process. With new ships, however, new safety and stability problems emerge, while some old problems resurface in a different form. There is a possibility that, if the educational process does not evolve as well, we may end up in educating the engineers of yesterday that are to be struggling with the challenges of tomorrow.

There are some warning signs already. A recent conversation with a young naval architect, employed in a shipyard of a considerable size, who stated that "the ship stability is solved" and that "the seakeeping is the next big thing", indicated that there is a false impression on what ship stability is in the first place. It is reasonable to assume that the organization of the educational practice was one of the factors that contributed to this misleading image.

So, what is the ship stability about? The idea that the metacentric height represents the stability of a vessel sufficiently well was gradually superseded by the understanding that the characteristics of the righting arm provide a better insight into the problem, which ultimately led to the founding of the statistical criteria. Further progress resulted in the stability criteria based on the assessment of static and dynamic heel of the ships exposed to external loads, including the "severe wind and rolling criterion" better known as the Weather Criterion. Forty-year history of STAB conferences and workshops was instrumental in shaping the contemporary notion of stability as dynamics of ships (and other floating structures) exposed to the environmental loads (waves, wind and current) where (nonlinear) roll is not the only motion of interest. As a result, modern notion of ship stability in intact condition has become a subject closely related to seakeeping and manoeuvring, whereby the term "intact ship stability" is often used to refer to "large amplitude ship motions and manoeuvring in waves". The associated phenomena are dealt with methods "borrowed" from nonlinear dynamics and/or are analysed in a probabilistic manner. Of course, the "basic" ship stability problems have not vanished in the meantime. According to some statistics a considerable number of stability failures of small container vessels happen in port, i.e. in calm water conditions.

The assessment of stability in damaged condition evolved from the deterministic approach to a probabilistic one, through at the times turbulent process, triggered by a series of catastrophic accidents involving large number of fatalities. In addition, the knowledge gained through model experiments and numerical simulations performed over the years revealed the importance of flooding dynamics (progressive flooding, sloshing in internal flooded compartments, water accumulation on deck, etc.).

Within the academic community, there is a dilemma whether (and to what extent) these developments are addressed in the classrooms, at least at the undergraduate / M.Sc. level. Therefore, herein, an effort is made to identify the factors that could hamper the implementation of contemporary concepts of ship stability in the teaching process. Is there a need for an additional, "advanced" course on ship stability and what are the obstacles to the introduction of such a course?

In order to efficiently carry out an "advanced" course on ship stability, a number of conditions are to be met. Due to the fact that it deals with genuinely nonlinear phenomena, ship stability has an inherent "deficiency": it is complex. The students should be familiar with a list of topics, some of which fall out of the scope of the traditional undergraduate naval architecture courses. Regarding the standard naval architecture subjects, in addition to the knowledge of intact and damage stability in calm water, the comprehension of seakeeping and manoeuvring, beyond the basic level, would be necessary as well. Other desirable "skills" include the understanding of fundamental probability concepts, statistical analysis and stochastic processes. A brief survey of the curricula of several European universities revealed that the courses on probability and statistics are more often than not elective ones and, as such, sometimes in collision with other, equally important engineering subjects. The use of methods of nonlinear dynamics in ship stability problems has become widely accepted. Nonlinear dynamics, however, is normally taught at the postgraduate level. As a result, does it mean that one should obtain a Ph.D. in order to become a "stability engineer"?

The limited availability of appropriate literature is also evident. The available books on the subject either deal with the basic problems of static and dynamic stability in calm water, suitable for introductory courses on ship buoyancy and stability, or discuss much more advanced topics, better fitting for the postgraduate level. Finding an appropriate balance between these two extremes presents a considerable challenge for the lecturer. It should be added, however, that some books that could be used in the ship stability education of young naval architects were authored by well known researchers within the stability field [8.2, 8.3, 8.4]. Furthermore, the Contemporary ideas on ship stability series [8.1, 8.5] could also be considered as reference material for providing students with a modern approach to ship stability-related issues.

The problem is, however, that although we may refer to such a course as to an advanced one in comparison to the present programs (which inevitably generates a sense that it could be an "elective" subject intended for those that are more research-inclined) the topics discussed are either becoming or have already become a part of everyday engineering practice. Such is the case with, e.g. present probabilistic damage stability regulations; while the floodable lengths curve was a straightforward and an easily understandable tool, that could be incorporated without difficulty in the students' exercises, the current probabilistic rules are not effortlessly explained (let alone applied in the classroom) whereby the lack of sufficient previously-acquired knowledge of the probability concepts is just a part of the problem. The application of the methodologies embedded in present proposals for "Second Generation Intact Stability Criteria" requires the knowledge of a considerable amount of all the aforementioned subjects. Some experiences indicate that this could be the next "bottleneck" of the engineering practice. Given that the naval architect's work is guided by the regulatory regime, it sounds reasonable to reiterate the dilemma whether future engineers will be appropriately "armed" under present state of undergraduate education. Without a proper understanding of theoretical foundations of present and future stability criteria, the increase of ship safety may not be proportional to the evident rise of the level of knowledge.

How to introduce these new topics efficiently, without producing a sense of saturation with the ship stability issues and also having in mind that the available time is limited? From the pedagogical point of view, the evident complexity of the contemporary ship stability topics underlines the need for a "wise" approach to the teacher-student interaction. Such an approach, if based on the understanding of modern perception, may capitalize on the present day tools. The importance of the experimental work can never be overestimated, but it should be noted that complex phenomena are not easily reproduced when resources are limited. Video recordings of successful experiments (nowadays available more than ever) may seem to be a feasible alternative. Indeed, the effect of visually-aided lessons on students' attention is undisputed. Some believe, however, that the extensive use of videos may oversimplify the teaching process and limit (or even replace) the ability of abstract thinking, very much needed in engineering disciplines. That said, we should be reminded that teaching is about the development of: conceptual understanding; engineering design skills including creativity and judgment; personal and interpersonal skills such as communication and team work; abilities to identify own limitations; active approach to continuous learning throughout lifetime, etc.

The topic is far from being exhausted. The intention herein is merely to put the observed issues on the table and hopefully initiate a wide-ranging discussion on the matter. There isn't a more competent forum to start such a debate than the STAB conference. In relation to that, the following should be noted. The ship stability as an academic discipline may considerably benefit from an inherent quality of the ship stability as a scientific field: it has a distinct international dimension. In the end, this contribution is an example of collaboration at the international level. International cooperation in the education, including exchange of students and lecturers (i.e. the experts in various areas) cannot solve the problem, but could be a good step towards the understanding of its proportions. Within the framework of the Stability Research & Development Committee several activities in that direction have been already facilitated.

9. FINAL REMARKS

In this paper, a review has been presented of recent developments and elaborated on ideas for future directions on the subject of ship stability, dynamics and safety. The added-value for such an undertaking is explained by the need of a clear and structured overview of past research and results available, before proceeding with future research and the directions and focus it should take.

It is hoped that this work will be useful to both young and experienced researchers in providing a concise reference of the research undertaken in the past six years, and in driving forward with improvements in our knowledge of ship stability and ship dynamics, and on how to improve ship safety through new, innovative and more efficient concepts. This work could be stimulating for identifying lines of research, having a more immediate evidence of the efforts spent in the considered period by many different researchers and institutions.

As a final suggestion, it could be recommended that this massive review exercise is carried out on a regular basis by covering a shorter period than the six years covered herein. A suggestion is that future similar contributions could be done covering the period between two subsequent STAB conferences, in a way that there is some overlap between subsequent reviews. In this way, this effort can become systematic and would provide the means for continuous monitoring of research on the subject of ship stability, dynamics and safety.

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Due to the resulting large number of reviewed papers, for the benefit of the reader, the list of references is presented in accordance with the section of the paper each reference has been reviewed in. A limited number of papers appear in more than one sub-list.

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Description of abbreviations used in the list of references:

Proc. STAB2009 – Proceeding of 10th International Conference on Stability of Ships and Ocean Vehicles, 22-26 June 2009, St. Petersburg, Russia

Proc. ISSW2010 - Proceeding of 11th International Ship Stability Workshop, 21-23 June 2010, Wageningen, The Netherlands

Proc. ISSW2011 - Proceeding of 12th International Ship Stability Workshop, 12-15 June 2011, Washington D.C., USA

Proc. STAB2012 - Proceeding of 11th International Conference on the Stability of Ships and Ocean Vehicles, 23-28 September 2012, Athens, Greece

Proc. ISSW2013 - Proceeding of 13th International Ship Stability Workshop, 23-26 September 2013, Brest, France

Proc. ISSW2014 - Proceeding of 14th International Ship Stability Workshop, 29 September - 01 October 2014, Kuala Lumpur, Malaysia

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