An overview of the current research on stability of ships and ocean vehicles: the STAB2018 perspective

Teemu Manderbacka, *NAPA Ltd*, teemu.manderbacka@napa.fi

Nikolaos Themelis, *National Technical University of Athens*, nthemelis@naval.ntua.gr

Igor Bačkalov, *University of Belgrade*, *Faculty of Mechanical Engineering*

ibackalov@mas.bg.ac.rs

Evangelos Boulougouris, *MSRC*, *University of Strathclyde*,

evangelos.boulougouris@strath.ac.uk

Eleftheria Eliopoulou, *National Technical University of Athens*, eli@deslab.ntua.gr

Hirotada Hashimoto, *Kobe University*, hashimoto@port.kobe-u.ac.jp

Dimitris Konovessis, *Singapore Institute of Technology,*

Dimitrios.Konovessis@SingaporeTech.edu.sg

Jean-François Leguen, *DGA Hydrodynamics*, jean-francois.leguen@intradef.gouv.fr

Marcos Míguez González, *University of A Coruña*, mmiguez@udc.es

Claudio A. Rodríguez, *Universidade Federal do Rio de Janeiro*, claudiorc@oceanica.ufrj.br

Anders Rosén, *KTH Royal Institute of Technology*, aro@kth.se

Pekka Ruponen, *NAPA Ltd*, pekka.ruponen@napa.fi

Vladimir Shigunov, *DNV GL SE*, *Hamburg*, vladimir.shigunov@dnvgl.com

Martin Schreuder, *Chalmers University of Technology*, martin.schreuder@chalmers.se

Daisuke Terada, *National Defense Academy*, *Japan*, dterada@nda.ac.jp

ABSTRACT

The paper provides an insight into contemporary research on ship stability and identifies the possible directions for future research by reviewing a selection of papers published in STAB2015, ISSW2016 & 2017. These works have been organized in different sections, according to the main thematic areas of research, covering intact and damage stability, regulatory issues including probabilistic approaches, advanced numerical methods for ship motion and stability failure prediction including roll damping, operational issues related to ship stability and environmental modelling. Furthermore, the educational potential of STAB/ISSW is exemplified. This review paper is a joint effort within the SRDC (Stability R&D Committee).

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

1. INTRODUCTION

Ship stability is an area of vital importance for the design and operation of ships and other floating structures. Thus, it is a subject of continuous and extensive research aiming at enhancing safety. The International Conference on the Stability of Ships and Ocean Vehicles (STAB), held every three years, and the International Ship Stability Workshop (ISSW), held annually between the STAB conferences, cover the key research topics related to the stability of ships, providing significant contributions to the maritime community. Bačkalov et al. (2016) reviewed the most relevant contributions reported in the STAB and ISSW proceedings of the period 2009-2014, identifying and analysing the trends of research in ship stability. In the present work, a review of the research presented in STAB conferences and ISSW workshops in the period 2015-2017 (which includes STAB 2015, ISSW 2016 and ISSW 2017) is performed, and categorised in sections covering all major aspects of ship stability.

During these conferences and workshops, a total number of 168 articles were presented, including 103 in the main conference (STAB 2015), and 65 in the workshops, which are more discussion-oriented events. Although as it can be seen in Table 1 through Table 3 the distribution of articles in sessions in these three events has not been uniform, there are two topics which have always had specific sessions, and that have concentrated a large amount of the research efforts (including more than a 25 % of all the papers). These are the study and development of the so called Second Generation Intact Stability Criteria (SGISC) (most popular topic on ISSW 2016 and ISSW 2017), and the evaluation of the different aspects of the vessel damage stability (most popular topic on STAB 2015). These two topics are strongly related with the development of international rules which promotes enhanced safety as well as enables progressive designs for enhanced performance. A large amount of the research presented in the events reviewed in this work, has significantly contributed to the International Maritime Organization (IMO) work on development of the SGISC as well as to the IMO's work on SOLAS 2020 damage stability regulations, highlighting the importance of these series of conferences and workshops in the field of ship stability.

In order to carry out this review, the analysed articles have been divided in the six main topics shown in Figure 1, together with an additional one in which the papers with a remarkable educational value have been included. Research on intact stability is reviewed in Chapter 2, concentrating the work related with the development of the SGISC, including the assessment of dynamic failure modes with both simplified methods and direct calculations. In addition, the review on the research on the analysis of the five failure modes considered in the SGISC, but outside of the regulatory framework, is also considered in this section. Chapter 3 reviews the research on the damage stability, presenting new methods for assessment of survivability contributing to the regulatory framework. The possibilities for development of operational limitations and operational guidance (in context of intact stability) as well as operational means for assisting the crew in cases of flooding accidents, is the subject of the research reviewed in Chapter 4. Development of the computational capabilities has enabled the application of Computational Fluid Dynamics (CFD) in practical ship stability research. Recent development on CFD methods and their application to roll damping and special stability problems are reviewed in Chapter 5. Research of special ship types, such as fishing and naval vessels, high-speed craft, and other ship types, which require specific considerations, is reviewed in Chapter 6. The research on modelling of the sea environment, including wave conditions and wind, is reviewed in Chapter 7. The possible role of the recent research in improvement of the education on ship stability is acknowledged and highlighted in Chapter 8.

Table 1. STAB2015.

STAB2015-Glasgow	**#papers**
Second Generation Intact Stability	17
Damage Stability	19
Dynamic Stability	11
Decision Support	4
Extreme Behaviour	13
Naval Ship Stability	7
Risk-Based Stability	4
Instability Other Than Roll Motion	4
Stability In Astern Seas	3
Liquefaction	3
Others	18
total number	**103**

Table 2. ISSW2016.

ISSW2016 - Stockholm	**#papers**
Second Generation Intact Stability Criteria	6
Validation of numerical methods	3
Novel approaches to ship stability	3
Computational and stochastic methods	4
Damage stability of passenger ships	5
Roll damping	4
Operational aspects of ship stability	4
Stability of naval vessels	4
total number	**33**

Table 3. ISSW2017.

ISSW2017 - Belgrade	#papers
Challenges in the development of Second Generation Intact Stability Criteria	5
Onboard intact stability management using advanced technologies	3
Operational aspects of damage stability	3
Stability of naval vessels	3
Probabilistic computation in stability assessment	4
Stability and safety of inland and river-sea ships	3
Issues of stability modeling	3
Stability of fishing vessels	5
Stability of high-speed craft	3
total number	**32**

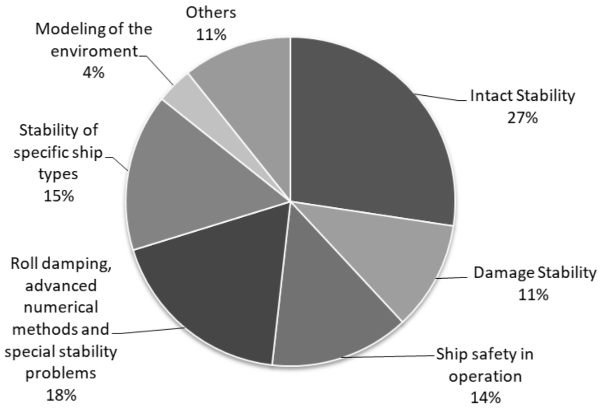


Figure 1: Distribution of number of papers in the categorization of this review paper.

2. INTACT STABILITY

Regarding intact stability, in the period under review, the IMO work on preparing the Second Generation Intact Stability Criteria (SGISC, SDC 3/WP.5, annex 1) dominated the research agenda. In fact, the vast majority of presented papers is related either directly to the Criteria or to some of the five failure modes which are dealt with in SGISC, thus being mainly focused on the vessel intact stability in waves. Other intact stability – related topics, such as water on deck effects, analysis of stability criteria on design, crew training in stability matters or still water stability issues, have not gathered as much attention as they did in the past. Within the works directly related to SGISC, the first group includes papers which focus on analysing the simplified stability failure assessment methods used in the current Level 1 (L1) and Level 2 (L2) criteria of the SGISC (Umeda and Francescutto, 2016). The second group focuses on studying the more advanced methodologies which constitute the Direct Stability Assessment (DSA), representing the third-tier criteria in SGISC. The third group of papers involves studies of the main five dynamic stability failure modes, i.e. parametric roll resonance, pure loss of stability, surf-riding and broaching, dead ship condition and excessive accelerations, but from a perspective outside of the SGISC's framework. These studies target the nonlinear dynamics in a stochastic wave environment or the capturing of stability failure modes through mathematical models. Finally, the fourth category includes papers dealing with probabilistic approaches for prediction of extreme events and capsizing dealing mainly with the treatment of rarity. In the following subsections, the most relevant contributions in each of the previous four categories are described.

Simplified dynamic stability failure assessment methodologies

Considering that in the years under review a draft version of the first two tiers of the IMO SGISC has been accomplished, a very representative effort has been directed at testing the applicability and consistency of these two first levels in the stability evaluation process set up in these regulations. These studies consider many ship types, including for example Ro-Pax and container ships (Krueger et al., 2015a), the well-known C11 class container ship (Liu et al., 2015, Tompuri et al., 2017), cruise ships (Tompuri et al., 2017), a whole set of 17 vessels of different types (Schrøter et al., 2017), a patrol vessel (Ariffin et al., 2015) and fishing vessels (Mata-Álvarez-Santullano and Pérez-Rojas, 2015, Míguez González et al., 2015) and naval vessels (Petacco et al., 2017), despite not being considered within the scope of SGISC.

In Figure 2, the results obtained for the 17 different vessels analysed in Schrøter et al. (2017) is shown, where the five failure modes are evaluated for the full set of operational draughts and three trims (levelled keel and bow and stern trim).

Id	Type	L [m]	Fn	Built
1	RoRo Passenger	159.3	0.303	2016
2	RoRo Passenger	135.0	0.262	1997
3	RoRo Passenger	183.6	0.298	2009
4	RoRo Passenger	92.3	0.246	2010
5	RoRo Passenger	88.8	0.298	2013
6	RoRo Passenger	39.6	0.287	2011
7	Ro-Ro Cargo	180.5	0.261	2009
8	Ro-Ro Cargo	185.9	0.241	2014
9	Installation Vessel	155.6	0.170	2009
10	Installation Vessel	79.3	0.169	2011
11	Supply Standby	39.2	0.315	2011
12	Supply Cable Layer	120.4	0.175	2016
13	Supply Anchor Handler	81.6	0.310	2000
14	Bulk Carrier	174.6	0.173	2012
15	Container Ship	382.6	0.208	2006
16	Container Ship	324.6	0.222	1997
17	Feeder Vessel	154.1	0.250	1991

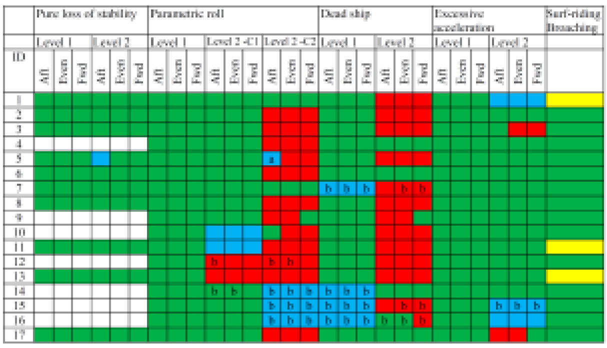


Figure 2: Results of the evaluation of the five failure modes contained in the SGISC for 17 different vessels with the following nomenclature: Green - OK, only one GM limit for a given draught. Red - Not OK, several GM limits for a given draught. Blue - Computational problems, no useful results. White - Not calculated, criterion does not apply to ship (Froude number lower than 0.24). Yellow - Ship does not comply with criterion (surf-riding). a - No results for smaller draughts. b - Results for smaller draughts only / no results for higher draught. Adapted from Schrøter et al. (2017).

The need for this type of studies, that could be used for benchmarking of the user – implemented codes especially in L1 and L2, is highlighted in Reed (2016, 2017), where the process of verification, validation and accreditation of numerical tools is explained for L1 and L2 of the

SGISC. Apart from the applicability and consistency studies described above, some other authors have focused their work on studying more in depth the numerical methodologies proposed for the L1 and L2 criteria for different failure modes.

Broaching and surf riding failure mode is tackled in Feng et al. (2015) and Umeda et al. (2015). Although the former work focuses on fishing boats and small-size high speed vessels, and the latter investigates larger ships (container ships, RoRo, PCC and naval vessels), both studies conclude that surf-riding probability is greatly affected by the accuracy of calm-water resistance and the wave-induced surge force, particularly with respect to the diffraction effects. Additionally, Feng et al. (2015) find that surf-riding probability index is not sensitive to uncertainties in the propeller thrust coefficient, wake fraction and thrust deduction coefficients, while wave force calculation and especially the diffraction effect affect significantly the probability index. This last fact is shown in Figure 3, which presents the critical surf-riding boundaries corresponding to a mid-sized purse seiner, including and not the influence of diffraction in the wave – induced surge force.

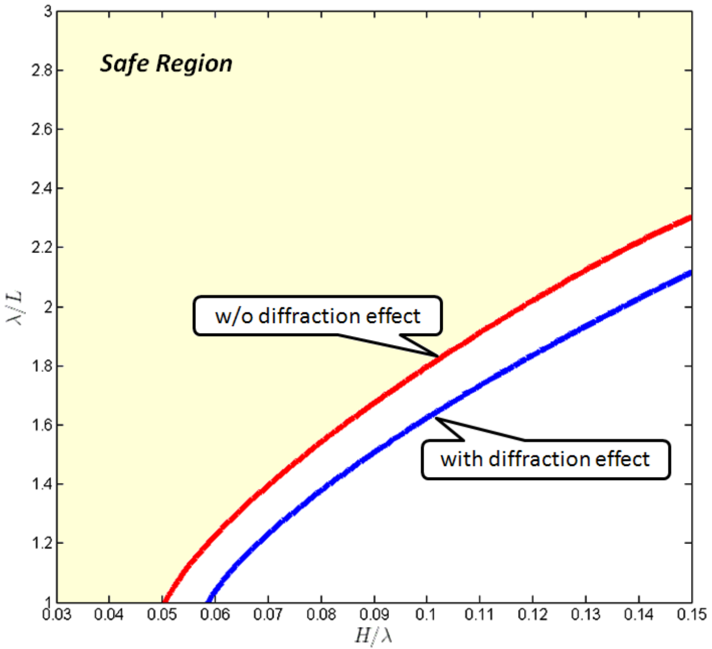
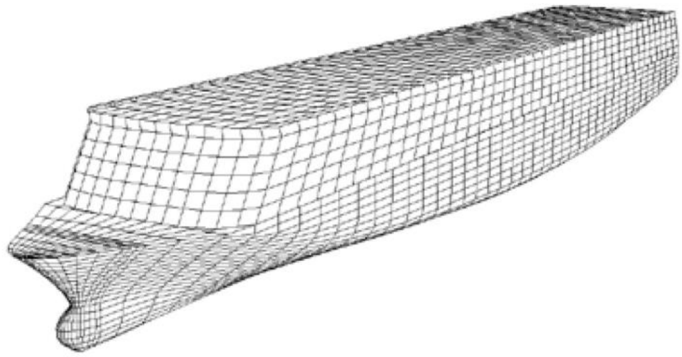


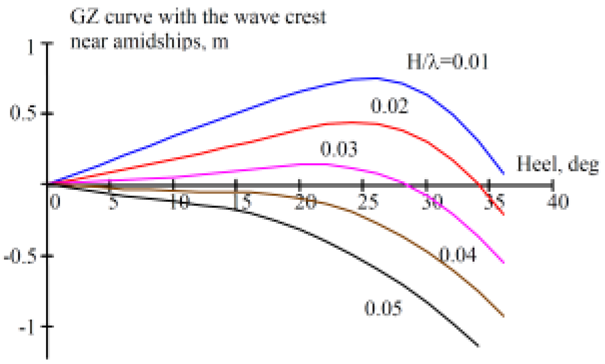
Figure 3: Surf riding occurrence boundaries considering (blue line) and not (red line) the effect of diffraction on wave induced surge force, as a function of wave steepness (H/λ) and wavelength to ship length ratio (λ/L). Mid-sized purse seiner. Adapted from Feng et al. (2015).

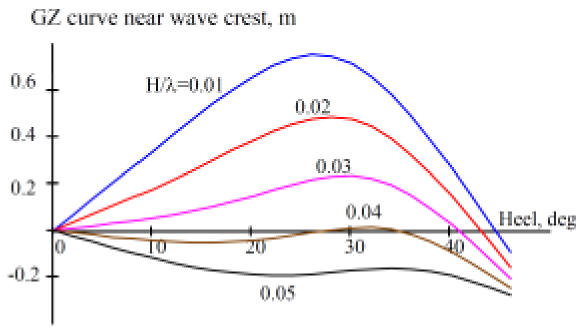
During this period, contributions regarding parametric roll resonance, which has been historically one of the failure modes that concentrated most of the research efforts, have reduced in number, as the rest of failure modes have gathered more interest. Regarding parametric rolling, Grinnaert et al. (2016a) assess the effect of the duration of the one-degree-of-freedom roll simulation, initial roll angle and linearization of GZ curve in the computation of maximum KG associated to L2 stability criteria for this failure mode. Their numerical results for two container ships, a RoRo vessel and a tanker show that ten roll cycles are sufficient to achieve steady parametric roll amplitudes, that initial roll angles greater than 5° have no influence on the maximum KG, and that the linearization of GZ curve has little effect on the parametric rolling L2 vulnerability index, especially when the GZ curve is close to linear up to 25° heel.

Peters and Belenky (2016) study the consistency of pure loss of stability L1 and L2 criteria for large *B/d* ratio vessels using a large cruise vessel as a test case. The inconsistency found between the two levels is eliminated by including the weathertight superstructures within the vessel buoyant volume in the GZ computation, which seems to be a reasonable solution for the case under analysis. Figure 4 shows the hull forms of the vessel under analysis and the differences of the GZ curves in waves when the weathertight superstructure is not included (b) and when it is considered (c). However, the authors also suggest the inclusion of some operator model that would lead to a more realistic L2 standard that, otherwise, could be largely conservative.



(a)





(b) (c)

Figure 4: (a) Case study cruise ship hull forms. (b) GZ curves for different wave steepnesses (H/λ) and wave crest amidships. D = 17 m, KG = 19.78 m. No weathertight superstructures included. (c) GZ curves for different wave steepnesses (H/λ) and wave crest amidships. D = 17 m, KG = 19.78 m. Weathertight superstructures included. Adapted from Peters and Belenky (2016).

Peters and Belenky (2017) analyse L1 and L2 vulnerability criteria for dead ship condition and point out that the different mathematical models used in these criteria frequently lead to inconsistency, i.e. stricter L2 than L1. A methodology is proposed to allow some controlled level of probability of inconsistency. Besides, the issue of integrity is raised: because L1 is based on the Weather Criterion, making L2 less restrictive than L1, as usually, may lead to situations that loading conditions failing the Weather Criterion are recognized as safe by SGISC.

Direct stability assessment (DSA) and operational guidance (OG) methodologies

The study of Direct Stability Assessment (DSA) methodologies has been mainly tackled by Shigunov (2016, 2017), whose works have largely contributed to the development of the third–tier criteria of the SGISC. Shigunov (2016) studies two approaches to solve the problem of rarity in DSA, extrapolation of the time to stability failure over wave height and reducing assessment to few selected combinations of wave height, period and direction and ship speed (design situations). Whereas the former method works well, the latter one shows significant scatter, therefore, it is suggested to use different design situations for different stability failure modes. Shigunov (2017) tests this suggestion for stability failures in beam seaway and confirms the suitability of the design situations method. Several approaches to select design situations are proposed and compared. Besides, a quicker solution, combining design situations with non-probabilistic safety criteria is tested but shows very poor performance.

Figure 5 presents the design sea states (a), the short-term stability failure rate for a 14000 TEU containership at GM = 1.0 m (b) and the correlation of simplified criteria with long-term stability failure rate (c and d) in beam seas at different forward speeds.

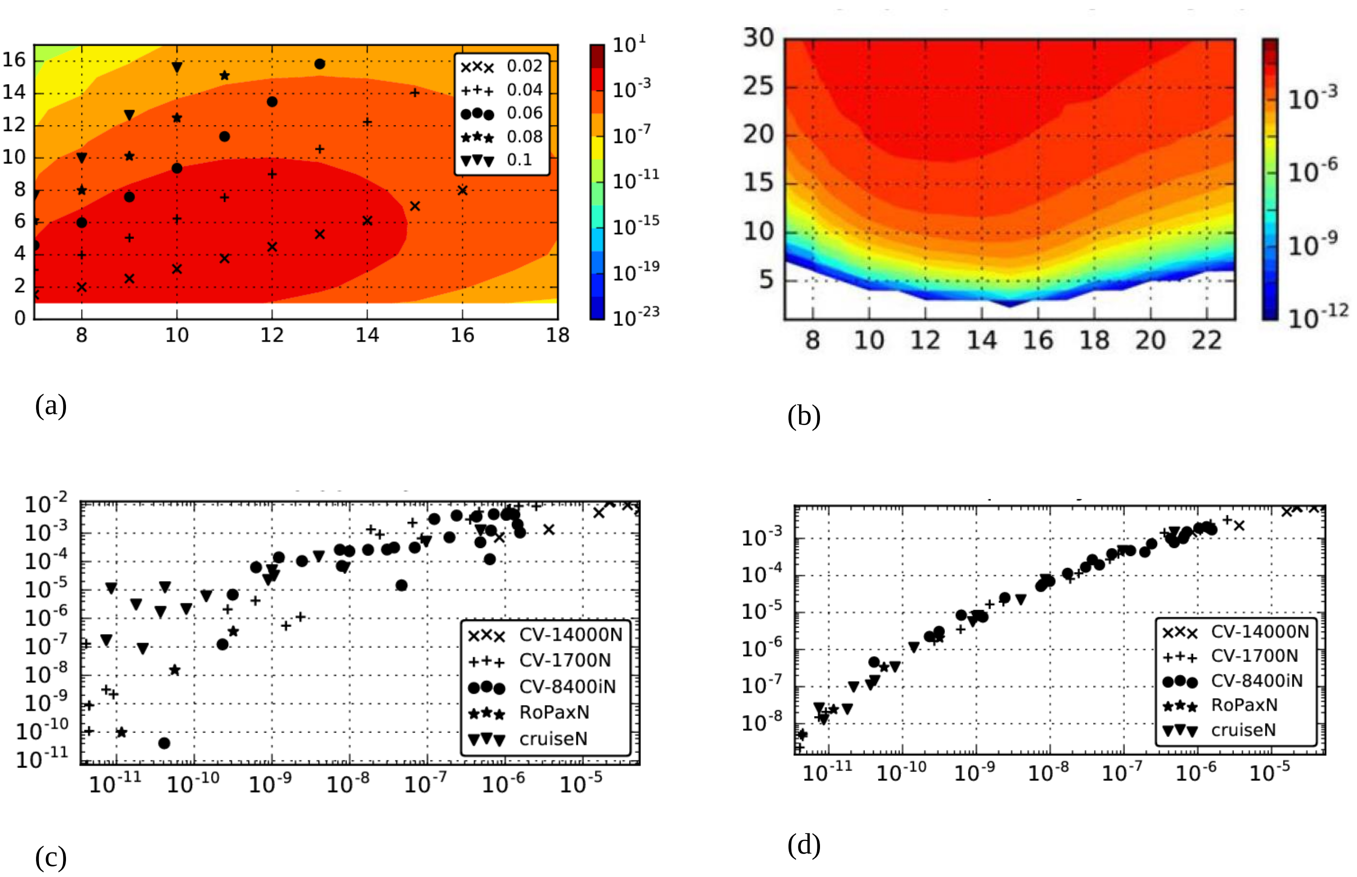


Figure 5: (a) Design sea states (symbols: constant steepness, colours: constant seaway occurrence probability density) vs. mean wave period, s (x) and significant wave height, m (y); (b) short-term stability failure rate of 14000 TEU container vessel in beam seaway vs. mean wave period, s (x) and significant wave height, m (y); (c) and (d) simplified criterion (y), maximum failure rate in design sea states of constant steepness (c) and constant seaway occurrence probability density (d), vs. long-term stability failure rate, 1/s (x). Adapted from Shigunov (2017).

Hashimoto et al. (2017) tackle the influence of operational limitations on navigation when a vessel is vulnerable to a stability failure. The authors investigate the influence of operational limitations on the routing of C11 container ship in trade between Japan and US, using parametric roll criterion, and consider effects of wave height, period and encounter angle and ship speed on the vessel motions.

Analysis of dynamic stability failure modes

The third main group of papers comprises the studies of the five dynamic stability failure modes from a perspective outside the framework of SGISC. The studies either focusing on the examination of the nonlinear dynamics underlying the failure modes and the treatment of critical response under a stochastic sea environment, or through utilising mathematical models aiming at capturing the critical behaviour through numerical simulations.

Regarding surge dynamics and broaching, Themelis et al. (2016) examine surf-riding in random sea through the concept of “high-runs’ events which are defined as the time periods where a ship attains abnormally high speed due to waves’ effect, thus they are defined as a speed crossing problem. Instantaneous wave celerity is used as a threshold value and its correlation with mean ship speed is examined. The statistics of high-runs occurrence are investigated by direct counting based on numerical simulations. From another viewpoint, Kontolefas and Spyrou (2016) study the problem of time-dependence of nonlinear dynamics of surge motion in a multi-chromatic wave environment, by identifying phase-space objects, the so-called hyperbolic Lagrangian Coherent Structures (LCS). Spyrou et al. (2016) use this technique along with extended numerical simulations for the identification of new bifurcation phenomena of ship surge dynamics as more frequencies are added in the wave excitation. Figure 6 presents the erosion process of the surf-riding basins provoked by LCS tangling, when the wave excitation is gradually transformed to irregular.

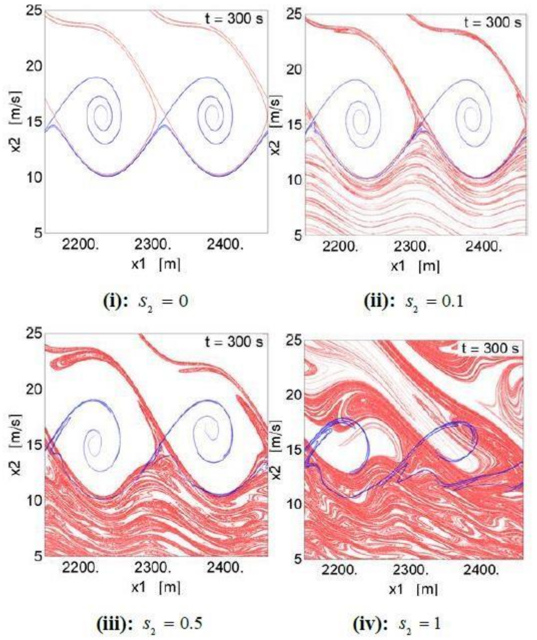


Figure 6: Transformations of phase space arrangement as one moves from a regular (s_2=0) to a fully irregular excitation (s_2=1) which is controlled by a spectrum parameter. A JONSWAP spectrum with wave peak period and significant wave height equal with 9.93 s and 7 m has been used, while ship’s nominal speed is 12 m/s. Adapted from Spyrou et al. (2016).

De Jong et al. (2015) perform extended numerical simulations of a 6 d.o.f. numerical simulation model targeting broaching behaviour in following and stern-quartering regular waves and examine the effect of ship speed, wave heading and steepness. Broaching zones are estimated, however the issue of their utilisation in real wave environment remains open. Belenky et al. (2016a, 2016b) use the concept of split-time method for the estimation of the probability of surf-riding and capsize due to pure loss of stability in irregular waves. By this concept, two problems are set: non-rare and rare, where a metric of the danger of the rare event is defined and computed utilising data from the non-rare problem (exceedances of an intermediate threshold) and statistical extrapolation techniques. However, problems could be from the nature of each stability failure in irregular seas, such as the time dependence of phase-space and roll stiffness

As it has been already mentioned, the interest in parametric rolling has slightly decreased in the period under review. Most of the works dealing with the parametric roll resonance have focused on the reliability of various mathematical models in predicting the phenomenon occurrence and on the accuracy of estimating the roll amplitudes. Umeda et al. (2016a) propose a 5 d.o.f. mathematical model considering manoeuvring forces for numerical prediction of parametric roll resonance in regular oblique waves and compare the results with the free-running model tests. A 6 d.o.f. mathematical model is used by Liu and Papanikolaou (2016) to predict parametric roll in regular and triple-frequency head waves; the results are compared with semi-captive model tests. Ma et al. (2015) compare results obtained by a 3 d.o.f. mathematical model with model tests for parametric roll in regular head waves. Lu and Gu (2016) employ a 1 d.o.f. mathematical model, whereby the calculated instantaneous wetted surface due to heave and pitch motions is considered in the calculation of restoring variation. The numerical results are compared with free-running model experiments, with emphasis on the influence of radiation and diffraction forces on restoring variation. Rodríguez et al. (2016) develop a pre-calculated derivative model for fast parametric roll prediction in irregular head waves which, in contrast to full hydrodynamic codes, does not require high computational capacity.

Regarding pure loss of stability, Umeda et al. (2017) compare the performance of a coupled 4 d.o.f nonlinear model with model tests for a research vessel that sank while sailing in stern-quartering waves. Results show a good correlation between the model and the experiments and confirm that the accident could be due to pure loss of stability. The authors highlight the possibility to use this tool for the direct stability assessment of pure loss of stability under SGISC framework and confirm that, similarly to Peters and Belenky (2016), the bulwark and weathertight superstructures should be included within buoyant hull due to the transient characteristics of the phenomenon under analysis (see Figures 4 and 17).

With respect to stability in beam seas, Anastopoulos and Spyrou (2016) propose a stability assessment method based on the “realistic wave groups” (sequences of waves with high probability of occurrence in a given sea state). Figure 7 presents the correlation surface used for determining the most expected wave heights of the wave sequency, obtained by regression analysis and best-model-fit method of the so-called transition kernels.

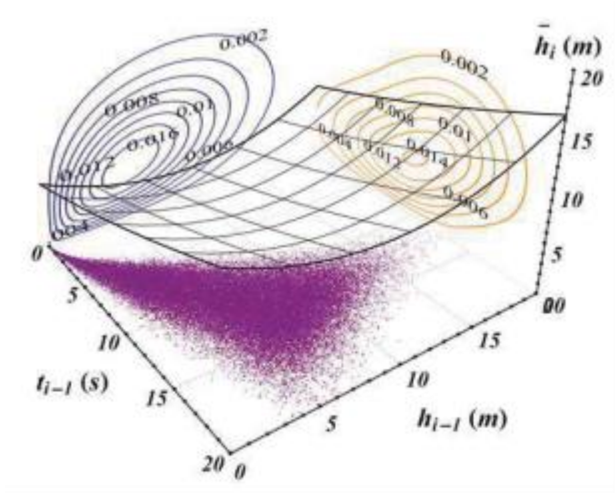


Figure 7: Correlation surface for the prediction of the "most expected" consecutive wave heights ($\bar{h}_i$) from previous height (h_{i-1}) and period (t_{i-1}). Adapted from Anastopoulos and Spyrou (2016).

In another study of stability in beam waves, Anastopoulos and Spyrou (2017) estimate the probability of exceedance of a critical roll angle, by assessing the probability of encountering wave sequences exceeding previously identified critical wave groups. The wave groups approach could be framework for treating the low probability of occurrence of failure modes, given the proper association of group characteristics with the nonlinear dynamic character of ship's response. It is to be noted that very few papers addressed the excessive accelerations stability failure mode. Borisov et al. (2015) suggest a L1 vulnerability criterion for excessive accelerations, which uses the roll amplitude from the IMO Weather Criterion and examine a set of measures that could be implemented in the proposed criterion to improve its accuracy. Another analysis of stability failures in beam waves (Hinz, 2015) utilizes risk analysis to estimate the safety of a RoPax ship based on the number of fatalities due to capsize in dead ship condition and compares the results of the analysis with the stability assessment carried out with the presently used procedures (i.e. minimum *GM*). The paper exemplifies that the consideration of the stability failures within the risk-based framework could be a possibility to arrive at the appropriate safety levels, but not without difficulties.

Probabilistic procedures

One of the key issues when examine stability failure through numerical simulations is the treatment of the problem of rarity arising due to the low probability of encounter such events for the expected sea environments and given the limited duration of simulations. The following studies proposing statistical methods and models to overcome this issue. Campbell et al. (2016) further develop the envelope peaks over threshold (POT) method to extrapolate the probability of occurrence of extreme events over the response amplitude from limited time series, providing application of the generalized Pareto (GP) distribution to approximate the tail of the roll amplitude probability density function, recommendations for the definition of the threshold and for the estimation of the shape and scale parameters of GP, and uncertainty estimates of the probability of exceedance obtained by extrapolation. Smith and Zuzick (2015) apply statistical extrapolation of the exceedance probability over response amplitude for large-amplitude roll and pitch motions, as well as vertical and lateral accelerations, using the GP distribution. For validation, the extrapolated values based on a subset of a time history are compared to the directly computed values. Belenky (2015) describes mathematical methods to account for data dependency in computing the variances of the estimates of mean and variance and proposes methods for their computation for an ensemble of independent records of different durations. Belenky et al. (2016c) study the tail of the probability density distribution of large roll amplitudes, showing that the tail is heavy up to some roll amplitude (close to the unstable equilibrium) and then becomes light, with the right bound at the unstable equilibrium. It is shown that the tail structure is related to the shape of the stiffness curve. Weems and Belenky (2017) perform perturbed motion simulations with a high-fidelity potential code to provide input for solving the rare problem of critical roll rate as a part of the split-time method for the example of pure loss of stability.

3. DAMAGE STABILITY

The main categories of studies are related with numerical methods for damage stability, including validation studies using model tests, as well as accident analyses. In addition, the survivability and safety assessment of damaged ships were studied.

Numerical and Experimental Methods

A series of model experiments to assess the flooding process in a ship like structure is presented by Lorkowski et al. (2015), together with a validation of a numerical simulation method. The test model (Figure 8) has adjustable bulkheads and multiple external and internal openings that could be closed to test different flooding scenarios. Motions and floodwater levels are measured during the calm water experiments. The numerical model assesses floating positions in a quasi-static manner and employs a Bernoulli type flooding rate calculation with discharge coefficients, determined experimentally. Two of the tested flooding scenarios are used to validate the method, while some limitations of the numerical model are discussed.

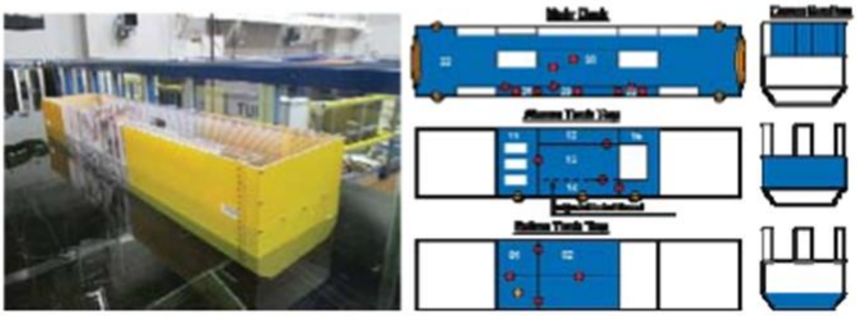


Figure 8: Test model. Adapted from Lorkowski et al. (2015).

Lim et al. (2015) present results for free-running model tests of a damaged ship, both in head and following seas. The focus is on the propulsion and manoeuvring performance of a flooded ship, related to the Safe Return to Port (SRtP) requirements. It is noted that in damaged condition the distinguishable roll period is identical to the wave encounter period, whereas in intact condition resonance in the natural roll period is observed. Dankowski and Krüger (2015) present an extension to a numerical time-domain flooding simulation method to properly deal with the roll dynamics during the transient flooding in calm water. Validation results with model tests are also presented. Manderbacka and Ruponen (2016) study the effects of the breach size and internal openings on the roll motion during the transient flooding stage using dynamic simulation with lumped mass method. Furthermore, the effect of the inflow momentum flux is studied. It is concluded that a quasi-static approach is applicable when there are large internal obstacles in the flooded compartment. On the other hand, when the breach is large and internal obstacles are small, accounting for the inflow momentum flux becomes more important. Lee (2015) introduces a new simulation method for progressive flooding, based on a dynamic orifice equation, whereas the common practice is to use quasi-static Bernoulli method. The new approach is shown to avoid numerical stability problems, and it is demonstrated with the simulation of the Sewol accident. A CFD approach using URANS to a zero-speed damaged ship in calm water and in waves is presented by Sadat-Hosseini et al. (2016). This paper includes extensive validation of both flooding and roll damping characteristics against model test.

Accident Analyses

Krueger (2016) presents an overview of using time-domain flooding simulation in the analysis of accidents. Several cases are briefly presented, including the Costa Concordia and Sewol. The main conclusion is that current time-domain flooding simulation tools, based on Bernoulli's theorem, are very useful for investigation of marine casualties. However, it is also pointed out that the main challenge is obtaining accurate data on the damage, actual loading condition, possible cargo shift and environmental factors. The flooding of the Sewol ferry (Figure 9) is also studied by Lee (2015), as an example of using the dynamic orifice equation for flooding simulation.

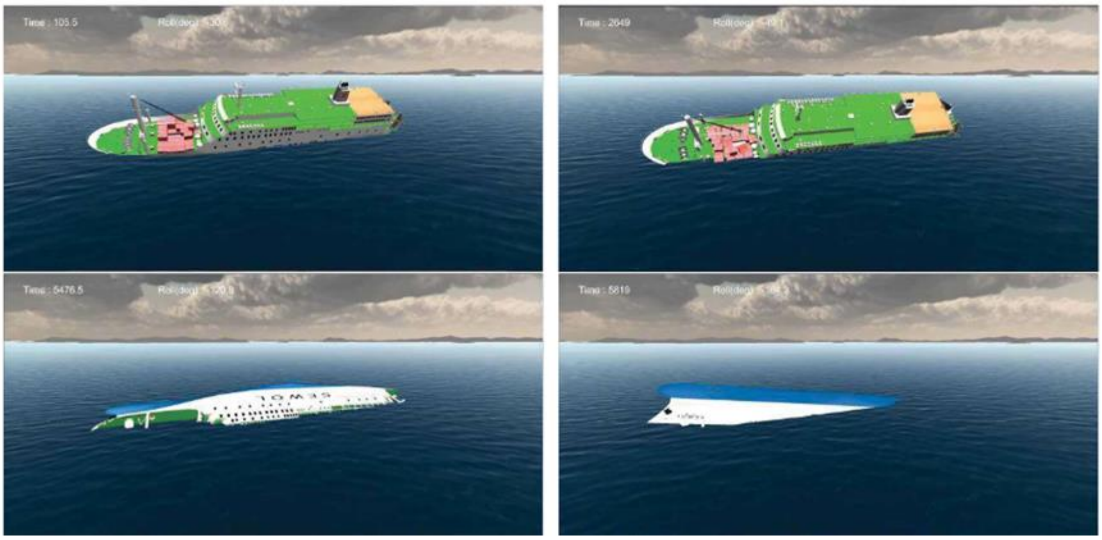


Figure 9: Visualizations of the simulation results (upper left; initial stage, upper right: when the coast guard arrived, lower left: when the last rescue action, lower right: final state). Adapted from Lee (2015).

Survivability Assessment

SOLAS 2009 does not explicitly address the accumulation of water on car deck spaces. Thus, many concerns have been raised regarding the level of safety required by SOLAS 2009 damage stability regulations and the one provided by Stockholm Agreement. The SDC sub-committee of IMO proposed amendments to SOLAS chapter II-1, including the survivability assessment of RoPax ships. Among others, a new s-factor concerning the RoRo spaces has been adopted in the new SOLAS 2020.

The particular s-factor formulation is investigated in Skoupas (2015). Calculations were performed for two large RoPax ships. The results show that the revised formulation seems to account the water on deck effect satisfactory, but a more systematic investigation is needed in order to drawn consistent conclusions. Bergholtz et al. (2016) review existing, as well as proposed amendments, to Ro-Ro passenger ship safety regulations from a holistic perspective. Operational issues, decision support systems and emergency safety procedures are significant contributors of ship safety and need to be addressed in a systematic way.

Krueger et al. (2015b) investigate the effect on entrapped water in vehicle deck spaces of RoPax ships. Given the fact that majority of relevant ship accidents happened in an intact ship condition with respect to the watertight subdivision, water on deck is formulated as an intact stability criterion and it is proposed to be covered by the intact stability regulatory framework. The proposed methodology is quite simple in principle, and it can be applied on calculations pertaining water accumulation due to firefighting. However, further development is needed with respect to the amount of water and the resulting roll period as well as to the proposed criteria.

As naval vessels are designed and built to support high-end combat operations, survivability as well as ability to 'fight hurt' is a vital design objective. A new probabilistic approach on estimating the level of survivability of a surface combatant is presented in Boulougouris et al. (2016). The proposed approach is applied in a generic frigate and the results are compared to the current in force semi-empirical deterministic criteria. The assumed damage length is also discussed and proposed to be refined in a more rational way in order to account current weapon threats.

An alternative formulation of the critical wave height, derived in the GOALDS project, is presented by Cichowicz and Murphy (2016). The formulation includes the damage GZ curve properties (GM, GZ area and range), as well as the total residual buoyancy of the ship. The formulation from the HARDER project (and implicitly SOLAS 2009) is based on GZ_{max} and positive range of stability. A better agreement, compared to that of the HARDER formulation, between predictions of the GOALDS formulation and measurements from model tests is presented. Furthermore, the physical rationale behind the alternative formulation is outlined, as well as examples of how it could be utilized in the design of ships.

The starting point of Paterson et al. (2017) is that the wave height distribution behind the s-factor formulation of SOLAS 2009, derived from recorded accident sea states at the time of collision, cannot distinguish between either operational area or ship type, and that new formulations are needed to rectify this. A new s-factor formulation is thus proposed based on 129 accidents involving passenger ships only, between 2005 and 2016. New s-factor formulations based on wave height data of different key operational areas is presented. Finally, a large container ship is used to determine an attained index for all the presented s-factor formulations, and it is concluded that all new methods rendered a lower index than that of SOLAS 2009, in particular, the proposed formulation of the new accident database.

4. SHIP SAFETY IN OPERATION

Stability during ship's operational phase is influenced by various operational parameters such as environmental or loading conditions that could lead to various instabilities. Human reactions in emergency cases are very crucial and operational guidance is considered essential in all circumstances. In the framework of IMO's SGISC, the use of operational guidance/limitations will be a necessity for the vessel which does not pass the different three tiers of the criteria. Under these conditions, some authors have focused their work in this field. For example, Terada et al. (2017b) test a methodology based on the use of a GPS with motion measurement capabilities and considering Wave Buoy Analogy in order to predict ship motions and thus generating operational information. In investigating suitable signal processing methods for analysing non-stationary stochastic ship motions, as part of the development of guidance systems for heavy weather operation, Iseki (2015) reports the development and application of Discrete Wavelet Transform which can be considered as a very powerful tool, according to the results.

Responding to the need for norming the manoeuvrability in adverse conditions, Shigunov et al. (2016) address an assessment framework based on a simple mathematical model and allowing alternative methods for components of forces (see Figure 10). Two procedures with reduced level of complexity (comprehensive and simplified) were developed to determine the required installed power as a function of ship's deadweight, windage area, rudder area, propeller characteristics and engine type.

Operational guidance is also important to prevent accidents related to stability failures. In this respect, an investigation of a safety level regarding excessive acceleration is presented in Ogawa (2015) based on a very serious marine casualty of a 8,750 TEU container ship during ballast transit. Taguchi et al. (2015) reports the technical investigation of a Japanese pusher tug which capsize during travelling without the box barge and propose a manual to explain precautions for pusher tug boats in navigating solely, limitations on loaded fuel oil and wind and wave conditions as well as appropriate way of steering. Operational stability of car carriers is discussed in Huss (2016) as experienced by a shipping company and in relation to the corresponding rule development and compliance. The sensitivity of this type of ships to stability variations in waves is highlighted noting that the existing requirements in the Intact Stability Code and other IMO regulations and guidelines so far, give very limited operational guidance. Stability management activities are discussed including design measures, decision support systems on board, training and monitoring.

Modern passenger ships are equipped with loading computer as a statutory requirement. Following a flooding accident, the loading computer can produce information on the final equilibrium of the damaged ship for decision support. However, the timeline of the propagation of the flooding including the estimation of events, e.g. submergence time of non-watertight openings and time to capsize, is not assessed. More advanced decision support systems capable of assessing the timeline are available but not yet in wide use. In this respect, Pennanen et al. (2017) compare the outcome and performance of loading computer and advanced decision support system in accident. Possible crew response and statutory requirements to the decision support systems are also discussed. The Vessel TRIAGE method – intended for on-board use for assessing and communicating the safety status of the vessel in accidents – is described together with a demonstration of its use in a collision damage of a large passenger ship by Pennanen et al. (2016) (see Figure 18). The safety status is determined by the most severe of similarly labelled threat factors of which two, related to damage stability, are presented. In the demonstration case it is shown that the predictions were influenced by crew actions, e.g. closure of an open watertight door. Another method of assessing ship's survivability on-board of a damaged ship is presented in Ruponen et al. (2015). Floodwater level sensors are used to detect the hull breach and then calculations of progressive flooding in time-domain are performed. Critical factors, such as stability of the ship and the evacuation time are accounted for. The proposed method is tested with two realistic damage scenarios for a large passenger ship. As an effective means to reduce the risk of losing lives in case of a flooding accident, Karolius and Vassalos (2017) discuss methods on improving active measures to reduce flooding and prolong the time to capsize, such as closing of external/internal openings, counter-ballasting and recovery of buoyancy with deployable emergency floating devices.

Fishing vessels have been historically characterized by a very large number of stability-related accidents. Simplified stability guidance systems have been proposed by many authors as one of the feasible solutions for providing stability information to the masters under the main premises of simplicity of use and low cost. Scarponi (2017) presents application examples of the so-called Wolfson simplified stability guidance, taking as a basis minimum freeboard and maximum sea state and displaying the level of safety of the vessel in a color-coded poster (see top of Figure 11).

Examples of two sank vessels show that they were operating in dangerous conditions under the criteria of this method. Míguez González et al. (2016, 2017) describe a methodology to determine the natural roll frequency of the vessel and use it in a simplified computer stability guidance system. This method, based on sequential spectral analysis of the vessel roll motion, is applied to a stern trawler in regular and irregular head and beam waves, showing promising results (see bottom of Figure 11).

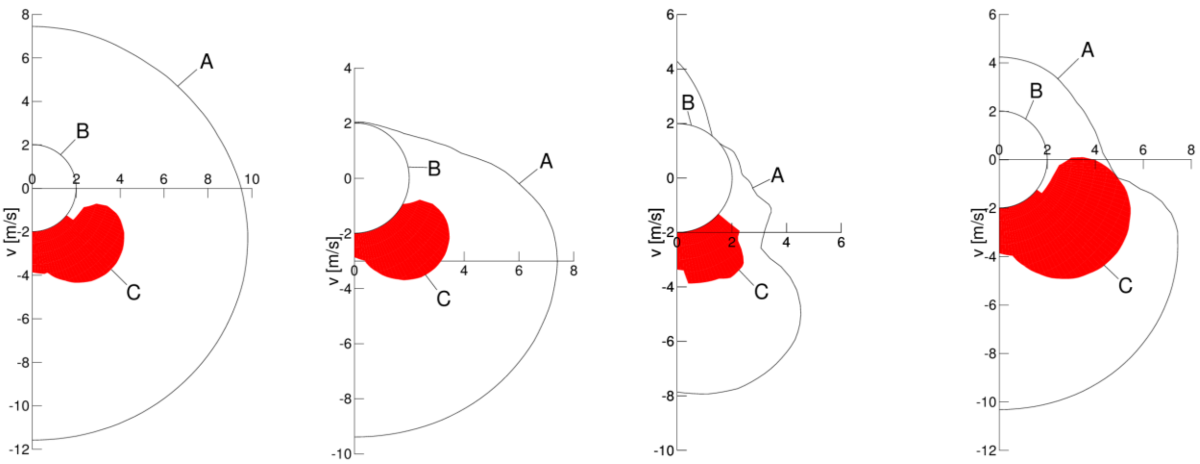


Figure 10: Examples of assessment results in polar coordinates ship speed (radial coordinate) – seaway direction (circumferential coordinate, head waves and wind come from top): along line A, required power is equal to available power, line B corresponds to advance speed 4.0 knots, and along line C, rudder angle is 25°. Adapted from Shigunov et al. (2016).

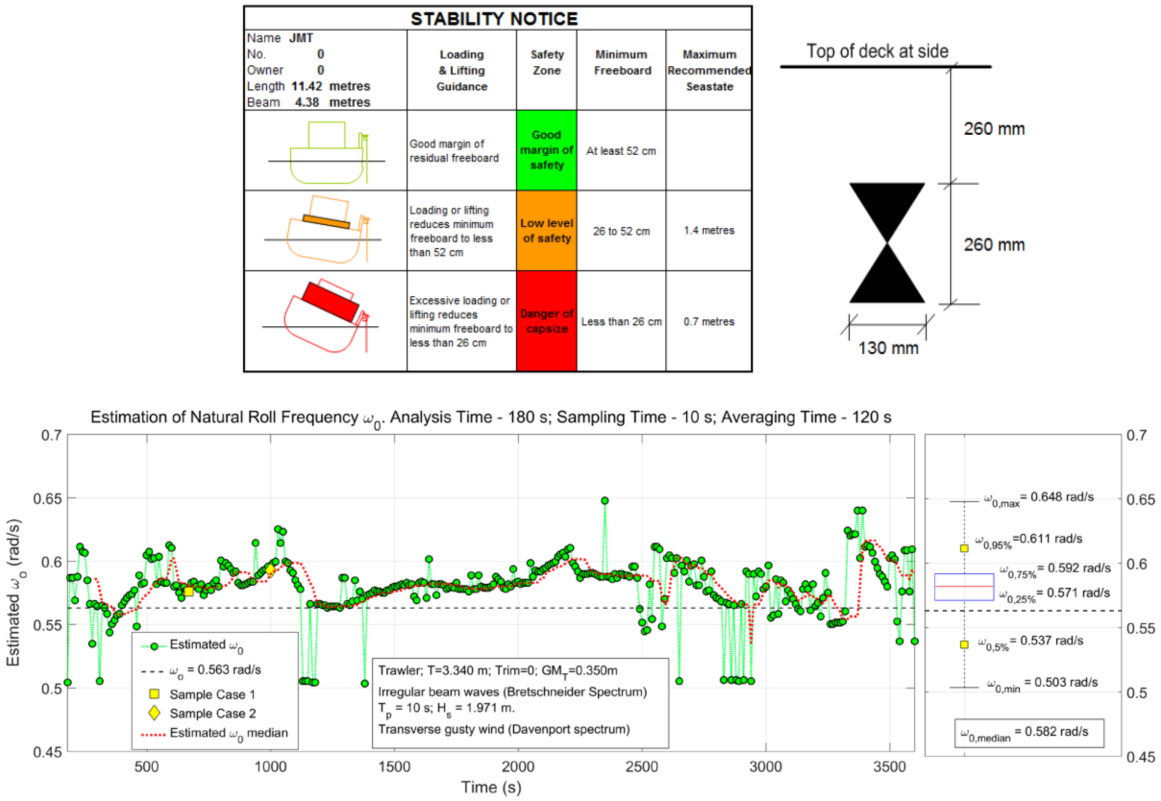


Figure 11: Top: Example of simplified Stability Notice and guidance mark for a small sized fishing vessel. Bottom: sample results from natural roll frequency estimations for a medium sized fishing vessel in irregular beam waves and gusty winds. Adapted from Scarponi (2017) (Top) (Fig. 4) and Miguez Gonzalez et al. (2017) (Bottom).

5. ROLL DAMPING, ADVANCED NUMERICAL METHODS AND SPECIAL STABILITY PROBLEMS

Development and improvement of models used in seakeeping codes concern roll damping (contributions due to bilge keels and wind, memory effect, stall effect for anti-roll fins and scale effect), nonlinear wave-induced forces and models of anti-roll tanks. Simulations based on direct numerical solution of flow equations are becoming a practical tool for the investigation of complex phenomena: besides definition of roll damping, they proved their applicability for the simulation of fluid motions in anti-roll tanks (ART), severe green-water events, parametric roll, behaviour of granulated cargo and fluidisation of particle cargo.

Modelling of roll damping

Wassermann at al. (2016) compare roll damping defined from free roll decay and harmonically excited roll, recommending the Froude energy conservation approach and Fourier transform, respectively, for their post-processing. Katayama and Umeda (2015) propose a ‘memory effect’ correction to Ikeda method for the bilge keel component of roll damping. The memory effect depends on the difference between the Keulegan-Carpenter (KC) number in the previous and current swings. RANS and experimental results are presented for forced irregular roll motions. Söder et al. (2015) propose an estimation method for aerodynamic roll damping and show that it is of the same order of magnitude as the hydrodynamic roll damping. Yıldız et al. (2016) numerically investigate the effect of vortex shedding and its interaction with free surface on bilge-keel roll damping. A decrease in roll damping is observed at large roll amplitudes due to proximity of bilge keels to the free surface. Söder and Rosén (2016) propose a framework for holistic multi-tier roll damping prediction. A scale effect correction is proposed for roll damping due to bilge keels, based on RANS simulations.

Wassermann et al. (2016) apply RANS to investigate forced roll motion of an ellipsoid equipped with normal plates at various flow speeds, roll frequencies and amplitudes and plate dimensions and propose an improvement of the empirical formula of Ikeda for roll damping due to bilge keels, valid in a wider range of KC numbers. Besides, a procedure is proposed to extrapolate the frictional component of roll damping from model to full scale. Rudaković and Bačkalov (2017) investigate the applicability of the Ikeda methods for roll damping prediction to typical European inland vessels and show that the simplified Ikeda method may considerably under-estimate the eddy-making component or even provide negative values for full hull forms even with block coefficient within its applicability limits.

Anti-roll devices

Cercos-Pita et al. (2016) combine a 6 DOF ship motion simulation code with an SPH numerical method for fluid motions in a tank to investigate nonlinear dynamics of the system in regular beam waves. The SPH solver is validated using experimental data. The results of simulations indicate nonlinear effects, e.g. decreasing efficiency of the tank with increasing wave steepness and bending of the response curves due to the hardening restoring of the vessel. Fernandes et al. (2016) simulate two-dimensional flow around a wing profile with harmonically oscillating angle of attack using RANS to study the behaviour of lift and drag with changing angle of attack and improve models of anti-roll fins in seakeeping codes. A big improvement potential is found in predicting stall of fin sections: whereas typical models are comparable to RANS results for upstroke motion, they vastly under-estimate the stall effect for down stroke.

For efficient nonlinear time-domain simulations of responses of an anti-roll tank (ART), Carette (2016) employs amplitude-dependent retardation functions, based on harmonic ART response data, and Hilbert transform for time-dependent interpolations. Using the effective gravity angle (EGA) as excitation parameter significantly improves the prediction when sway motion is significant.

Application of CFD in ship stability

Hashimoto et al. (2016) combine RANS solver with overset grids and free-surface level-set method to investigate the wave-induced surge force in following waves and validate the empirical formula used in the SGISC ~~pure loss~~surf-riding criterion. Zhou et al. (2015) study parametric roll with a potential-theory solver, where roll damping is defined with various methods (RANS simulations of roll decay and forced roll in calm water, roll decay model tests and Ikeda method), and direct RANS simulations of ship motions in waves and compare numerical results with experiments. Galbraith and Boulougouris (2015) study parametric roll in regular head waves using a RANS solver combined with an overset grid method.

Kawamura et al. (2016) develop an SPH flow solver to predict 6 DOF ship motions in waves including severe water shipping (green water) events and validate it against model tests for a fishing vessel, captive or fully unrestrained, in following and stern-quartering regular waves (see Figure 12). Agreement with tests worsens for sway force and roll moment (for captive model) and sway and roll motions (for free sailing model). Gu et al. (2015a) simulate roll decay at zero speed with a RANS solver to compare roll damping for various positions of the bilge keels along a two-dimensional section of an FPSO.

Gu et al. (2015b) simulate forced roll of a two-dimensional section and free roll decay of a three-dimensional container ship at zero speed using RANS, showing good agreement with experiments for the forced roll and less favourable for the free roll decay simulations. Begovic et al. (2015) simulate free roll decay at zero speed for DTMB 5415 naval ship in intact and two-compartment damage conditions. Comparison with experiments shows small error for the roll period and poorer agreement for roll damping in both intact and damage cases. Gu et al. (2016) compare two methods for tackling ship motions, sliding grid interface and overset grid, combined with a RANS solver to simulate roll decay of a pure car carrier and 2792 naval ship at zero speed. In comparison with model tests for the pure car carrier, the overset grid method better predicts roll period, whereas the sliding interface method better predicts roll damping. For the 2792 hull, both roll period and roll damping are better predicted with the overset grid method.

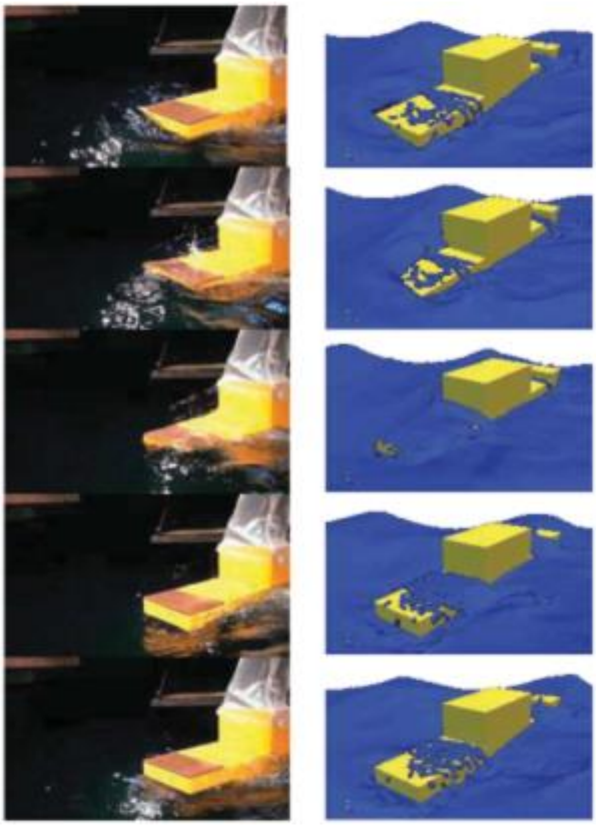


Figure 12: Water on deck from model tests (left) and numerical simulations (right) in 60 degree off stern waves. Adapted from Kawamura et al. (2015).

Advanced cargo behaviour modelling

Ju et al. (2016) apply a FEM-based numerical method to simulate fluidization of particle cargo. The method is validated vs. experiments for three-axial compression and cyclic direct simple shear (DSS). The influence of the frequency and amplitude of oscillations and the initial degree of saturation of cargo on the liquefaction onset is studied for a centrifuge test and a shaking table test. Spandonidis and Spyrou (2016) study coupled motion of dry granular cargo with ship roll in regular beam waves to identify critical parameters affecting response. The cargo is modelled as individual particles, interacting through nonlinear elastic and frictional forces. The resonance of roll motion with and without granular cargo is studied. For wave excitation below a certain limit, the presence of dry cargo reduces roll amplitudes, whereas for larger wave excitation, the vessel can show larger roll motions or even capsize due to cargo motions.

6. STABILITY OF SPECIFIC SHIP TYPES

Recognising the particular challenges faced by specific ship types, a number of authors have addressed on their distinct stability issues. The types addressed during the review period included fishing and naval vessels, high speed crafts, multipurpose ships, offshore support vessels (OSVs), as well as river-sea ships and sailing yachts.

Fishing vessels

Stability related issues, both static and dynamic, mainly leading to capsizing, are among the most common causes of accidents involving fishing vessels. In addition, flooding, especially of the main fish holds and engine room, is also usually pointed out as another major reason. However, in both cases, accidents occur in a sudden way, preventing the crew from taking any corrective action or even being able to escape from the vessel. These statements are proven for the case of the Spanish fishing fleet in Mata-Álvarez-Santullano (2015), through an extensive analysis of more than 300 accidents occurring between 2008 and 2014.

In Matsuda et al. (2017), another extensive analysis, in this case using towing tank experiments of 17 different vessels, shows that the Japanese fishing fleet is prone to experiencing dynamic stability failures. These include pure loss of stability, broaching and bow diving, thus also highlighting the importance of dynamic stability related accidents within the fishing fleet. The issue of flooding is tackled in Atzampos et al. (2017), where the authors propose the use of a high expansion foam system (Damage Stability Recovery System – DSRS, shown in Figure 13) to reduce the flooding volume in high risk compartments, and thus increase the vessel survivability in critical flooding scenarios. A test case using a coastal UK fishing vessel is presented, showing a large reduction of risk by protecting the high-risk compartments (which, among others, include engine room and fish storage areas) with this system.

Naval Vessels

Naval ship stability papers mainly focus on two topics linked to the improvement of naval and merchant ship stability rules. The improvements of the Naval Ship Code, based partially on similar to IMO’s Goal-Based Standards, underline the need for these two directions of work. The first is to find the justification of current rules in order to know if they are to be changed or not. The second is related to the associated tolerable risk and the probability of capsizing, similar to level 3 of IMO’s SGISC.

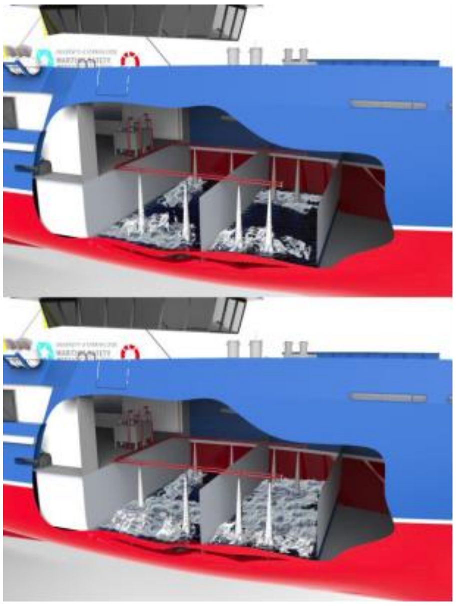


Figure 13: DSRS Graphical Representation. Adapted from Atzampos et al. (2017).

Hayes et al. (2015) study the wind speed parameters used in merchant and naval intact stability analysis. In particular the nominal wind speed and gust factor used is investigated. It is noted that there are no clear and obvious justification for some of the values used. The authors explain the two philosophies that lead to very different nominal wind speed and they propose the introduction of a standardised set of wind speeds for stability analyses, which would make both naval and merchant rules more transparent. Luquet et al. (2017) show that numerical aerodynamic calculations (CFD) could be used in a near future to check or adjust the rules (see Figure 14). Creismeas et al. (2017) compare the naval and commercial approaches on the impact of ice accretion on the stability of ships, a topic of great significance given the increasing importance of polar navigation and patrolling in polar areas.

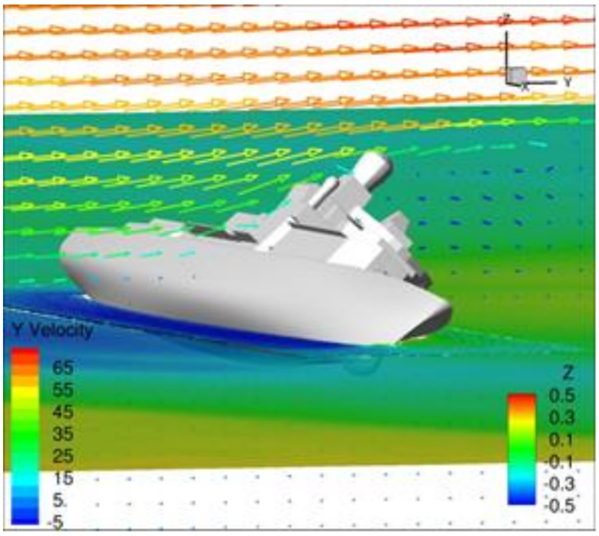


Figure 14: Wave elevation (m, on the RHS) and transverse speed (m/s, on the LHS) around a frigate at +45° heel angle. Adapted from Luquet et al. (2015).

Regarding the estimation of the operational capsizing risk, a number of researchers have utilised numerical dynamic stability tools to investigate the performance of naval vessels. Verboom and van Walree (2015) compare the accuracy of two time-domain, panel method, 6 d.o.f. codes to simulate the large amplitude motions of a frigate operating in stern quartering seas. The first method is partially body exact while the second method utilised is fully body exact. The comparison with model tests proves the significant improvement achieved by using the second method. On the other hand, Le Pivert et al. (2015) select a simpler solution and use one degree of freedom to derive analytically the probability density function of roll angle, roll speed and roll excitation moment and estimate the probability of capsize introducing a suitable criterion. A more sophisticated seakeeping code, namely FREDYN is used in Perrault (2015, 2016) to estimate the probability of exceeding a critical roll angle. A study is performed to find the most accurate correlation parameters to this probability. A list of regressors are suggested where GZ parameters showed always strong correlations over the set of ships tested (8 frigate-type ships). Attempts to check some naval ships against SGISC is performed in Kahramanoğlu et al. (2015), Grinnaert et al. (2016) and Petacco et al. (2017). Some inconsistencies are pointed between L1 and L2 criteria. It is also pointed that the request of a maximum value of KG requested by the four other failure modes and the minimum value for excessive acceleration, contradict in some cases.

High-speed craft

Depending on the prevailing conditions in the market, high-speed craft (other than surface combatants) may not get sufficient attention at the STAB and ISSW events. During the review period considered in this paper only a handful of papers on high-speed craft has been presented. Most of these papers do not tackle traditional roll motion related stability phenomena, but instead large amplitude heave and pitch motions, excessive vertical accelerations, and related operational limitations, operational guidance and safety issues.~~Nevertheless, high-speed craft in planning mode are subject to numerous hazardous, and from a modelling point of view challenging, dynamic stability phenomena.~~

Katayama and Amano (2015) present model experiments with three different high-speed craft hulls in regular and irregular head seas. Various aspects of the experimental setup, such as sampling frequency, are discussed. The longitudinal distribution of the vertical accelerations and the vertical acceleration stochastic process in irregular seas are characterized. Rosén et al. (2017) consider vertical accelerations for high-speed craft in irregular head waves, both through model experiments (see Figure 15) and time-domain simulations with a non-linear strip method. The results are discussed in relation to the prevailing safety philosophy and semi-empirical design methods in the IMO HSC Code and classification rules. A number of questions are raised regarding the validity of these methods and the possibility of introducing direct methods is discussed. Also van Walree and Thomas (2017) present simulations and model experiments with a high-speed boat which is free-running in different relative angles towards the waves. Various operating limits, such as excessive accelerations, water ingress and surf riding, are investigated. The simulations are performed with a non-linear panel method, where very good correlation to measured motions is presented, and also the accelerations correlate fairly well. Terada et al. (2017a) present a method which could be used on-board high-speed craft for automatic avoidance of dangerous situations related to the craft vertical impact accelerations. It is based on recursive fitting of a time series model to real time measurement of the vertical accelerations on-board. The method is validated, and the influence of various modelling parameters is investigated based on pre-recorded acceleration time series. Also, de Alwis and Garme (2017) consider the situation on-board high-speed craft. A field study is presented where both subjective data in terms of the crews' experience of the operational environment and various pain and fatigue symptoms, and objective data in terms of vertical accelerations measured on-board, are collected. Clear correlation between subjective and objective data is found and the methods used for the data collection are concluded feasible for further studies.

Figure 15: UNINA model experimental set up (photo at model speed V = 5.75m/s). Adapted from Rosén et al. (2017).

Other ship types

Lübcke (2015) presents the investigation results for the accident of the multipurpose ship MV ROSEBURG, which occurred in the Bay of Kiel, in 2013. As a consequence of improper loading and subsequent incorrect on-board stability management, the ship with the timber cargo on deck heeled due to wind gusts. This initial heel caused the sliding of cargo and failure of cargo securing equipment, which in turn, increased the heel. As a result, the ship lost some 75% of the cargo, but managed to avoid capsize. Chopra (2015) analyses the existing stability criteria of several offshore support vessels through their limiting KG for several conditions and/or operational modes. Oliveira et al. (2015) propose an alternative method to carry out inclining tests for offshore vessels in their operational location, considering the environmental conditions and the effects of mooring and risers. The method has been validated through model tests experiments and full-scale tests using a semisubmersible unit (see Figure 16). Wang et al. (2015) analyse the response of taut mooring lines subjected to single and bi-frequency parametric excitation. It is observed that, depending on the damping level and the amplitude of the harmonic excitation components, the safe regions of the stability chart may greatly change compared to those of single parametric excitation.

Figure 16: SS Model in LabOceano Basin. Adapted from Oliveira et al. (2015).

Mazarakos et al. (2015) investigate the dynamics of a TLP platform supporting three oscillating water column (OWC) devices and a wind energy turbine using frequency and time domain numerical models. Umeda et al. (2016a) address the occurrence of "false negatives" in the application of Level 2 of pure loss SGISC to offshore supply vessels (OSV), through model tests and numerical simulations (Figure 17).

Figure 17: Free-running model experiment of the OSV in astern quartering waves. Adapted from Umeda et al. (2016a).

The river-sea ships are inland vessels suitable for restricted navigation at sea. Chatelier et al. (2017) present research on the development of appropriate classification rules for river-sea ships that would consider stability in waves and seakeeping of inland vessels. Angelou and Spyrou (2015) present a mathematical model intended for sailing yachts behaviour prediction. The model aims to estimate the variation of forces and moments acting on sails, caused by the wind-induced sails deformation and recognize the influence of these variations on the course-keeping instabilities in downwind sailing.

7. MODELLING OF ENVIRONMENT

To evaluate the stability appropriate, the modelling of environment such as ocean waves, winds and so on is important. Gankevich and Degtyarev (2015) present a theoretical method to estimate velocity and wave pressures of potential flow under given information of a wavy surface elevation. This work proposes a new method for the efficient calculation of the velocity and the wave pressures of potential flow in actual sea, which cannot be handled by numerical calculation of elliptic equation. It is demonstrated that the velocity and the wave pressures of potential flow in the actual sea state can be reproduced by the wavy surface elevation generated by an autoregressive model. This method can use the real time evaluation with respect to waves around a ship. Reed et al. (2016) present a new modelling procedure with respect to incident irregular waves for use in a time-domain numerical ship-motion simulation code, using an autoregressive modelling procedure, which is a type of the statistical modelling procedure. The procedure has several significant advantages compared with the classical Fourier series modelling, such as the Longuet-Higgins model, where the most important presented to be the computational time. Regarding to an evaluation method of the wind force, Ariffin et al. (2016) examine several assumptions of the weather criterion code based on a new wind tunnel experiment method considering the effect of roll motion. Two models are used; a merchant ship with simple geometry and a naval ship. They have pointed out that experimental values of roll angle are lower than those predicted by the criterion.

On the other hand, from the viewpoint of the operational aspects, the monitoring of the ocean waves is also important. Susaki et al. (2017) propose to estimate the crests of incident waves in real time using radar. Specifically, the wave period can be estimated with an error of 7.0% and error of 6.6% compared with the wave buoy data by the radar mounted on the actual ship. It is also mentioned that it is possible to predict the wave profile of the incident wave to encounter, but verified results exist for wave heights below 3 m.

8. EDUCATION

In the previous reviews of papers presented at STAB conferences and ISSW events (Bačkalov et al., 2015 and Bačkalov et al., 2016), a growing concern was expressed that the contemporary research on ship stability and engineering education on this subject do not advance at the same pace. Therefore, the research and the educational process become increasingly disconnected and the implementation of research results in university courses on ship stability turns into a challenging task. The papers highlighted the potential deficiencies of “classic” ship stability education, which could result in lack of knowledge necessary for proper understanding of complex stability problems that are nowadays gradually becoming an integral part of engineering practice. The papers also indicated some possibilities for facilitating these difficulties in teaching process. Yet the question how to attain the required level of ship stability knowledge through university education remained open, which in turn instigated the initiative to include this topic in the present review paper as well.

The present review focuses on the role of STAB and ISSW events in improvement of education of young professionals. The main objective of this section is to highlight those papers, among those presented in STAB2015, ISSW 2016 and ISSW2017, which could be helpful in bridging the gap between the research and the education on ship stability. This includes papers that could assist in understanding of the future (or even present) stability rules on a conceptual level; papers that could help in implementation of advanced computational methods; and papers that put the well-established methods and approaches to test and re-examine the boundaries of their application.

An overview of the process of development and the current status of the SGISC is presented in Umeda and Francescutto (2016), offering an insight into the underlying assumptions and reasoning behind the formulation of standards to be used in novel regulatory requirements and providing information necessary for proper understanding and, consequently, successful implementation of rules. The paper of Peters and Belenky (2016) has a similar significance for the educational process. Focusing on pure loss of stability failure mode, the authors discuss the consistency of vulnerability levels of SGISC and consider the options for resolving such issues. Moreover, the paper offers a broader view of requirements that intact stability criteria should comply with in order to be successfully applied.

The implications of use of different mathematical models of the same phenomenon in analysis of ship stability in waves are the subject of Peters et al. (2015). Shigunov (2016) addresses the problem of rarity of stability failures and deliberates upon accuracy and suitability of two possible approaches that could be used in probabilistic direct stability assessment of ship stability. Both papers treat novel methods, typically above the scope of classis ship stability courses, and offer lessons on importance of proper mathematical modelling of stability phenomena and thorough understanding of underlying assumptions and boundaries of models’ application, which students often fail to consider.

While presenting a procedure implemented in software intended for decision support in flooding events, Pennanen et al. (2016) reintroduce the concept of floodable lengths curve to safety of passenger ships (see Figure 18). Although this could unintentionally create some confusion in the classroom over the role of floodable lengths in the present subdivision and damage stability regulations, the paper is interesting from the educational point of view, as it invokes benefits of using this somewhat neglected tool which is still taught in ship stability courses. On the other hand, Smith and Silva (2017) propose a method for assessment of applicability of linear strip-theory seakeeping approach in high sea states. In both cases, the papers deal with the revaluation of well-known methods that are standard parts of the naval architecture curricula.

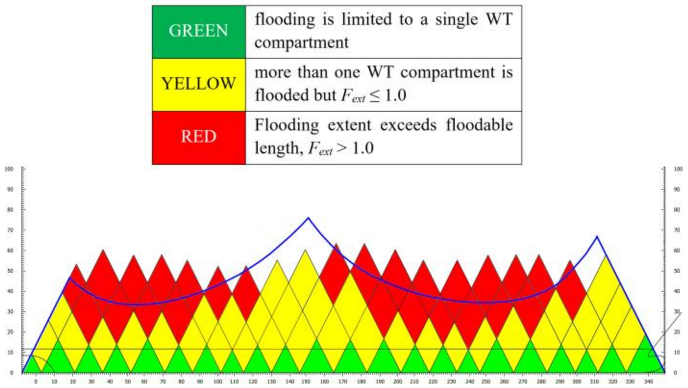


Figure 18. Color coding for flooding extent based on the floodable length curve as a part of the Vessel TRIAGE decision support system methodology. Adapted from Pennanen et al. (2016).

In the previous review papers (Bačkalov et al., 2015 and Bačkalov et al., 2016), the lack of literature suitable for university education in ship stability was stressed as one of the main challenges. Some books, however, authored by the prominent researchers and members of the STAB community, were indicated as valuable references in the teaching process. The new installment in the Contemporary ideas on ship stability series (see Belenky et al., 2019) providing a comprehensive yet careful selection of research in the field should be added to this list. Also, the present review paper is aimed at providing an accessible overview of current research for students and young professionals entering the field of ship stability, dynamics and safety.

It is interesting to notice that most of the authors of the papers herein recognized as valuable from the educational point of view are neither (active) teachers nor they are (presently) affiliated with academic institutions. This emphasizes the substantial educational potential of the STAB conference and ISSW events. Therefore, as a final point, the authors of papers that are going to be presented in the future STAB and ISSW events are invited to consider the importance of their work for education of prospect generations of engineers and, where applicable, to strive to present their results in a pedagogical manner. The teachers, on the other hand, are invited to embrace the abundance of knowledge on the subject, contained in the proceedings of ship stability conferences and workshops and to join and take active part in the work of international ship stability community gathered around STAB and ISSW.

9. CONCLUSIONS

STAB and ISSW are the most comprehensive scientific events addressing the issues of ship stability, dynamics and safety. Although valuable research on these topics is published also outside of STAB community, the present review aims to provide a helpful insight into contemporary ship stability developments. The paper summarises research published in STAB and ISSW proceedings since 2015 following the previous review work of Stability R&D Committee, Bačkalov et al. (2016).

The research was significantly stimulated by the current regulatory developments. A considerable number of papers concerned simplified assessment methodologies (level 1 and 2) of

SGISC, e.g. consistency between these levels. However, only few papers concerned comparison of level 2 with model tests or numerical simulations, and very few papers dealt with Direct Stability Assessment (DSA). Very limited number of investigations~~No papers~~ concerned consistency between level 2 and DSA (since DSA guidelines were finished only in 2019), thus this should become an important research area in the future.

On the other hand, work on SGISC has stimulated developments in related fields beyond the regulatory framework. In particular, a great number of papers concerned in-depth analysis of the five dynamic stability failure modes, which generates knowledge for future regulatory developments. A significant amount of work on probabilistic approaches for extreme events and capsizing, problem of rarity and statistical extrapolation methods will not only contribute to the implementation of DSA and Operational Measures within the SGISC but also provide a scientific basis for future developments. Finally, this work has stimulated attempts to improve or develop new simple methods for the prediction of roll damping: although this task was not completed, it will remain an important topic for future applied research. Parallel to DSA development in SGISC, direct stability assessment attracts increasing attention for naval vessels.

Ship safety in operation is being addressed in an increasing number of papers. On the one hand, this is related to regulatory developments, to address operational limitations and operational guidance within the SGISC, but also extends well beyond that, concerning, in particular, real-time simulations to address intact stability and decision-support for damaged ships in a flooding accident, based on progressive flooding simulations in the time domain. Improved data collection capabilities, better onboard observations and improving weather forecast are making the real-time operational guidance increasingly feasible. Operational measures to improve safety are becoming a key research topic for the future.

During the covered period, damage stability has attracted less attention, and concerned in-depth refinement of the advanced aspects of damage stability, such as simulation of transient flooding, dynamics of water on a vehicle deck and s-factor formulation for RoRo vessels, refinement of s-factor accounting for ship type-specific accident data, and resistance and propulsion characteristics of damage ships for safe return to port requirements. There has also been research towards development of a new, probabilistic, approaches for naval vessels. Most of the research on damage stability has concentrated on passenger ships, especially large cruise ships and Ropax vessels. This trend is expected to continue, but hopefully focus will be also on safety of damaged cargo vessels.

CFD increasingly becomes a practical tool in ship dynamics and stability: apart from becoming a feasible practical alternative to model tests for the definition of roll damping, both for intact and damaged ships, recognised in SGISC, it has become a practical tool for in-depth study of complex flow phenomena: progressive flooding, anti-roll tanks and fins, green water behaviour, parametric roll and broaching-to, as well as complex cargo behaviour, instead of or additionally to model tests.

Concerning particular ship types, a substantial number of papers dealt with naval vessels, mainly with the objective to eventually determine tolerable risk for the Naval Ship Code. Few papers concerned fishing vessels and high-speed craft (in the context of vulnerability to dynamic stability failures), perhaps due to lower budgets for these types in combination with the complexity of the problem. In the case of fishing vessels, another main reason for this, is the lack of an international mandatory regulatory framework and the fact that SGISC, which drove many of the research efforts during these years, are not intended to be applied to these vessels.

The STAB and ISSW events can play a significant role in the education of young professionals: at least six papers were found to be helpful in bridging the gap between the research and the educational process. However, there is a general concern that some important topics still need to be addressed from the teaching and learning perspectives, in particular, probabilistic approach to damage stability, which is found to be difficult to be implemented in practical teaching. It would be appropriate to expect that a solution to this issue would be proposed by the STAB community.

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