ITTC2024
30TH INTERNATIONAL TOWING TANK CONFERENCE
22–27 SEPTEMBER 2024 | HOBART TASMANIA AUSTRALIA

Report of the Stability in Waves Committee

STABILITY IN WAVES COMMITTEE

1. INTRODUCTION

Membership and Meetings

The members of the Stability in Waves Committee of the 30th ITTC are:

- Dr. V. Belenky, (Chairman)
  Carderock Division, Naval Surface Warfare Centre (NSWCCD), USA
- Mr. J.-F. Leguen, (Secretary)
  DGA Hydrodynamics, France
- Dr. T. Kim
  Samsung Heavy Industries, South Korea
- Mr. A. Matsuda
  Japan Fisheries Research and Education Agency, Japan
- Dr. S. Bu
  China Ship Scientific Research Center (CSSRC), China
- Dr. Y. Liu
  Marine Design & Research Institute of China (MARIC), China
- Prof. E. Boulougouris
  University of Strathclyde, United Kingdom.
- Dr. C. Rodríguez
  Laboratory of Ocean Technology, Brazil.

Stability in Waves committee face to face meetings have been held during the work period:

- The first kindly hosted by Prof. P. Krata at University of Gdansk, Poland, the 15th September 2022, just after ISSW 2022.
- The second at Strathclyde University, Glasgow, UK, from the 30th May to the 1st June 2023.
- An opportunity meeting during the 19th International Ship Stability Workshop held in Istanbul in September 2023.
- The last face-to-face meeting at Carderock Division, Naval Surface Warfare Centre (NSWCCD), USA from 26th to 28th February.

A series of video meeting (more than 10) was also organized, regularly approximately every two months.

1.2 Tasks

The recommendations for the work of the Stability in Waves Committee as given by the 29th ITTC were as follows:

1. Update the state-of-the-art for predicting the behavior of bottom founded or stationary floating structures, including moored and dynamically positioned ships, emphasizing developments since the 2021 ITTC Conference. The committee report should include sections on:
   A) the potential impact of new technological developments on the ITTC
   B) new experimental techniques
   C) new benchmark data

   D) the practical applications of computational methods to prediction
   E) the need for R&D for improving methods of model experiments, numerical modelling.

2. Review ITTC Recommended Procedures relevant to stability, including CFD procedures, and
   A) identify any requirements for changes in the light of current practice, and, if approved by the Advisory Council, update them,
   B) identify the need for new procedures and outline the purpose and contents of these.
3. Update ITTC Procedure 7.5-02-01-08, Single Significant Amplitude and Confidence Intervals for Stochastic Processes when new information becomes available.
4. Develop new ITTC recommended procedures in support of direct stability assessment within 2nd generation IMO intact stability criteria:
   A) Avoiding self-repeating effect in time-domain numerical simulation of ship motions,
   B) Procedure of Estimation of Frequency of Random Events by Direct Counting,
   C) Statistical Validation of Extrapolation Methods for Time Domain Numerical Simulation of Ship Motions.
5. Develop a new procedure, Computational procedure for instantaneous GZ curve during time-domain numerical simulation in irregular waves.
6. Investigate the current state of the art on flooding dynamics of damaged ship in waves, including EFD and CFD.
7. Continue the identification of benchmark data for validation of stability-in-waves predictions.

For the 30th ITTC, the modelling and simulation of waves, wind and current is the primary responsibility of the Ocean Engineering Committee with the cooperation of the Seakeeping and the Stability in Waves Committees.

2. STATE OF THE ART (TOR 1)

2.1 Potential impact of new technological developments on the ITTC (TOR 1 A)

Leveraging the combined strengths of neural networks and a spectrum of machine learning techniques, ship motion prediction has entered a new era of precision and adaptability. These sophisticated AI methodologies—encompassing artificial neural networks, support vector machines, and decision tree, etc.—excel in dissecting and learning from the vast and complex datasets related to maritime environments and vessel behaviors. They not only provide nuanced insights into ship movements across varying sea states but also enhance safety protocols and operational efficiencies through their ability to dynamically adapt and refine predictions based on continuous data ingestion. In the modern seafaring landscape, the integration of AI surpasses traditional prediction models, providing a robust and precise toolkit for navigating the complex challenges of maritime operations.

Pickering et al. (2022) addressed a computational framework by combining output-weighted training schemes in Bayesian experimental design (BED) with an ensemble of deep neural operators (DNOs) (Figure 1). This model-agnostic framework pairs a BED scheme that actively selects data for quantifying extreme events with an ensemble of deep neural operators that approximate infinite-dimensional nonlinear operators. It is concluded that it is scalable artificial intelligence (AI)-assisted experimental infrastructure that can efficiently discover and forecast extreme events.

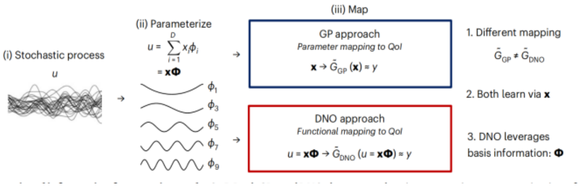

Figure 1: DNOs leverage functional information for mapping to the quantity of interest (QoI) (Pickering et al. 2022)

Zhou et al. (2023) propose a "grey box" algorithm consisting of a deep learning network and parametric roll equation to provide the parametric roll simulations, which can accurately recognize the time histories induced large-amplitude parametric roll of the C11 container ship.

Li et al. (2023a) used the Power-activation Feed-forward Neural Network (PFN) to achieve real-time prediction of the ship's parametric roll motion. The theoretical rationality of real-time prediction based on the ship's rolling motion time series data is verified. Results show that the simplified PFN model has advantages in real-time prediction of parametric roll motion due to its time-varying weight adjustment methods, with the safer mapping mode, higher accuracy, and shorter computing time.

González et al. (2023a) investigated the deployment of a ANN model for real-time forecasting parametric roll in ships, with an emphasis on its use for stability guidance on small to medium-sized fishing boats.

Louvros et al. (2023) introduced a methodology that integrates Machine Learning (ML) and Case-Based Reasoning (CBR), using pre-built databases for real-time analysis of damage scenarios. The approach can be easily applied, relying on straightforward inputs like crew observations and effectively managing prediction uncertainties, particularly in survival predictions. The authors argue that the outputs are consistent, and informative, encouraging further exploration of Machine Learning for dynamic damage stability assessments. Its accuracy depends on the range of pre-calculated scenarios, offering a robust alternative to conventional approximations. The methodology was demonstrated in the H2020 SafePASS project as part of a decision-support methodology during flooding incidents.

Mauro et al. (2023a) developed a surrogate model to enhance real-time onboard risk assessment for ship collisions, utilizing SHARP software's Super-Element methods for efficient scenario generation. This model, validated with over 4,400 damage scenarios, identified forest tree models as the most accurate approach, though simpler multiple linear regression models are also effective at the initial stage. Enhancing the model's accuracy involves increasing the variety of simulated collisions rather than just the number of experiments. Initially, multiple linear regression is advisable due to its simplicity and the uncertainty in direct damage calculations. As more data becomes available, a shift to forest tree models is recommended, with neural networks needing more extensive data to be effective. The developed methodology is an integral part of the real-time flooding risk evaluations proposed by Vassalos et al. (2023).

2.2 New experimental techniques (TOR 1 B)

Model testing is an effective means for investigating the GZ curve in the wave. CSSRC (Gu et al., 2014) constructed a partially restrained model test equipment for the GZ curve in waves, see Figure **2**.

The setup, shown in Figure **2** consists of five main components:

1. A pedestal with four locking jaws to secure the equipment to the towing carriage.
2. A guide rail bracket, a linear guide rail pair, a displacement sensor using a guide wire, heaving rod and a block.
3. Three diverging combination sensors that use rods to measure the surge force, sway force, and yaw moment. The measurement is done by a strain gauge.
4. A mechanism for measuring pitch, roll motions with potentiometers; roll moment is measured with a double flange torque sensor. The mechanism locks a model with a given roll angle.
5. A system for balancing the weight of the second and third components, which includes a pulley block, a vertical guide road and a counterweight.

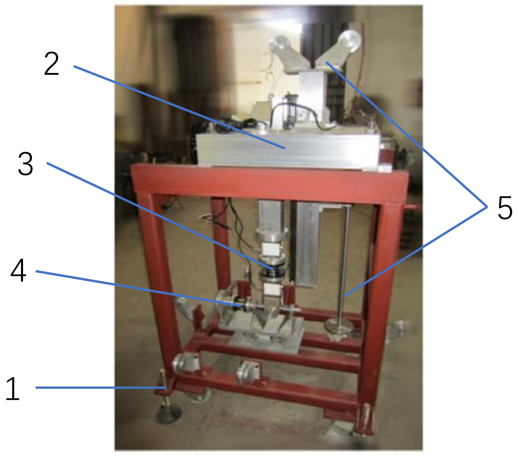

Figure 2: Equipment for GZ curve in waves (Lu et al., 2017)

Surge, sway and yaw motions are restrained, heave and pitch motions are free. Roll motion can be free or restrained depending on the test setup. Roll, pitch, and heave can be measured simultaneously. When roll is fixed at a given angle, the roll moment and the sway force are measured simultaneously, and the restoring moment can be recovered.

Examples of an experimental setup are shown in Figure 3 and Figure 4, from the model test at CSSRC's seakeeping basin with models of C11-class container carrier and ONRTH configurations respectively.

Figure 3: Ship model of C11 Containership in partially restrained experiment (Bu et al. 2019)

Figure 4: Ship model of ONR tumblehome hull in partially restrained experiment (Bu et al. 2021)

2.3 New benchmark Data (TOR 1 C)

The new benchmark on damaged ship stability is described below, see also in Section 8.

Ruponen et al. (2021, 2022, 2022a) present an international benchmark study on simulation of flooding and motions of damaged vessels that was conducted within the EU Horizon 2020 project FLARE, using new dedicated model tests as a reference. The benchmark was divided into three separate parts, each concentrating on specific phenomena:

- Part A: flooding fundamentals, with captive models and simplified geometries
- Part B: transient and progressive flooding of a cruise ship
- Part C: transient and gradual flooding of a ROPAX ship

In total, 11 organizations provided results to some parts of the benchmark:

- Brookes Bell (BROO)
- DNV
- HSVA
- MARIN
- University of Strathclyde, Maritime Safe-ty Research Center (MSRC)
- NAPA
- China Ship Scientific Research Center (CSSRC), China
- Korea Research Institute of Ships & Ocean Engineering (KRISO), Republic of Korea
- University of Applied Science Kiel (UAK), Germany
- University of Naples “Federico II” (UNINA), Italy
- University of Trieste (UNITS), Italy

Part A of the benchmark study (flooding fundamentals) studied three different flooding scenarios. Figure 5 depicts up-flooding in a box model with two compartments and down-flooding in the same box model with different openings. The time history of water levels in sensors

23 and 27 were measured. The third case considers extensive progressive flooding along a typical deck layout of a cruise ship, including a long central service corridor (see Figure 6) and the water levels were recorded at various locations on the deck, see Figure 7.

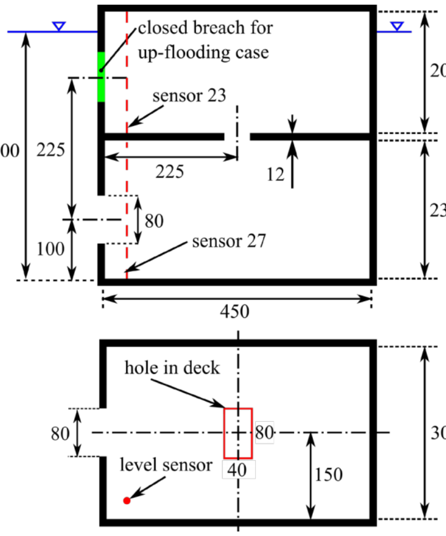

Figure 5: Box model arrangement and dimensions for the up-flooding case (Ruponen et al. 2021)

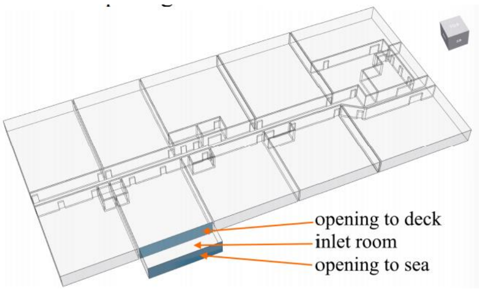

Figure 6: Arrangement for deck flooding case (Ruponen et al. 2021)

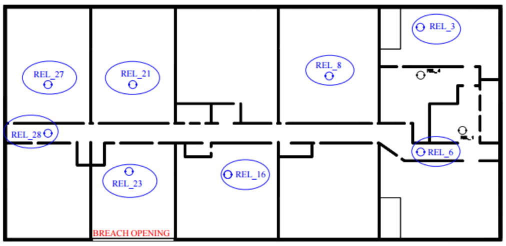

Figure 7: Locations of selected water level sensors (Ruponen et al. 2021)

Part B investigated an unbuilt large cruise ship design (about 95,900 GT) provided by Chantiers de l'Atlantique. Table 1 lists the main dimensions. As seen in Figure 8, the hull of the model extends vertically over 8 decks with floodable compartments positioned on 6 lower decks. The hatched rooms were filled with foam and thus not floodable, and the red squares mark the selected water level sensors, red "×" symbols denote holes in the deck and thick red lines mark the large breach.

In total, the model contains 60 floodable rooms bounded by bulkheads and decks. The rooms are connected by 82 internal openings in the bulkheads and 11 openings in the decks.

Model tests were performed at MARIN using a 1:60 scale model, see Figure 9. The flooding progression and ship motions were measured in three separate test cases: Transient flooding in calm water; Transient and progressive flooding in irregular beam seas; Up-flooding in calm water with smaller breach size.

Table 1: Main dimensions of the studied cruise ship and the applied initial intact condition in model tests. (Ruponen et. al., 2022)

	Full scale	Model scale
Length over all	About 300 m	About 5.0 m
Length between perpendiculars	270.00 m	4.5 m
Breadth	35.20 m	0.587 m
Draught (in tests)	8.20 m	0.137 m
Trim (in tests)	0.00 m	0.000 m
Height of bulkhead deck form base line	11.00 m	0.183 m
Gross tonnage	95 900	-
Metacentric height (in tests)	2.36 m	0.0393 m
Radius of inertia for roll	13.904 m	0.2317 m

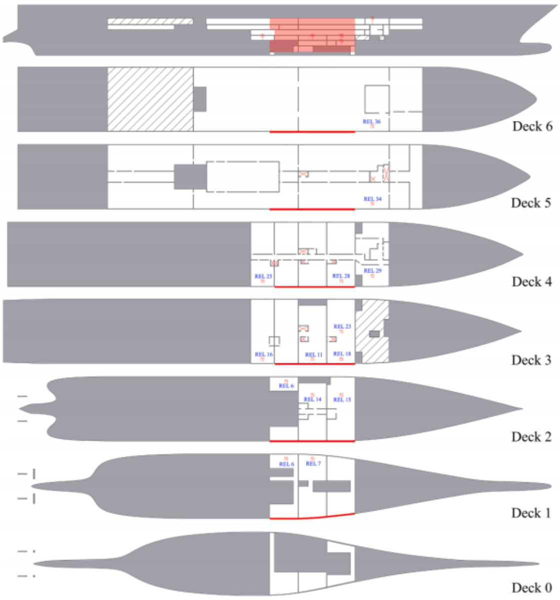

Figure 8: Arrangement of the ship model

Figure 9: Model of the cruise ship, courtesy of MARIN (Ruponen et. al., 2022)

Before the test, a magnetic cover sheet sealed the breach, see Figure 10. The coversheet was pulled upwards with a winch at zero time. In the model scale, the speed was about 2.5 m/s. As a result, the breach opened quickly- in less than 4 seconds at full scale. A nominal capsize limit of 40° was used in the tests. With a roll angle of positive to the breach side (starboard) and a pitch (trim) angle of positive towards the bow, all results are presented in full scale.

In the model tests, the model`s six degrees of freedom motion and the water levels in various locations within the flooded compartments were measured. As seen in Figure 11, the floodable compartments were vented using large air pipes on the leeward (intact) side. In this respect, the effects of air compression were considered small, and consequently full ventilation was assumed by most participants. Air pressures inside the model were not measured, so this assumption cannot be confirmed.

Figure 10: Breach opening and the magnetic cover (photo courtesy of MARIN)

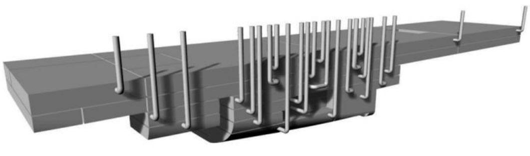

Figure 11: Rendering of the 3D model of the compartment and ventilation pipes (courtesy of MARIN)

Part C investigated an unbuilt ROPAX design that Meyer Turku provided, weighing roughly 28,500 GT. At HSVA, tests were conducted using a 1:28 scale model. Table 2 lists the ship's main parameters in both full and model scales.

Figure 12 and Figure 13 illustrate how the floodable compartments are arranged. The compartments are not internally connected to each other. The impact of a two-compartment collision is examined. There is a casing on the port side of the centerline on the vehicle deck, having an impact on the accumulation of water on the deck in waves. All damaged compartments were ventilated through ventilation pipes in the compartment corners.

Three test cases were investigated separately: Transient flooding in calm water with two different initial metacentric height (GM) values and a third one with slower opening time for the breach; Transient flooding in waves with two small variations in the initial steady heel angle; Gradual flooding of the vehicle deck in waves in two different sea states.

Table 2: Main dimensions of the studied ropax vessel

	Full scale	Model scale
Length over all	About 162 m	About 5.8 m
Length between perpendiculars	146.72 m	5.24 m
Breadth	28.0 m	1.00 m
Draught	6.1 m	0.218 m
Height of ro-ro deck from baseline	9.2 m	0.329 m
Height of tank top from baseline	1.5 m	0.054 m
Gross tonnage	28 500	-

All the tests were conducted for a freely drifting model. For the tests in waves, bow and stern lines were occasionally used to correct the model orientation back to beam seas condition. For practical reasons, the roll angle of 36° was used as the nominal limit for capsizing, and the test was interrupted when the roll angle exceeded this limit.

The model was equipped with instruments to measure the 6 Degrees-of-Freedom motions, the relative wave elevations at several positions on and below the main vehicle deck. Four video cameras were used to record the tests, two outside cameras focusing on the ship motions, one recording the water elevation in the compartment R1 below the main vehicle deck, and one showing water ingress to the vehicle deck (room R3).

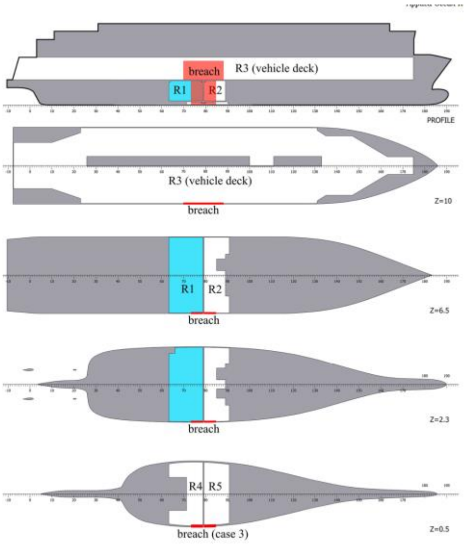

Figure 12: Breach and floodable compartments of the ropax model

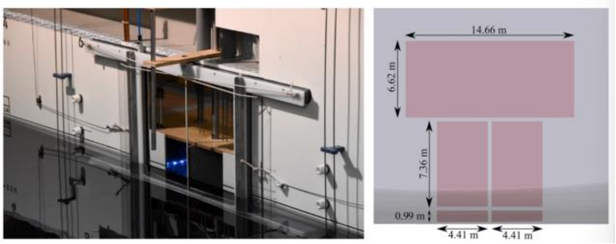

Figure 13: Breach opening mechanism for the transient flooding tests and full-scale dimensions of the breach

For transient flooding cases, the volume of water and its centroid in the blue compartment R1 were analyzed by HSVA based on the six water level sensors in the compartment. These sensors were located transversally, and therefore, the analysis is based on the assumption of two dimensional water surface.

2.4 The practical applications of computational methods for prediction and scaling (TOR 1 D)

2.4.1 Deck immersion

The false-negative inconsistency issue in the vulnerability criteria of stability under dead ship condition for low freeboard ships is examined by Munakata et al. in 2021. According to the model experiments, the deck immersion, which raises roll damping and lowers the effective wave slope coefficient, is mostly to blame for the inconsistency. These consequences were not taken into account by the level 2 vulnerability criteria that is in use to-day. According to the author, roll damping and the effective wave slope coefficient can be estimated using the model experiment. In the event that the experiment is impractical, an alternative method could be to calculate the effective wave slope coefficient using the non-linear strip theory and roll damping using Rakhmanin's empirical formula.

Subramaniam et al (2021) experimental investigate the effect of trapped deck water on the roll dynamics of one low weather deck offshore supply vessel (OSV) in both regular and irregular stern quartering waves. The study found that there is an increase in the roll angle due to the reduction of the positive damping effect at a higher Froude number. At very severe sea states, the possibility of large roll angles occurring at low Froude number exists, due to excessive static moment caused by the trapped water, see figure 14 and figure 15.

Figure 14: Movement of deck water due to ship roll with a phase lag for one of the irregular wave trial, Froude number 0.3 with open openings

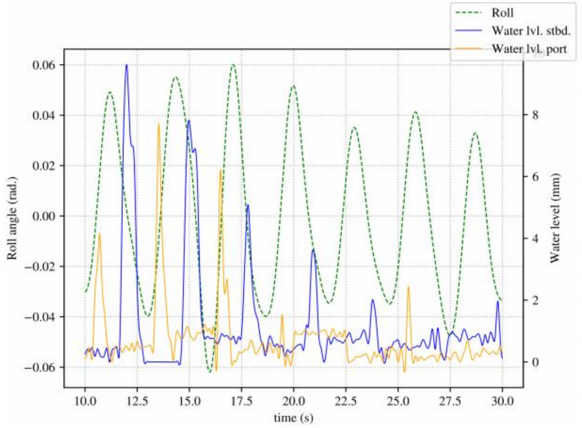

Figure 15: Time history of ship roll and deck water motion, Froude number 0.31

Masamoto et al. (2023) described experiments where trapped water on the deck affects the transverse stability of purse seiners running in stern quartering seas. The influence of trapped water on the deck is quantitatively evaluated by conducting a phase difference analysis of the measured trapped water on the deck motion and the time series of the ship model’s rolling motion.

2.4.2 Sloshing

Sloshing impact loads are not usually relevant to stability in waves. Sloshing is here only considered as a factor, influencing on the dynamics of the vessel as a whole.

Liu et al., (2022a) performed the numerical simulations of the parametric roll of a ship coupled with liquid sloshing. Wu et al. (2021) introduced two improvements to the original Moving Particle Simulations MPS. Then the improved MPS was applied to solving two-dimensional liquid tank sloshing problems, and studied the coupled motion of swaying and rolling motion with different loading rates, which is aiming to provide some reference for further study on the influence of the sloshing impact loads on the motion of real ships.

Igbadumhe et al. (2022) carried out a series of roll decay tests for a FPSO model with a pair of two-row prismatic tanks. The results show that an increase in liquid cargo, the location of cargo load, and the geometry of the cargo tank affect the damping of the vessel. Interaction between sloshing and and ship motions at forward speed was considered by Lyu et al (2022).

2.4.3 Fundamentals

Hori published many papers recently, and a good summarised in 2021 (Hori, 2021). It is a proof that the centre of buoyancy is equal to the centre of pressure. Even if it was commonly used and verify in many studies, the proof was not really written as a demonstration before. An elegant proof was proposing by Hori for arbitrary shape of floating body applying Gauss’s theorem and solve the undetermined solution of the equilibrium by solving it in a non-equilibrium position and go to the equilibrium at its limit, see Figure 16. Similar subject was considered by Spyrou (2022).

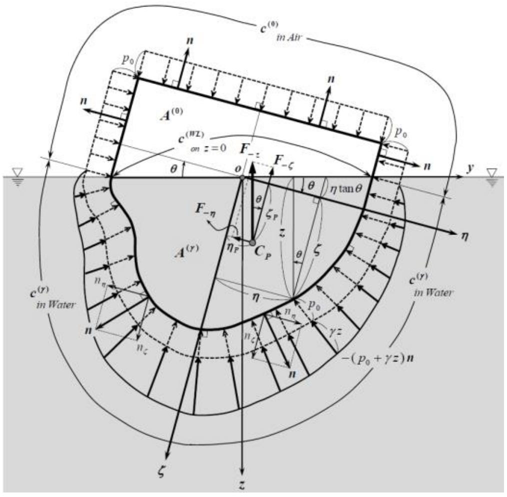

Figure 16: Hydrostatic pressure and centre of pressure acting on the inclined floating body with arbitrary form from Hori, 2021

2.4.4 GZ curve

Bu et al (2021) focused on the accurate prediction of roll restoring arm in waves. The investigations showed that the conventional FK assumption in which GZ_{RD} (GZ curve computed with diffraction and radiation) is ignored can be employed for the calculation of roll restoring arm of zero speed in different wave directions, because GZ_{RD} is negligible at zero speed. Considering that there is no obvious improvement on the prediction accuracy in following waves with forward speed even though GZ_{RD} is taken into account, the FK assumption can also be used.

Zhou et al. (2022a) aimed to study the Parametric Roll characteristic of ships with extended low weather deck, and carried out an experimental investigation and numerical comparison. The effect of highly nonlinear water-on-deck phenomena caused by ORV's extended low weather deck on Parametric Roll response is specially investigated. Regarding numerical simulation of ORV's parametric roll, the effects of assessment accuracies of GZ curves in waves and roll damping coefficients are analysed.

2.4.5 Motion in random waves

Evaluation of the probability of rare events, such as occurrence of maximum reactions over ship design life, from direct numerical simulations requires significant computational time.

For the “operational limitation” introduced by the framework of SGISC in MSC.1/Circ. 1627, the standard environmental conditions are substituted by specific environmental conditions, and this substitution generally has an impact on the calculation parameters of the criteria. Bulian and Francescutto (2021) developed a rational simple procedure for the limitation of information when the level 1 vulnerability are used for dead ship condition.

Due to significant nonlinearity of hydrostatic and Froude-Krylov forces, probability distribution of roll motion can significantly deviate from Gaussian distribution. To find the shape of this non-Gaussian distribution, Maki (2017) proposed to consider neglect self-dependence in expiation and describe as white noise. The distribution of response then can be found by solution of Fokker-Plank-Kolmogorov (FPK) equation. The resting distribution then can be scaled with outcome of numerical simulation.

For the prediction of the joint probability density function (PDF) of roll angle and rate, Maki et al. (2021) validated the method by comparing them with the Monte Carlo when the wave period is close to the natural roll period.

Katayama et al. (2023) looks into a way to derive a suitable non-Gaussian distribution for a short-term stability assessment. Maki et al (2022) describes application of this technique to roll angular accelerations. FPK equation is solved numerically with PDF line integral method. The results are compared with an outcome of Monte-Carlo simulation.

Maruyama (2022b) used the stochastic averaging method using Hamiltonian proposed by Maki et al. (2023) and the PDF of roll amplitude and Hamiltonian are derived from the equations of roll motion.

Zhou et al. (2023a) presented a novel extreme statistics strategy for predicting extreme values of ship parametric rolling motions based on limited model test observations. The synthetic moment method to estimate the distribution of extreme ship rolling motions, incorporating Hermite transformation to address the skewness and kurtosis in the data was used. This step helps in accurately representing the statistical properties of parametric roll. The Markov chain model is applied for correction, enhancing the precision of extreme value predictions from limited observations by considering the temporal sequence of rolling motions. By applying this strategy to the C11 container ship model, the study successfully predicts extreme rolling angles from minimal data, demonstrating the method's superiority over traditional approaches in small sample scenarios.

Rajaraman and Hariharan (2023) explored the steady-state ship rolling motion in random beam seas with nonlinear damping and restoring moments mathematically by using Hermite wavelets.

Chai et al. (2022) studied excessive roll motion for the cases of the dead ship condition and the parametric rolling. Two different methods, i.e. the traditional Gumbel method and the average conditional exceedance rate (ACER) method are applied in order to predict the extreme values of the stochastic process.

Glotzer et al. (2023) provided an important update on constructing confidence interval for mean and variance estimates for ship motions in irregular waves. Ship motions are characterized with self-dependence, strongly affecting the width of confidence intervals. The cited reference proposes to account for this self-dependence with an estimate of long-run variance and its square. The approach has been extended for the case of an ensemble with several independent records. Additionally an alternative algorithm of “self-normalization” is proposed. The information from the cited reference was use to update ITTC recommended procedure 7.5-02-01-08 as required by TOR 3. See details in section 4 of this Report.

Li et al. (2023) simulated the extreme roll motion of ONRH by using an in-house CFD solver in irregular beam waves without for-ward speed. Coupled roll-pitch-heave (3-DOF) and coupled sway-roll-pitch-heave (4-DOF) were considered to understand the impact of sway motion on ship stability. The results indi-cated that roll motion amplitude under 3-DOF conditions is significantly larger than under 4-DOF, with CFD predictions closely aligning with experimental findings, highlighting the importance of including sway in stability anal-yses under extreme conditions.

2.4.6 Second Generation Intact Stability Criteria (SGISC)

Umeda and Francescutto (2023) describe current status of the IMO SGISC, just prior finalization of the Explanatory Notes to the Interim , Guidelines of the Second Generation Intact Stability Criteria by IMO in April 2023 with MSC.1/Circ.1652 referred further simple as “the Explanatory Notes” . There are five stability failure modes considered: dead ship condition, excessive acceleration, pure loss of stability, parametric roll resonance and surf-riding / broaching-to. The Interim Guidance on the criteria was issued by IMO in 2020 as MSC.1/Circ. 1627. The criteria have tiered structure, where the first tiers are intended to detect possible vulnerability to stability failures, while the third tier is focused on application of state-of-the art numerical simulation techniques, referred as Direct Stability Assessment (DSA). As directed by the Term of References, the ITTC contributions to the DSA is addressed in sections 3, 5 and 9.

Peters et al. (2023) considers the relation between the second generation intact stability criteria and achieved safety level of a vessel, satisfying these criteria, emphasizing the connection with new approaches being promoted by IMO such as Goal Based Standards and Formal Safety Assessment.

Schrøter et al. (2023) describes systematic evaluation of the vulnerability criteria to obtain GM limit curves and identifies inconsistency between the levels of the criteria. The inconsistencies between the level 1 and 2 for dead ship condition and pure loss of stability is also studied in Peters and Belenky (2023), considering the relation of the former with the current IMO Intact Stability Code (IMO 2008). It was concluded that some inconsistency between level 1 and 2 of vulnerability criteria is unavailable. The level 1 vulnerability criterion is similar to weather criterion, which cannot be given a unique probabilistic interpretation, while level 2 vulnerability criteria is probabilistic.

Umeda et al. (2023c) considers inconsistency in vulnerability criteria for pure loss of stability encountered with offshore supply vessels, having an extended low deck. The reason of inconsistency is that the deck is likely to be flooded at large roll angles. Large extent of the deck means that the green water changes dynamics of roll motion beyond what was included in the vulnerability criteria. The described model tests do confirm that the water of the deck is a source of inconsistency.

Peters et al (2023a) gives a scientific background for the level 2 vulnerability criterion for surf-riding. This criterion is a good example of using Nonlinear Dynamics for practical calculation. The detection of dangerous surf-riding situation is based on Melnikov analysis, determining the speed setting leading to surf-riding at all initial condition at a given wave.

Shigunov (2023) considered specification for DSA focusing on the Poisson process, which is the main probabilistic model, relating probability of stability failure with time of exposure. As a result, complete probabilistic characterization of stability in wave can be done through rate of failures. General basis of use of Poisson process for stability regulations is described in Chapter 1 of Belenky and Sevastianov (2007). A brief description of application Poisson process for stability in waves can be found in Section 2 of IMO document SDC-8/INF.2, submitted by ITTC and prepared by 29th ITTC Stability in Waves Committee.

Wandji et al. (2024) provide mathematical basis for three methods of direct counting, described in the Explanatory Notes, including a formal analysis of bias and variance of estimators. Benchmarking of three estimators and their confidence interval is carried out using synthetic data, following Poisson process that also can be found in Shigunov et al. (2022). Wandji et al (2023) carry out this benchmarking on ship motion data, produced by numerical simulation.

Reed (2023) considers a formal process of Verification, Validation and Accreditation (VV&A) of numerical tools for simulation of ship motions, if such tool is to be applied for DSA. A formal VV&A process is essential for uniform application of DSA.

Umeda et al. (2023a) describes a comparison between numerical simulation and model test for dead ship condition and pure loss of stability. Special attention was paid to wind generation. Validation of numerical tools for pure loss of stability and parametric roll was addressed in Umeda et al. (2023b).

Francescutto (2023) examines a history of stability criteria, describing how this matter was developed starting from purely empirical approach of Rahola (1939) towards development of the weather criterion, forming the current International Intact Stability Code (IMO 2008), being the first generation intact stability criteria.

Weems et al. (2023a) considers application of fast volume-based simulation tool for direct stability assessment. Comparison with well-established, engineering-level potential flow/ hybrid simulation tool LAMP (Large Amplitude Motion Program, Shin et al. 2003) is provided.

Peters and Belenky (2021) suggested a methodology for the comparison of the alternatives with current criteria and its relevance to operational experience using pure loss of stability as an example. This was in response to comments regarding the testing and trial use of the SGISC.

Petacco (2021) investigated the sensitivity of ship stability performance in waves to geometric variation by means of a simulation-based design framework. A method developed in-house, combining the subdivision surface and free-form deformation approaches, has been used to create the whole set of design alternatives. The generated design configurations have been assessed analysing the results derived from application of the first- and the second-level SGISC vulnerability criteria for both the selected stability failure modes. To strengthen the correlation behaviours, the design space has then been further explored by using 10k design configurations exploiting the capabilities of a surrogate model–based approximation, relying on a Gaussian process formulation.

2.4.7 Surf-riding and Broaching-to

Umeda (1990) suggested a critical wave approach for the stability failure risk of broaching associated with sur-riding in both irregular following waves and stern quartering waves (Umeda et al. 2007). Matsubara et al. (2021) used a free-running model experiment and numerical simulation to validate the approach in irregular waves with both short and long crested waves.

Ma et al. (2021) studied the influence of hydrodynamic derivative on surf-riding using CFD method. The authors compared the course stability with hydrodynamic derivative in waves and also in clam water.

Tigkas and Spyrou (2023) focused on the surge dynamics of a ship operating in long following waves. A quite robust irregular version of hybrid surging was identified. The mathematical model includes three DoF (surge-pitch-heave) and it accounts for hydrodynamic memory effects.

Gong et al. (2022) applied a hybrid method coupling potential flow method and viscous flow method to simulate the autopilot trimaran in stern waves, aiming to study the process of being captured by waves and the surf-riding characteristics of the trimaran.

Feng et al (2023) focused on the level 2 surf-riding/broaching vulnerability criterion and proposes complements to the assessment procedures regarding two important issues. One is that the current procedure is only applicable to ships using propellers. The second issue is addressed through the proposal of a practical method to estimate the wave surge force correction factor based on the ratio between the first order wave surge force and its FK component.

Yu et al (2022) simulated surf-riding and broaching in irregular waves by using a previously developed 6-DOF numerical model. The surf-riding / high run is defined as exceedance of the instantaneous wave celerity. The approach identified “likely broaching” as 10 degree yaw deviation. Dependence on wave heading and speed has been studied. It is found that the ship capsizes after experiencing a relatively long duration of high run, which suggests correlation between capsizing and high run. High run in irregular wave is proved to be a good representation of surf-riding.

Liu et al. (2022b) investigated the capsizing behaviour of a free-running ONR Tumblehome model in stern quartering seas by an unsteady Reynolds-averaged Navier-Stokes (URANS) solver coupled with dynamic overset grid approach.

Spyrou et al. (2023) describes two calculation techniques to estimate probability of surf-riding in irregular waves. The first technique identifies points in the phase space where all the longitudinal forces are equal (pseudo-equilibria). As these points do move with acceleration they cannot be a solution of the equations of motion. The second technique detects “high-runs” – increases of the forward speed above the predetermined threshold. The values, estimated with both techniques, are compared.

Spyrou et al. (2023a) looks in the fundamentals of surf-riding in irregular waves, examining how the surge response changes when wave excitation goes from monochromatic to bichromatic and following with the further frequency increase. The surf-riding phenomenon goes through a qualitative transformation with addition just one more frequency, including a possibility of chaotic response.

Belenky et al. (2023) consider application of split-time method for estimation of probability of surf-riding in irregular waves. The metric of likelihood of surf-riding is computed by perturbation of the dynamical system in its phase space towards the pseudo-equilibria until the surf-riding response is observed. The latter is defined as an exceedance of the instantaneous wave celerity.

Belenky et al. (2023a) attempts to extend the split-time method for estimation of probability of broaching-to preceded by surf-riding. Similar to surf-riding, the metric of likelihood is computed as a perturbation in phase space towards a “dangerous” point. The latter is defined as an origin of significant deviation from the commanded course; it is searched numerically in the vicinity of pseudo-equilibrium.

2.4.8 Parametric roll

In order to reduce the risk of roll resonance incidents for sailing ships, Koop et al. (2021) developed a new operational method to identify the critical sea states by evaluating 2D wave spectra using radial basis function in on-board warning systems, see Figure 17.

Luthy et al (2021) extend the energy method to non-linear GZ for the prediction of parametric roll, see Figure 18.

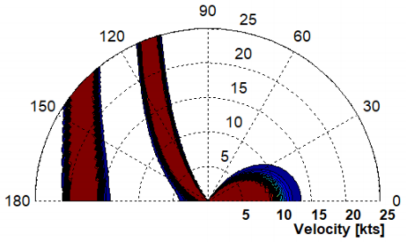

Figure 17: Polar diagram of critical combinations of sailing speed and incident wave angle for the C11 containership using the proposed basis functions. (Koop, 2021).

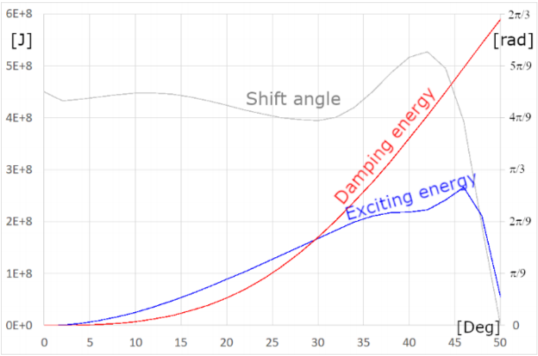

Figure 18: Damping and exciting energies and fitted, from Luthy et al (2021).

Luthy et al. (2022) introduced a method to calculate the steady state roll amplitude on monochromatic longitudinal wave when the encounter period is twice the natural roll period, which is the parametric roll condition. He extended this method to the speed of any ship, aiming to propose an alternative method for single degree of freedom simulation in the head sea, see Figure 19**Error! Reference source not found.**. It identifies the most conservative spreading angle for equivalent sets of waves, with a polar-plot summary of maximum roll angle.

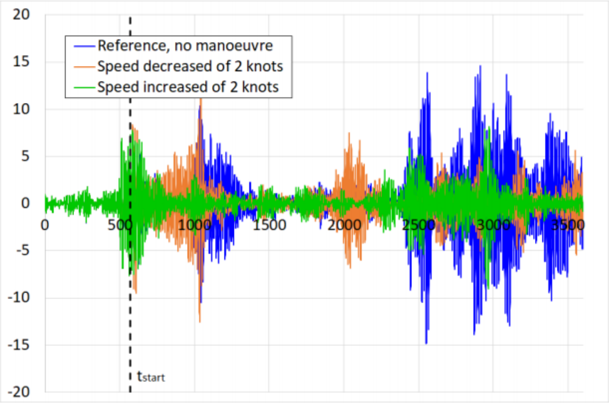

Figure 19: Effect of speed modification on the roll motion (Luthy et al., 2022).

Uchida et al. (2022) simplified the estimation of fundamental parametric rolling in longitudinal waves. An averaging method applied to an uncoupled roll model is used to estimate the amplitude of fundamental parametric rolling. A harmonic balance method is utilized to estimate the occurrence of fundamental rolling.

González et al. (2023a) presented a study of using neural network for predicting parametric roll. The neural network was trained with numerical simulation data and the compared to a model test results.

Liu et al. (2021) presented a computational fluid dynamics (CFD) prediction of a full-scale ship parametric roll in a regular head wave.

Jiang Y. et al. (2023) proposed a method of predicting the stability zone and checked by numerical simulation based on computational fluid dynamics. The relationship between the outrigger position and the potential risk of the parametric roll was analysed by the obtained stability zones. It was found that the decrease in the outrigger displacement ratio and the increase in the clearance can significantly raise the risk of parametric roll of a trimaran.

Wu et al. (2022) present a numerical investigation for the wavelength effect on the parametric roll in head waves. The computational fluid dynamics (CFD) simulations are carried out for a model-scale ONR Tumblehome to predict the heave, roll, and pitch motions as the parametric roll occurs. An in-house unsteady Reynolds-averaged Navier–Stokes (URANS) solver coupled with a dynamic overset grid approach is applied to the numerical simulations, along with the systematic verification and validation studies based on the experimental data from INSEAN model tests.

Yang (2023) conducted an extensive numerical study on the possibility of parametric rolling of a containership based on Mathieu instability. It reveals the coincidence and difference between the analysis results at each level of numerical analysis by presenting the analysis results obtained based on different numerical models pertaining to the possibility of the parametric rolling of the target containership. Li J. et al., (2023) applied an in-house CFD (computational fluid dynamics) solver and conducted the URANS (unsteady Reynolds-averaged Navier–Stokes) simulations to predict the roll motion of ONR Tumblehome in irregular beam waves without forward speed. The results show that the amplitude of ship roll motion under 3-DOF condition is significantly larger than that under 4-DOF condition.

Liu et al. (2022c) established a single-degree-of-freedom rolling equation under parametric excitation. Based on strip theory, the righting arm is calculated by numerical simulation with different roll angles, wave heights, and phase angles of the wave position. As a result, conditions for applicability of the stochastic averaging method of energy envelope for practical engineering problems are given. The follow-on studies are described in Liu et al. (2023, 2023a).

Zhou et al. (2022) constructed a 6-DOF three-dimensional weakly nonlinear time-domain model based on the IRF (Impulse Response Function) method to predict ship parametric roll in head waves.

A number of examples of the operational restrictions imposed on the parametric rolling failure model are provided by Hashimoto and Furusho (2021). They examined the effects of season, area, and route restrictions on the susceptibility to parametric rolling stability failure.

2.4.9 Following and stern quartering waves

Bonci et al. (2022), investigated the dynamics of capsize of a frigate, sailing in stern quartering waves, with nonlinear time-domain simulations. Using FREDYN from CRNAV, a numerical sensitivity study was conducted for the modelling of the dynamic linear and nonlinear maneuvering forces acting on the ship hull, and the effects of maneuvering forces on ship capsize was also examined, see Figure 20.

Zeng et al. (2023) carried out the CFD computation that simulates the pure loss of stability of a fully appended ONRTH in following waves. Forces and moments on individual appendages including propellers, rudders, and bilge keels are analyzed, see Figure 21.

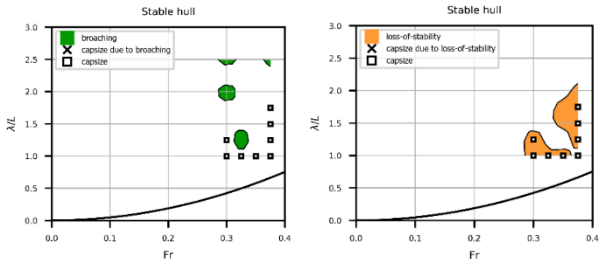

Figure 20: Broaching-to and pure loss of stability region. Wave heading: 30deg; wave steepness 0.067 (Bonci, 2022)

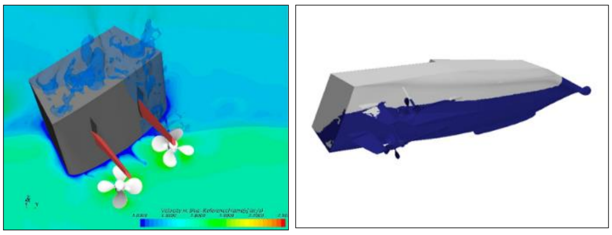

Figure 21: Flow field and wetted surface of the large rolling ONR tumblehome in following waves (Zeng et al. 2023)

Lu and Gu (2023) studied the 6-DoF coupled mathematical models for surf-riding/broaching and pure loss of stability in stern quartering waves. Rudder exposure and wave-particle velocity are considered for ship broaching, and the wave-excited surging force with instantaneous wet hull also shows an important role on predicting the pure loss of stability, see Figure 22figure 22.

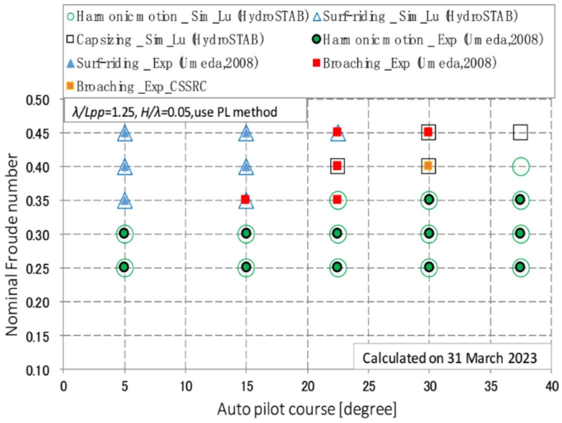

Figure 22: Ship motion modes with and without considering rudder exposure and wave particle velocity (Lu and Gu, 2023).

Based on the numerical study combined with the accident of the bulk carrier, Lu et al. (2021) observed synchronous rolling with yaw motions in stern quartering waves, see Figure 23.

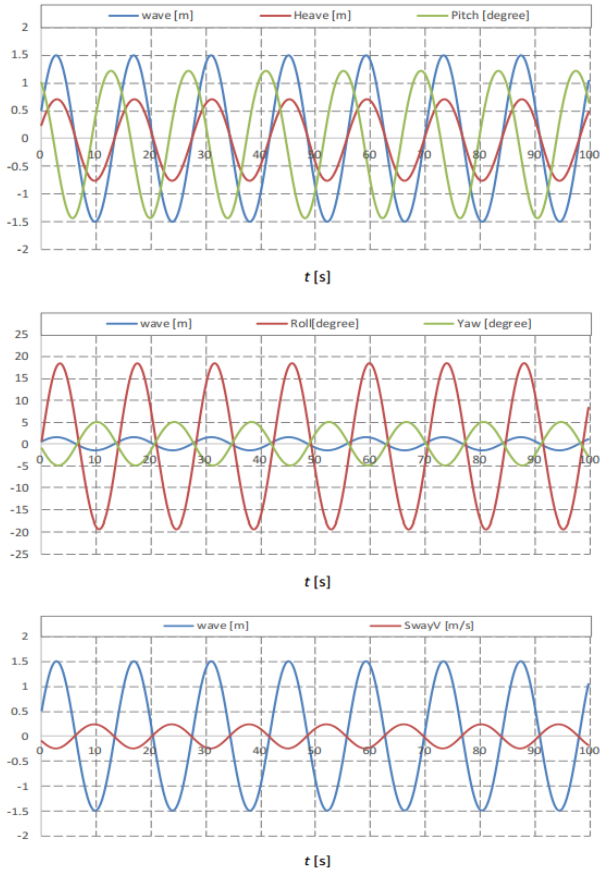

Figure 23: The time-domain simulation of ship motions with H=3m, λ/Lpp=1.20, heading angle=40 degrees, Fn=0.10, and Yaw=5 degrees.

2.4.10 Damage stability of ships in waves

Vassalos et al. (2023a) consider possible measures for improvement of survivability of Ro/Ro passenger ships after damage. The motivation came from the recent IMO decision to increase subdivision index and made it applicable to the existing fleet. Vulnerability screening is proposed as one of the risk mitigation options.

Bulian et al. (2023) considers additional aspects, not currently accounted for in damage stability regulation such as bottom grounding and side grounding or contacts. Monte-Carlo simulation is used to generate damage information based on a given distribution of the position and extent of those damages; the approach is referred to as “non-zonal”.

Atzampos et al. (2023) focuses on survivability-in-waves of cruise vessels after damage. Flooding of cruise ships bears very heavy consequences; despite those vessels do not have an open deck. A new formula was proposed for the s-factor, based on numerical simulation with cruise ships of different sizes. Another objective was finding a significant wave height where a cruise ship retains sufficient stability after damage.

2.4.11 Numerical tools

Weems and Belenky (2023) describe theoretical background and recent advances of fast volume-based numerical tool. The tool is built around the body-nonlinear formulation for hydrostatic and Froude-Krylov forces. Fast calculations are achieved with transition from surface to volume integral and decrease of necessary evaluation of irregular wave (Weems and Wundrow, 2013, Weems and Belenky, 2015). Approximation of diffraction and radiation forces (Kim et al 2023) recently has been added to the tool.

2.4.12 Roll damping

Katayama et al (2021) experimentally investigate the characteristic of roll damping for two types of hull (PCC and LNGC) with shallower draft and higher center of gravity compared to the ships, which existed when Ikeda's method was developed. The authors also verified the modified Ikeda's method, which has some modifications related to the effects of the draught and height of the center of gravity. In Figure 24, a comparison of the bilge keel associated damping between Ikeda's method and modified method is shown.

To improve the roll motion prediction of a particular ship, Zhang et al. (2023a) made an investigation of roll damping model form and its coefficients calculation methods based on benchmark roll decay data, see Figure 25. They concluded that all roll angle, angular roll velocity, and angular roll acceleration should be considered in damping model determination. Damping models with angle and angular velocity as independent variables are proposed. A model formulation procedure is developed based on the Prony-SS method (Hu et al. 2013) from which approximate analytical expressions of roll decay data are obtained, and roll damping formula can be determined by multivariate function fitting. The Fig shows one of the formulation results of roll damping moment normalized by the total roll moment of inertia. The results performance well in roll motion prediction.

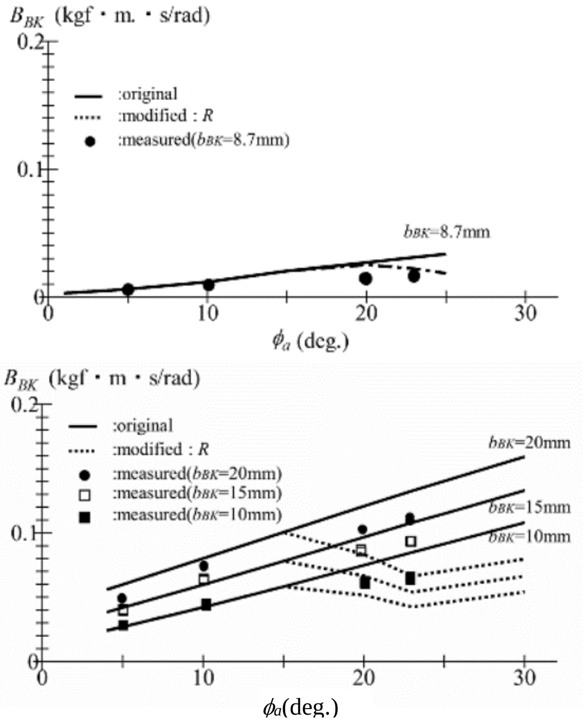

Figure 24: Comparison of bilge keel damping coef., B_{BK}, among measured, Ikeda`s original method and Katayama's modified method. (upper: PCC and T=1.96s, lower: LNGC at T=2.19s).

Katayama et al. (2022a) corrected a typographical error of Ikeda's formula of the eddy-making component for naked hull. They investigated a modified method that considers the effects of shallow draught.

Katayama and Yoshida (2023) investigated the effects of free surface on normal force component of bilge-keel component by using CFD computation (Figure 26). A new coefficient is applied to correct the drag coefficient of bilge keel, which improves the Ikeda's method for roll damping, see Figure 27.

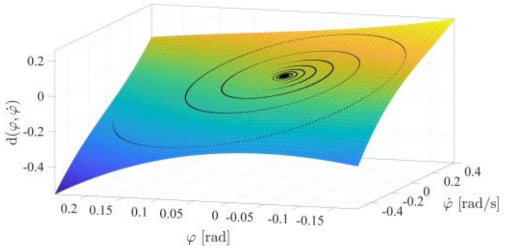

Figure 25: Normalized roll damping moment with angular roll velocity and angle, Zhang et al. (2023a).

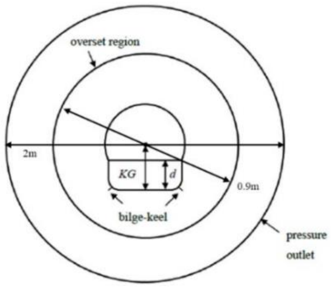

Figure 26: Computational domain and 2D model (Katayama et al., 2023)

Rudaković and Bačkalov (2023) considered roll damping for inland vessels with very full form and shallow draft (beam to draft ratio is over 4). Conventional semi-empirical methods may not be applicable to these vessels. In particular eddy making component or roll damping was a problem for cases with block coefficient more than 0.84. Correction to simplified Ikeda's method is proposed.

Rodríguez et al. (2022) showed the high dependency on roll damping coefficients by investigating the numerical simulations of VLCC roll responses in waves. Three different groups of roll damping coefficients were involved, which were obtained from roll decay tests, calibration of experimental roll responses in waves, and Ikeda's method, respectively (Figure 28).

Chen et al. (2023) investigated the roll natural period and damping coefficients in finite depth condition by using CFD computations. Water-depth effect has shown a strong influence on the roll behavior and ship hydrodynamic responses, see Figure 29.

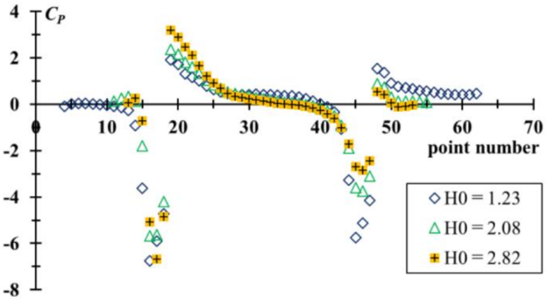

Figure 27: Distributions of hull pressure coefficient Cp for different water depths. (Katayama and Yoshida, 2023)

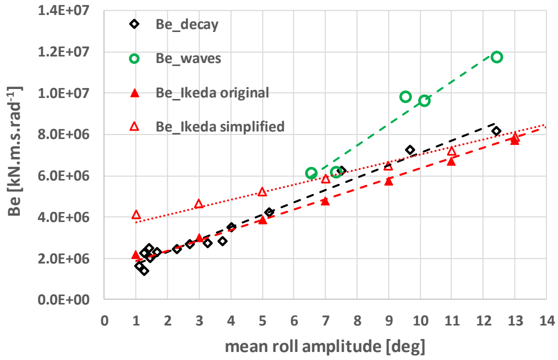

Figure 28: Linearized roll damping coefficients from decay tests, regular waves tests and Ikeda's original and simpli-fied predictions for the resonant roll period (Rodríguez et al., 2022).

Aram et al. (2023) developed a roll damping model for seakeeping codes through a series of CFD simulations with forced and free roll motions. The coefficients of damping model were obtained through an optimization procedure to minimize the difference between the hydrodynamic forces calculated by CFD and potential codes under prescribed roll motions.

Luthy et al. (2021) suggested an iterative optimization procedure to identified roll damping coefficient using the seakeeping tools used for roll analysis in irregular waves. The main advantage is to avoid double counting of some components.

Wassermann and Abdel-Maksoud (2023) describe CFD application for predicting bilge keel contribution into roll damping. The setup is based on ellipsoid with two normal-to-surface plates to model bilge keels. The cited reference also include an investigation on skin friction component.

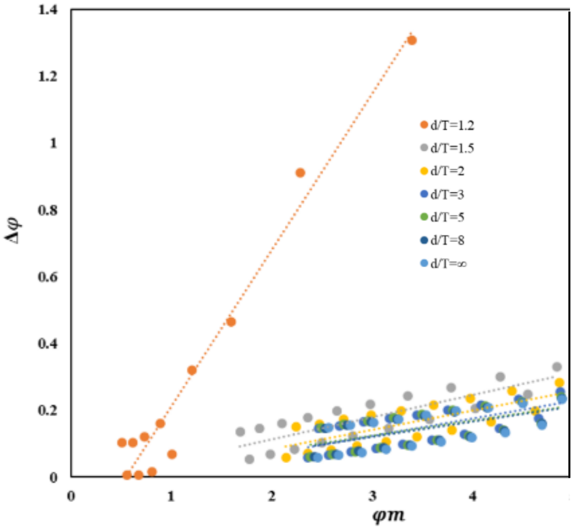

Figure 29: Curves of roll extinction of different depth to draft ratios (Chen et al. 2023)

Umeda et al. (2023) also look into the bilge keel component with CFD with a particular emphasis on roll motions in irregular seas. Certain type of memory effect was found, influencing evolution of the vortices.

Cichowicz and Vassalos (2023) offer a different perspective on roll damping. A study starts from a roll damping model test, aimed to determine hydrodynamic reaction and proceeds with derivation of roll/sway equations. Both intact and damage cases are considered.

Zhang et al. (2023) used a method of equivalent roll damping to study the parametric rolling of the KCS container ship. This method converts the nonlinear roll damping calculated by CFD into linear roll damping. Then the parametric rolling of the KCS container ship in regular waves is predicted based on the Rankine panel method.

2.4.13 High speed turn

Hinz et al. (2022) applied a 6-DoF ship dynamic model to predict the instantaneous maximum and quasi-static angle of heel developing during the ship steady turning maneuver.

2.4.14 Extrapolation Methods

Extrapolation is essentially a prediction beyond the range of data available. The statistical extrapolation is an essential technique for probabilistic assessment of stability in waves as most of engineering-level numerical simulation tools for ship motion are too slow to observe stability failure directly.

Reed (2023a) discusses interpretation of the results of numerical simulation, looking into linear and nonlinear dynamical systems. Extreme response of linear dynamical system is completely defined by its standard deviation. However, characterization of extreme response of nonlinear dynamical system will require handling rare events and fall into category of extrapolation methods. Statistical extrapolation method may be classified into three groups:

- Methods based on extreme value theory;
- Methods based on consideration critical wave groups (or single waves) and wave episodes;
- Methods based on extrapolation over environmental conditions.

The extreme value theory states that the largest number in a dataset of independent points follows a limit distribution – Generalized Extreme Value (GEV) distribution independently of underlying distribution. This leads to a conclusion that a tail of any distribution can be approximated with Generalized Pareto distribution (GPD).

While sounds very promising, practical application of GPD encounters a number of difficulties. Pipiras (2020), Anastopoulos and Spyrou (2023) have studied and summarized these difficulties. One of them is that the type of the distribution tail (heavy/exponential/light), approximated with GPD, is defined by a shape parameter, estimated from the data. Thus, the shape parameter estimate is a subject for statistical uncertainty. This uncertainty can make the tail too light, leading to appearance of a right bound in a random location of the tail. If this bound is below the target of extrapolation, the GPD-based method fails to deliver a result. Additionally, Anastopoulos and Spyrou (2023) note difficulty of comparison of the GPD outcome with Monte-Carlo and critical wave group results.

The practical way to resolve this problem is to determine the type of the tail, based on physical consideration. It was found in Belenky et al. (2019a) that the tail of distribution of roll peaks is heavy due to known phenomenon of “hanging roll”. Campbell et al (2023) modeled heavy tail with Pareto distribution with the Envelope Peak-over-Threshold (EPOT) method. Originally, EPOT used GPD, but due to the reasons above, the reliability of application was low, while uncertainty of extrapolated estimate was high. Introduction of Pareto distribution decreases the uncertainty by several orders of magnitude, reflecting how physical information can inform a statistical model and shrink confidence interval.

Campbell et al. (2023a) describe statistical validation of EPOT using large validation dataset generated by the fast volume-based method, see (Weems and Belenky 2023). The validation dataset was 1.9 million hours long, included 82 extrapolation targets; there was only one sea state but 8 headings. The subject ship was ONRTH (Bishop et al. 2005). Validation of EPOT with Pareto tail was not successful for oblique seas (heading 135 deg), but performed well for all other considered headings (15 to 90 deg). EPOT with GPD had reasonable performance for all headings, but was not as reliable as Pareto for stern and beam seas headings.

Belenky et al. (2024) describes application of split-time method (MPM) for estimation of capsizing probability. The essence of the split-time method is to separate a complex problem of capsizing into two less complex problems: non-rare and rare. The non-rare problem is an upcrossing of an intermediate level that can be observed during a reasonable duration of numerical simulation. The rare problem is determining conditions for capsizing after upcrossing. These capsizing conditions are determined by perturbing the roll rate at the instant of upcrossing until a capsizing is observed. The amount of perturbation, needed for capsize, serves as a metric of capsizing likelihood at the instant of upcrossing. Repeating the calculation for a number of crossing creates a dataset that can be extrapolated. Physical consideration suggested the exponential tail for the metric, however GPD was also used for comparison. Similar to EPOT, application of physics-informed statistical model lead to significant decrease of uncertainty. The cited paper reviews almost 3 decades of development and examines different numerical and statistical aspects of the method, including perturbation algorithm and quantification of uncertainty.

Weems et al. (2023) describe statistical validation of the split-time method (MPM) of capsizing probability. A fast volume-based method (Weems and Belenky 2023) was used to generate a validation dataset of 4.8 million hours of roll motions in 14 different sea states; 872 capsizing cases were observed. Small subset of this data was used to estimate probability of capsizing and compare with the “true” value, observed from the validation dataset. Both exponential and GPD tails were tested; as expected, performance of the split-time method with exponential tail was significantly better.

Positive outcome of validation of EPOT and split-time methods (MPM) justified inclusion both methods in IMO Explanatory Notes and ITTC recommended procedure 7.5-02-07-04.6 by 29th ITTC. An update to this procedure is described in subsection 3.1 of this Report.

Critical wave group approach is based on two ideas. The first that large waves do appear in groups, which are hydrodynamically related. That means, the neighbourhood of a large wave is almost deterministic, despite waves, in general, being random. This manifests the Quasi-Determinism principle, see Boccotti (2000, 2014). The second idea is that only certain groups can cause significant dynamic response that brings the word “critical” into the name of the approach. Themelis and Spyrou (2007) proposed to consider a seaway as a sequence of critical waves groups, separated by benign waves. Then, ship response only needs to be evaluated in the critical wave groups.

Anastopoulos and Spyrou (2023a) provide an update on the development of the critical wave group method. The critical wave groups cause significant motion response; as this response is expected to be nonlinear, it strongly depends on initial condition upon encountering the group. The cited reference discusses possible simplification for finding these initial conditions. The second simplification, proposed is on determination of characteristics of what wave group is critical. The idea is that a ship is likely to produce significant response in resonant conditions, so the wave groups with period close to natural period are likely to be critical for the failure modes where the resonance is important.

The wave groups are relatively short. That creates an opportunity to apply high-fidelity methods to evaluate a response to the group. That include a model test (Anastopoulos et al. 2016; Bassler et al. 2019) and more recently CFD (see Silva and Maki 2021). Both model test and CFD, however, do require physically realizable initial conditions at the wave group encounter. The latter reference describe initial condition handling method, suitable for CFD, where a deterministic wave group is embedded into previously simulated ship response. Having in mind high computational cost of ship response simulation with CFD (Silva et al. 2022; Silva and Maki 2022a, 2023, 2023a; Silva 2023), utilize a Long Short Term Memory (LSTM) neural network to reproduce needed ship response. Architecture and training of LSTM is developed by Xu et al (2021) as well as Silva and Maki (2022).

The wave episode approach differs from a wave group approach. A wave sequence in the former does not have to maintain hydrodynamic relation; it is just a wave set likely to cause significant ship response. This was the objective of the Design Load generator, where the wave episode was created by manipulating random phase shift in Longuet-Higgins model of irregular waves (Alford and Troesch 2009). The method searches for combinations of the phases that lead to an expected roll response (Kim and Troesch, 2013, 2019).

Edwards et al. (2021) proposed improvements to the method with an equivalent linear dynamical system that has the same zero-crossing period as the system of interest.

Another way to apply wave episode approach was proposed by Mohamad and Sapsis (2018) employed adaptive sampling, based on Bayesian approach. The results of initial calculations are approximated with Gaussian process regression, taken as “prior knowledge”. Then the conditions for the next calculation can be chosen to minimize the uncertainty — this is “a posteriori knowledge.” The problem of initial conditions is considered by Guth and Sapsis (2022) with a “stochastic prelude” approach to capture the transitional behavior.

Reed (2021) proposed the identification of extreme response with a fast reduced-order numerical model of ship motions in waves. The approach seems to be promising with development of tunable fast volume-based simulation tool (Weems and Belenky, 2023) that can be informed or tuned with higher fidelity simulation (Kim et al. 2023).

The idea of extrapolation over environmental conditions (currently over significant wave height only) is also straightforward. Numerical simulations are performed in several high sea states, where stability failure is observable and then extrapolated towards lower sea state, where observation of the failure is not possible due to computational costs (Tonguć and Söding 1986). The method was included in both in the Interim Guidelines for the SGISC and the Explanatory Notes. Shigunov (2023a) provides detailed description of the method with particular emphasis on quantification of uncertainty. Two criteria for validation of the proposed technique are considered. The cited reference also describes construction of confidence interval for extrapolated failure rate. Other aspects related to application of this method are considered in Shigunov (2023b).

Anastopoulos and Spyrou (2022, 2023b) have presented a formal argument on the equivalency between the extrapolation over the wave heights and the critical wave group method. Moreover, they have proposed and evaluated two improved formulae for extrapolation which retain the simple character of the original. The extrapolation over the wave height has been included in the proposed revision of ITTC recommended procedure 7.5-02-07-04.6 and is described in subsection 3.1 of this Report.

Shigunov (2023) reviewed statistical extrapolation method to reduce the required computational time and considers in detail the extrapolation of failure rate over significant wave height. Application of these criteria shows that the extrapolation of failure rate over significant wave height does not satisfy the proposed criteria with the sample size 20 and satisfies with the sample size 200.

2.4.15 Development of Operational Guidance

Some types of the stability failures in waves are more efficient to prevent during the operation rather than at the design stage. Parametric roll is a good example, as excluding parametric roll by the altering the lines may lead to a very energy inefficient ship. That is a reason why more attention is paid to calculation methods suited for development of operational guidance. Operational guidance and operational limitations are included in the SGISC and reflected in Interim Guidelines and Explanatory Notes.

Shigunov (2023a) focused on harmonized treatment of design and operation as an efficient way to provide the required safety level. The cited reference discussed criteria and standards as well as if operational measures can always be an acceptable way to ensure safety. Examples of application of operational measures were included.

Hashimoto et al. (2023) described a case study for the development of operational limitations concerning parametric roll. The limitations are based on significant wave height and are meant to be used as an aid for course selection.

Efficient application of operational guidance can be facilitated by real-time wave measurement. It is the focus of Yano et al. (2023), where a utilization of sensors is discussed, including wave radar, combined with measurements of roll motions with a gyroscope.

Levine et al. (2021, 2022, 2024) describe a method for development of adaptive operational guidance, expected to be suitable for autonomous as well as crewed vessels. The idea is to use fast volume-based simulation tool (Weems and Belenky, 2023) to generate operational guidance on-board as soon as the next weather forecast becomes available. To improve accuracy of prediction LSTM neural network, trained with an engineering level potential flow code is applied to the simulation outcome.

Among all ships, fishing vessels are the most vulnerable to stability failure. Not only being relatively small, compared to ocean waves, fishing vessels sometimes perform dangerous operation at sea and frequently change their loading conditions. Caamaño et al. (2023) compares two techniques for real time monitoring of natural frequency of a stern trawler, operating in irregular waves. The described system is capable to alert the crew if stability of a vessel becomes unacceptable.

González et al. (2023) describe an algorithm of GM monitoring using spectral analysis of the roll motions.

Howard et al. (2022) introduced a machine learning method to improve prediction of ship seakeeping statistics in rough, bimodal seas. A data-adaptive model was used to evaluate predicted ship motions in unidirectional waves with a bimodal spectrum. Data-adaptive LSTM neural networks were investigated as part of a multi-fidelity approach incorporating Large Amplitude Motion Program (LAMP), and a reduced-order model known as SimpleCode. LSTM networks were trained and tested with 3-DoF LAMP simulations as a target, and 3-DoF (heave, roll and pitch) Simple-Code simulations. LSTM networks were shown to improve the fidelity of SimpleCode seakeeping predictions relative to LAMP, while retaining the computational efficiency of a reduced-order model. Then the research group (Edwards et al., 2023) extended the LAMP and SimpleCode simulations with generation of 6-DoF motions, which provided improved accuracy as compared to previous simpler 3-DoF simulations.

2.4.16 Accident Investigation

Taguchi et al (2023) describe an experimental investigation of stability accidents with two Japanese fishing vessels with the objective to clarify the reason for the accidents. The first vessel, a purse seiner has capsized while anchored at sea after encountering two large waves. The second vessel, a stern trawler has capsized while sailing in head seas. Both cases involved flooding of a deck and internal spaces.

2.4.17 Neural networks

González et al. (2023a) explored the implementation of an Artificial Neural Networks (ANN) based system for real-time prediction of parametric roll in ships, focusing on its application in onboard stability guidance for small and medium-sized fishing vessels. The research utilized a 1.5 DoF nonlinear mathematical roll model to train the ANNs, aiming to provide a cost-effective alternative to extensive towing tank tests for system training. The ANN model demonstrated good performance in predicting parametric roll under specific conditions compared with the test data, highlighting the potential of machine learning approaches in enhancing maritime safety by enabling early detection and corrective actions against stability threats.

Silva and Maki (2022) proposed the CWG-CFD-LSTM framework, which combines the critical wave groups method (CWG), computational fluid dynamics (CFD), and LSTM neural networks to develop computationally efficient surrogate models. The CWG-CFD-LSTM framework can predict the 6-DoF temporal response of the vessel and recover the extreme statistics. Two modelling approaches are considered. A general model approach where one model is trained with all the speeds and headings and an ensemble model approach where multiple models are trained, each responsible for a single speed and heading combination. The developed neural network models with the general approach are capable of accurately representing the temporal response of the free-running DTMB 5415 in extreme waves and also recovering the extreme statistics of roll for different speeds and headings.

2.4.18 Direct Stability Assessment (DSA)

Wandji (2023) describes an analysis of several statistical estimates, relevant for stability assessment, such as mean-crossing rate, time to first event, time between events, maximum value over an interval, etc., to the results of numerical simulations of ship motions in waves. The focus was on the influence of nonlinearity, so the analysis was exercised on linear and nonlinear samples, the volume of which was quite large. Pearson chi-square test was utilized for more formal determination if the difference between the obtained results is significant. The results from seven sea states were close between three methods, but showed that failure rate and confidence intervals could be slightly different at higher sea conditions. Since the tests were made in ideal conditions or in beam waves, further study is necessary to use the data from various sea conditions.

Shigunov et al. (2022), Wandji et al. (2023, 2024) carried out a benchmark study for the three direct counting methods using the data which comply with Poisson processes assumptions and the true rate of events is known. As a result, all three approaches were able to correctly estimate the failure rate. The estimate of confidence intervals was considered to be correct when a percentage of successes was close to the accepted confidence probability.

Matsubara et al. (2023) utilized the critical wave method in a validation study for broaching and in long-crested and short-crested irregular waves. The examined critical wave method provided conservative estimates of the probability of a large heel due to broaching, with a much shorter computational time.

Weems et al. (2023a) further developed the multi-fidelity code, which employs the seaway-dependent diffraction and radiation coefficients to the hydrodynamic forces. They found the developed code has a limitation when compared with potential-flow simulation. Further study will be made to overcome the limitation.

2.4.19 Multihulls

It should be noted that SGISC have not been tried on multihulls. Papers related to multihulls can be found in other chapters of the reports.

2.5 The need for R&D for improving methods of model experiments and numerical modelling (TOR 1 E)

The book titled “Contemporary Ideas on Ship Stability – From Dynamics to Criteria” has been published by Springer (Spyrou K., Belenky V., Katayama T., Bačkalov I., Francescutto A., editors) as a part of their series “Fluids Mechanics and Application” (ISBN 978-3-031-16328-9). The book summarizes advancement in the field with selected papers from international stability workshops from 2013 through 2019; these selected papers were extended and updated to reflect state-of-the-art. It is the third book in the

Springer series focused on stability, following Neves et al. (2011) and Belenky et al. (2019). The first book, summarizing advances in stability field was published by Elsevier (Vassalos et al. 2000). Chapters of the book are given a brief review in the appropriate section of this report. The book opens with a comprehensive overview by the editor-in-chief Spyrou (2023), where contents of each of the 42 chapters is described within context of the state-of-the-art.

A virtual special issue of Ocean Engineering "Extreme Stochastic Dynamics of Ships" was published 2022-24. Publication of this special issue was inspired by long-term research program "A Probabilistic Procedure for Evaluating the Dynamic Stability and Capsizing of Naval Vessels" run by the US Office of Naval Research. Most important results of this program were published in the special issue along with other papers focused on extreme ship motions. Totally, the special issue contains 17 full-length research papers, relevant to this committee. A list of the papers at this special issue is available at https://www.sciencedirect.com/special-issue/100R65G877Z

The dynamic stability of ships is quite complicated due to the stochastic seaway, and thus stochastic approach is generally necessary. Since evaluating the stochastic response typically requires many simulations, R&D objecting to reduce the computation times has been one of the important issues.

Anastopoulos and Spyrou (2022, 2023b) used the stochastic wave group theory in order to extrapolate the significant wave height. They checked capsize of a ship in mild seas using the critical wave group. The analysis showed higher accuracy if the spectrum was narrow enough. The key finding is that IMO's current "extrapolation over wave height" formula is rather empirical since the theoretical background does not coincide with the suggested formula. Although the study only focused on the dead ship condition, their findings about reliability of IMO's current criteria need to be considered.

Wandji (2022) applied two extrapolation techniques to dynamic stability events: extrapolation using a fitted distribution and extrapolation over wave height. They have seen that these extrapolation methods are derived in closed form for linear processes and can be used successfully with some assumptions for nonlinear processes.

Silva and Maki (2022) suggested combining the critical wave groups method, CFD, and LSTM neural networks in order to develop computationally efficient surrogate models and to recover the extreme statistics. When sufficient training data are prepared, both the general model and the ensemble model are comparable. Their further work would be focused on developing generalized condition-agnostic frameworks for evaluating extreme events.

Silva and Maki (2023a) extended the critical wave group method to a free-running model. The extreme events were observed using the natural initial condition methodology of embedding deterministic wave groups into random irregular wave trains. The necessity of further study is stated which performs the statistical validation by combining the critical wave groups method with a numerical hydrodynamic simulation tool.

Maruyama et al. (2022, 2022a) applied linear filter and moment equations to the parametric rolling of ships in irregular waves. The probability density function were approximated using the coefficients obtained from moment equations, which showed reasonable agreement with those from Monte Carlo simulation. Maki et al., (2023) used the stochastic approach to the various kinds of ship hydrodynamics, such as wind and wave generation, stability of parametric rolling, method of moment equation and maneuvering stability. Since the various theories are available for stochastic processes, further study will be focused on finding the appropriate theory for each hydrodynamic problem.

Explanatory Notes of SGISC currently employ three direct-counting procedures. These approaches are based on the estimation of failure rate from sample data using exponential distribution, statistical frequency of failures and binomial distribution.

Brown and Pipiras (2023) consider the uncertainty of an extreme value estimated from the dataset, comprised from the sources of different fidelity, e.g. model test and numerical simulation, or potential flow simulations and ordinary differential equation, i.e. multifidelity approach. The proposed method is based on multi-dimensional extreme value distribution.

Hydrodynamic prediction coded based on potential flow or RANS have matured, but are still too expensive to directly apply to many extreme response problems. Weems et al. (2022) pointed out that the formulation of two general principles could be applied to the development of reduced-order models: schematization of hydrostatic and FK forces; and reducing dimensionality of the space of random parameters through regression or/and active sampling. In addition, uncertainty quantification is an important tool to check the confidence of reduced order models.

Lu and Gu (2023) introduced a unified mathematical model in order to simulate the surf-riding/broaching and pure loss of stability in stern quartering waves. Their model was able to predict the surf-riding/broaching and pure loss of stability in stern quartering waves when rudder exposure and wave-excited surging force are properly taken into account. As a future work, they found the necessity to identify the several parameters in the equations.

Dostal et al. (2023) considers the first passage problem for nonlinear ship dynamics. The first passage problem is about finding a distribution of time to reach a certain (usually large) value. The solution of this problem is not trivial if self-dependence of the excitation is preserved. The proposed approach is based on roll energy of the ship that can be expressed explicitly. The paper also incorporates an expansion of Grim effective wave for the case of short-crested seas.

Matsuda et al. (2023) presents experimental study to find out if a typical design of Japanese and European fishing vessels make a difference in vulnerability to several capsizing scenarios. It was reported that while the European design is less vulnerable to usual instability, a dangerous subharmonic roll behavior has been detected for this design.

Koromila et al. (2023) describes experiments on cargo liquefaction with “shaking table”. The liquefaction of a mass cargo is major risk factor for stability of bulk carriers. The objective of the study is to gain insight on transformation of wet granular cargo during liquefaction. The tested materials were sand and olive pomace with different moisture contents.

Rodríguez et al. (2023) studies behavior of mono-column structures in regular and irregular waves with a model experiment. Parametric resonance was observed in roll and pitch, caused by energy transfer between different degrees of freedom. It was also found that the mooring system configuration has significant influence on possibility of dynamic stability failure.

van Walree and Thomas (2023) compare results of numerical simulation and experimental study on dynamics of a rigid-hull inflatable boat (RHIB) in heavy seas. The objective is to see if existing simulation tools can handle a body of such unconventional form and, if positive, what are the limitations. In the other navy-related work, van Walree and Sgarioto (2023) consider landing craft motions as well as impact loads and water ingress in heavy seas. Numerical simulations are compared with experimental results.

Kim et al. (2023) considers a regression-based approximation of diffraction and radiation forces to be used in reduced-order models of ship motion. The regression is performed on a series of runs of a potential flow simulation tool: motions without wave for radiation and wave without motion for diffraction.

Tsoumpelis and Spyrou (2023) examine the self-repeating effect in the Longuett-Higgins model of irregular wave from the time series perspective. An algorithm for capturing repeating portions of the time series is proposed. The cited reference also contains important insights into the mechanism of self-repeating effect, explaining why the repetitions usually are not exact even at uniform frequency discretization and the condition for exact repetition. The self-repeating effect is also addressed by Umeda et al. (2023b).

Glotzer et al. (2024) provides mathematically rigorous consideration of dynamical systems with piecewise linear restoring force, deriving distributions of critical response (leading to capsizing). A Duffing oscillator is also examined. The cited reference is essentially a theoretical background for the split-time method (Belenky et al. 2024), included in ITTC recommended procedure 7.5-02-07-04.6.

Yu et al. (2023) adopted the time-domain method to study and analyzed the occurrence of non-linear harmonic rolling phenomenon of ultra-large container ship and subsequent motion behaviors.

3. REVIEW ITTC RECOMMENDED PROCEDURES (TOR 2)

Review ITTC Recommended Procedures relevant to ocean engineering, including CFD procedures.

3.1 Requirements and update (TOR 2 A)

Identify any requirements for changes in the light of current practice, and, if approved by the Advisory Council, update them.

Procedure 7.5-02-01-01 (Guide to the Expression of Uncertainty in Experimental Hydrodynamics) was reviewed and no change is proposed by the committee.

Procedure 7.5-02-01-07 (Guideline to Practical Implementation of Uncertainty Analysis) was reviewed and no change is proposed by the committee.

Procedure 7.5-02-07-02.3 (Experiments on Rarely Occurring Events) was reviewed and no change is proposed by the committee.

Procedure 7.5-02-01-08 (Significant Amplitude and Confidence Intervals for Stochastic Processes) was reviewed, and the committee proposes to update the evaluation of variance of the mean and variance estimate, using new information recently published by Glotzer et al. (2023).

Procedure 7.5-02-05-07 (Dynamic Instability Tests) was reviewed and found no changes necessary at this moment.

Procedure 7.5-03-01-01 (Uncertainty Analysis in CFD Verification and Validation, methodology and Procedures) was reviewed and no change is proposed by the committee.

Procedure 7.5-03-02-03 (Practical Guidelines for ship CFD application) was reviewed and no change is proposed by the committee.

Procedure 7.5-02-07-04.1 (Model Tests on Intact Stability) was reviewed. Three references are being added to the procedure. For instance, if wind forces need to be included in the model tests, the projected areas need to be corrected (Umeda et al., 2023). Furthermore, as shown by Hashimoto et al. (2019), roll decay tests performed carefully by hand can be sufficiently accurate. Finally, standard uncertainty analysis can be applied to all measured basic quantities and motions. Capsizing could be a different situation due to the extreme phenomenon involved. However, a properly designed experimental system is reproducible for strongly nonlinear phenomena as reported in Matsuda et al. (2016).

Procedure 7.5-02-07-04.2 (Model Tests on Damage Stability in Waves) was reviewed and no change is proposed by the committee.

Procedure 7.5-02-07-04.3 (predicting the Occurrence and Magnitude of Parametric Rolling) was reviewed, and the committee updated it with the most recent references, primarily from publications of the SGISC, i.e. Interim Guidelines MSC.1/Circ.1627, Explanatory Notes as well as recently issued documents of classification societies: BV (2019) and ClassNK (2023).

Procedure 7.5-02-07-04.4 (Simulation of Capsize Behaviour of Damaged Ships in Irregular Beam Seas) was reviewed and the latest international benchmark study on simulation of flooding and motions of damaged vessels was added, Ruponen et al. (2022, 2022a). New sections on real time flooding risk evaluation and machine learning/Artificial Intelligence methodologies have been added.

Procedure 7.5-02-07-04.5 (Estimation of Roll Damping) was reviewed and some equations were updated. Ikeda's formulae were review following recent work from Katayama et al. (2021, 2022, 2022a, 2023) as already mentioned in paragraph 2.4.12.

Procedure 7.5-02-07-04.6 (Extrapolation for Direct Stability Assessment in Waves) was reviewed and updated. The original procedure described the application of envelope peak-over-threshold (EPOT) for estimation of rate of roll motions failures when none of these failures were observed in the output of numerical simulation and the split-time / motion perturbation method (MPM) to estimate rate of capsizing events.

Direct Stability Assessment (DSA) as a part of the SGISC is described in section 3 of the Interim Guidelines, whereas stability failure is defined as exceedance of 40° in the paragraph 3.2.1.1 of MSC.1/Circ.1627. Provision of application of EPOT and MPM extrapolation procedures is included in subsection 3.5.5.4 of MSC.1/Circ.1627. Description of these procedures can be found in sections 5.3 through 5.5 of Appendix 4 of the Explanatory Notes.

Description of DSA in the Interim Guidelines and Explanatory Notes includes several extrapolation methods, not covered in the procedure 7.5-02-07-04.6: extrapolation over wave height, critical wave method and linear superposition method for excessive accelerations. Publication of the Explanatory Notes in 2023 creates a background for relevant ITTC recommended procedures to be updated.

To harmonize the procedure 7.5-02-07-04.6 with the Interim Guidelines and Explanatory Notes, the Committee proposes the following updates:

- Amend the description of MPM for extrapolation for stability failure as defined in the Interim Guidelines, i.e. for exceedance of large roll angle
- Add the description of extrapolation over wave height
- Add an example where all three methods are applied to the same input data
- Update the references with recently published IMO documents and relevant technical papers.

Procedure 7.5-02-07-04.7 (Inclining Tests) was reviewed and updated. More detailed description of wind effects and uncertainty analysis have been added. Procedure was update, including some effect of wind gust. The effect of wind fluctuations during an IT were investigated from Leguen et al (2023). For a given accuracy chosen by the surveyor, a maximum value of the mean wind is calculated. In the other direction, estimation of uncertainty of KG can be estimated by taking into account gust wind velocity measurement, see Figure 30.

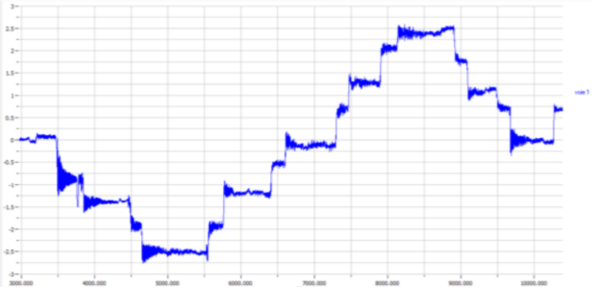

Figure 30: Heel measurement during an IT (3 hours), with gust wind effect visible, from Leguen et al (2023).

Procedure 7.5-02-01-09 (Avoiding Self-Repeating Effect in Time-Domain Numerical Simulation of Ship Motions) was submitted. The new procedure formulates a process for verification of absence of self-repetition effect and statistical validity of irregular waves and ship motions in a numerical simulation. More detailed descriptions of the changes are summarized in section 5.1 of this report.

Procedure 7.5-02-07-04.8 (Computational procedure for instantaneous GZ curve during time-domain numerical simulation in irregular waves) was submitted. The procedure describes the role that the instantaneous GZ curve and some calculation examples are included. It is the objective of TOR 4-A, detailed descriptions of this procedure are summarized in section 5.1 of this report.

Procedure 7.5-02-01-10 (Estimation of Frequency of Random Events) was submitted. The procedure addresses post processing of numerical simulation of roll motions or lateral accelerations. The draft procedure covers three methods of the rate estimations, and these methods offer different ways of addressing the independence of stability failures – the critical requirement of the Poisson model. It is the objective of TOR 4-B, detailed descriptions of this procedure are summarized in section 5.2 of this report.

Procedure 7.5-02-01-11 (Statistical Validation of Extrapolation Methods for Time Domain Numerical Simulation of Ship Motions) was submitted. This procedure describes the process for the validation of extrapolation methods used for direct stability assessment for the stability failure modes described in section 3.5.6 MSC.1/Circ. 1627. It is the objective of TOR 4-C, detailed descriptions of this procedure are summarized in section 0 this report.

3.2 Identify new procedures (TOR 2 B)

The Interim Guidelines on the Second Generation Intact Stability Criteria (MSC.1/Circ.1627) include provision for direct stability assessment (DSA). The intention of DSA is to "employ latest technology while being sufficiently practical to be uniformly accepted and applied using currently available infrastructure" (paragraph 3.1.3 of the Interim Guidelines). As ITTC members are a vital part of this infrastructure, developing ITTC recommended procedures, detailing and enhancing the Explanatory Notes to the Interim Guidelines (MSC.1/Circ.1652) is appropriate and beneficial for ITTC as well as Maritime Community in whole. ITTC has already developed 4 procedures in support of DSA, while another 4 procedures are cited in the Interim Guidelines and Explanatory Notes; three other ITTC-recommended procedures may be relevant for DSA, as described in IMO document SDC 10/INF.7.

The Stability in Waves Committee, in fulfilment of the item 2B of the Terms of References, identifies the following two procedures to be developed in support of Direct Stability Assessment within the framework of the second generation intact stability criteria.

3.2.1 Evaluation of Dynamical Characteristics of a Ship

The Interim Guidelines includes requirements for qualitative validation (section 3.4.2). The Explanatory Notes contains examples for several items, listed in the Interim Guidelines, specifically:

1. Backbone curve (section 3.4.2 and 2.1 of Appendix 4),
2. Response curve (section 2.2 of Appendix 4),
3. Change of stability in waves (section 2.3 of Appendix 4),
4. Principal parametric roll resonance (section 2.4 of Appendix 4).

While items 3 and 4 are already covered by ITTC recommended procedures 7.5-02-07-04.8 and 7.5-02-07-04.3, respectively, development of ITTC procedure(s) for items 1 and 2 is needed.

Other qualitative validation requirements, included in section 3.4.2 of the Interim Guidelines, but not reflected in the Explanatory Notes are:

5. Surf-riding equilibrium,
6. Heel during turn,
7. Turn in calm water,
8. Straight captive run in stern quartering waves,
9. Heel caused by drift and wind.

A detail step-by-step procedure, covering items 1, 2 and 5 through 9, will help with the qualitative validation of ship motion time-domain simulation software for trial application of the second generation intact stability criteria.

The new procedure is to include description of seven aspects of quantitative validation as indicated above. Each of these techniques may be outlined as follows:

- Objective and scope of application,
- Data requirements and preparation,
- Processing and post-processing,
- Analysis and adjudication of results.

The development effort is expected to be moderate to large.

3.2.2 Extrapolation Methods, not Covered by ITTC Recommended Procedures

A stability failure of an intact ship is a rare event even in high sea states. Therefore, there is a motivation to estimate the probability of stability failure from a limited sample of time histories that does not necessarily include observations of these stability failures. This objective can be achieved by application of a statistical extrapolation. Section 3.5.5 of the Interim Guidelines contains general provisions for application statistical extrapolation methods.

Paragraph 3.5.5.1 requires that a statistical extrapolation method has to be successfully validated in order to be applied for direct stability assessment. Details on statistical validation of specific extrapolation methods are available in sections 5.1.2 and 5.4.4 of Appendix 4 to the Explanatory Notes. Statistical validation of extrapolation is covered by ITTC Recommended Procedure 7.5-02-01-11.

The Interim Guidelines mentions four extrapolation methods:

1. Extrapolation over wave height in section 3.5.5.3,
2. Envelope peak-over-threshold (EPOT) in paragraph 3.5.5.4.1.1,
3. Split-time/motion perturbation method (MPM) in paragraph 3.5.5.4.1.2,
4. Critical wave method in in paragraph 3.5.5.4.1.3.

Additionally, section 5.6 of the Appendix 4 to the Explanatory Notes contains a description of

5. Linear superposition method for excessive accelerations failure mode.

The extrapolation methods 1, 2, and 3 are described in details in ITTC Recommended Procedure 7.5-02-07-04.6. This procedure originally was approved by 29th ITTC and with the description of extrapolation method 2 and 3 only. The revision 01 is presented to 30th ITTC includes method 1 as well. The next logical step would be developing procedures for application of statistical extrapolation methods 4 and 5.

It is proposed that the step-by-step descriptions of these extrapolation methods to follow the structure of 7.5-02-07-04.6, in particular:

- Data requirement;
- Data preparation;
- Statistical processing;
- Assessment of uncertainty.

It may make sense to include description of these two methods into revision 02 of ITTC Recommended Procedure 7.5-02-07-04.6. However, as the effort is expected to be moderate to large, it should be treated as a new development.

Some part of the proposed work need strong relationships with other ITTC committees, as manoeuvring committee for points 6 and 7 of the first suggested procedures. The propose contain with be consolidated in a fewer ITTC procedures.

4. UPDATE ITTC PROCEDURE 7.5-02-01-08, (TOR 3)

Item 3 of the Terms of References for the Stability in Waves Committee contains a task to update ITTC Procedure 7.5-02-01-08, titled “Single Significant Amplitude and Confidence

Intervals for Stochastic Processes" when new information becomes available. The new information became available (Glotzer et al., 2023) and the procedure was updated for the evaluation of variance of the mean and variance estimate.

The objective of the procedure 7.5-02-01-08 is to formulate the process for characterizing the uncertainty for data resulting from a stochastic process, such as ship motion data collected at either numerical simulation, model test or full scale trials.

A particular issue to be addressed is equation (4.1) (which appeared as equation (9) of the Revision 00 of the procedure). It defines the number of points of an estimate of auto-covariance function to be used when calculating variances of estimates of mean and variance of a stochastic process:

$$0.5\sqrt{N} \leq M \leq 2\sqrt{N}, \tag{4.1}$$

where N is the total number of points in a record, while M is a number of points of the autocovariance function estimate.

Essentially setting M meant to "cut" the autocovariance estimate where the self-dependence is still meaningful and to remove "statistical noise". An error causing this statistical noise is inevitable when estimating autocovariance function from time series. It is caused by natural decrease of available data when time lag increases. Manifestation of this error can be seen in Figure 31. As the mean value of this error is zero, averaging of the autocovariance estimate over several records quickly remove this noise, see Figure 32.

Equation (4.1) was based on Priestley (1981); Kiefer and Vogelsgang (2002); Brockwell and Davis (2006); and Sun (2014) as well as Crowson (1963, 1963a). However, practical application of this equation for long time histories with relatively small time increments, resulted in visually unreasonable choice of the cut-off point M.

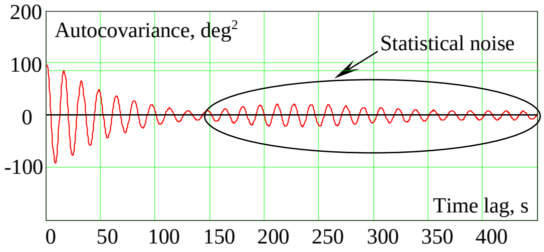

Figure 31: Autocovariance function (first 7.5 min) estimated on a single 30 min record

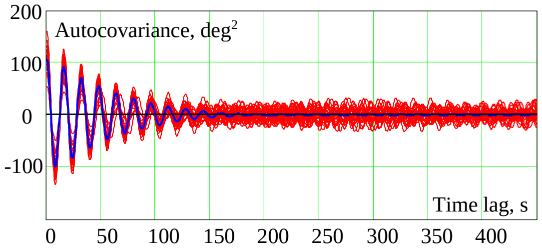

Figure 32: Estimate of autocovariance function averaged over several records (blue). Record estimates are shown in red.

To resolve the issue an optimization scheme by Lu and Park (2019) was considered. However, it was found that the approximate time to reach independence, found with an envelope of the autocovariance estimate, see Figure 33, produced similar results.

The approximate time to reach independence or decorrelation time is found when an envelope of the autocorrelation function estimate (autocovariance normalized by its first term) crosses the level of significance (paragraph 3.7.18 of Annex 4 to the Explanatory Notes, suggests using the value of auto-correlation of 0.05 to determine the limits of valid duration of a record). If the envelope never reaches the level of significance, the decorrelation time is ad hoc determined with the "minimum of the envelope". This minimum is found as an average between the first local minimum and the lowest point of the envelope observed. More details are available from Glotzer et al. (2023).

Besides the resolution for the cut-off point, there were several other updates to the procedure. It was restructured to make it easier to understand and apply. The procedure has three major sections:

- Uncertainty of mean and variance estimate of a time series,
- Uncertainty of single significant amplitude,
- Construction of confidence interval.

The two first major sections are focused on assessment of uncertainty of statistical estimates in terms of their variance. As all the considered statistical estimates (i.e. mean, variance and single significant amplitude) are assumed normally distributed, their variance characterizes their distribution completely. As these estimates are unbiased or their bias is small, they equal to its own mean values. Once the distribution of an estimate is characterized, confidence interval is ready to be constructed. The third major section is focused on the confidence interval.

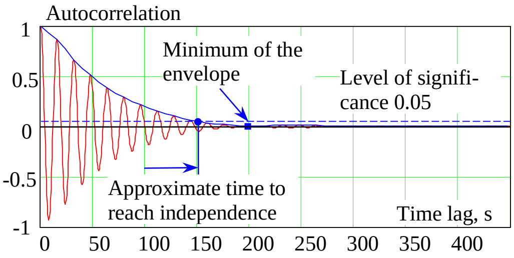

Figure 33: Determination of approximate time to reach independence.

Additionally, the procedure includes a new technique for construction of confidence interval, based on self-normalization algorithm. This technique is simple to implement as it does not require explicit account for autocorrelation of the data. Descriptions and comparisons are available from Pipiras et al. (2018) and Glotzer et al. (2023).

5. NEW ITTC PROCEDURES (TOR 4)

The Item 4 of the Terms of References directs the Stability in Waves Committee to develop new ITTC recommended procedures in support of direct stability assessment within 2nd generation IMO intact stability criteria. As it was already mentioned earlier in this Report, the Interim Guidelines on the Second Generation Intact Stability Criteria in MSC.1/Circ. 1627 includes a provision for application of direct stability assessment (DSA). The ultimate intention of DSA is to use the latest numerical simulation technology to ensure both exiting and future fleet has sufficient stability in waves. Application of these new technologies are especially important for unconventional vessels where design and operation experience is either insufficient or does not exist. ITTC member-organizations have an important role in support the innovation in maritime filed by providing DSA services.

ITTC-recommended procedures in support of direct stability assessment are meant to complement the Explanatory Notes for the Interim Guidelines. The ITTC procedures are specifically geared towards capabilities and skill sets, available to ITTC member-organizations that are expected to participate in trial application of the DSA.

Another benefit of ITTC involvement is an ability of prompt response. The ITTC-recommended procedures may be updated at each Conference i.e., every three years. That is a perfect opportunity for documenting DSA application experience. These updates may serve as a compliment to the submissions to IMO Subcommittee on Design and Construction (SDC) under the agenda item “any other business”.

In fulfilment of the Task 4 of the Terms of References, the Stability in Waves Committee has developed three draft procedures:

A) Avoiding self-repeating effect in time-domain numerical simulation of ships motions (QSG suggested number 7.5-02-01-09)
B) Estimation of Frequency of Random Events by Direct Counting (QSG suggested number 7.5-02-01-10)
C) Statistical Validation of Extrapolation Methods for Time Domain Numerical Simulation of Ship Motions (QSG suggested number 7.5-02-01-11)

More information on these procedures is available below.

5.1 Avoiding self-repeating effect in time-domain numerical simulation of ships motions (TOR 4 A)

The new procedure is made to formulate a process for verification of absence of self-repetition effect and statistical validity of irregular waves in a numerical simulation. The procedure targets on providing specific guidelines to check the self-repeating effect in the direct stability assessment defined in section 3.3.2.1 of Interim Guidelines and in section 3.3.2.1 of Explanatory Notes.

The superposition of *N* regular wave components is commonly used to construct time series of irregular wave elevations, ζ_W:

$$\zeta_W(t) = \sum_{i=1}^{N} A_i \cos(\omega_i t + \varphi_i) \qquad (4.2)$$

φ_i is i-th phase shift component, and it is uniformly distributed in [0, 2π]. The i-th component of wave amplitude, Ai, is determined from the segment of wave spectrum, $S(\omega_i)$, and selected wave frequency interval, $\Delta\omega_i$, and also directional probability if short-crested sea is assumed. The directional probability distribution function $D(\mu_i)$ for discretized heading angle μ_i has various form, and they can be found in ITTC Guideline 7.5-02 07-01.1.

For the purposes of detection of the self-repeating effect in wave model, the autocorrelation function *r* needs to be calculated from the spectrum using the same frequency discretization (constant $\Delta\omega_i$) as being planned to use for wave elevation reconstruction for ship motion simulations. The numerical integration has to be carried out with rectangles:

$$r(\tau_j) = V^{-1} \sum_{i=1}^{N} S(\omega_i) \cos(\omega_i \tau_j) \qquad (4.3)$$

S is e the spectrum, *V* is the variance of wave elevations respectively. The auto-correlation function *r* is the normalized version of auto-covariance function.

If the self-repeating effect does not present in the wave elevation time series of duration $T=\tau_{max}$ the auto-correlation function is “clean”, and does not show any increase after initial decay, as shown in Figure 34. If the self-repeating effect is present, its appearance may be different depending on the frequency discretization. If the frequencies distributed uniformly, i.e. frequency increment $\Delta\omega_i$ is constant, the presence of self-repeating effect is observed as “spikes” in the auto-correlation plot as shown in Figure 35. If a non-uniformed frequency distribution is applied (i.e. the frequency increment $\Delta\omega_i$ varies), the presence of the self-repeating effect is observed as a series of increasing oscillations, as like in the Figure 36.

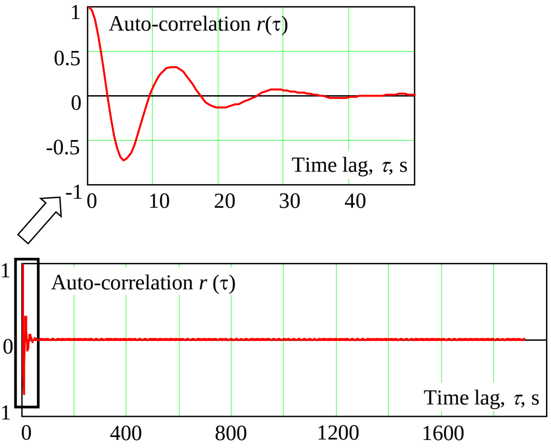

Figure 34: Auto-correlation function in absence of self-repeating effect.

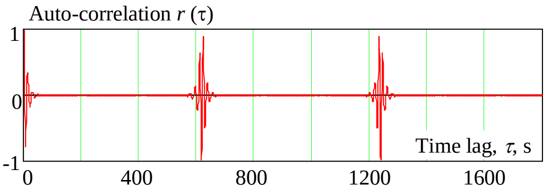

Figure 35: Auto-correlation function showing presence of self-repeating effect for uniformed discretization or constant frequency increment

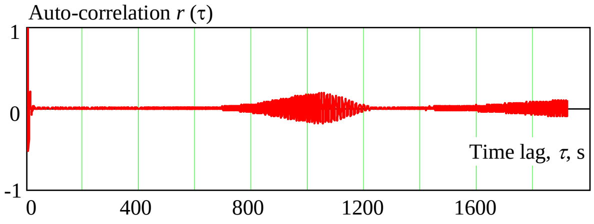

Figure 36: Auto-correlation function showing presence of self-repeating effect for non-uniformed discretization or variable frequency increment

Due to its nature the self-repeating effect will revel itself sooner or later. If the frequencies are selected uniformly, the beginning of the “spike” of the auto-correlation function limits valid duration of a record. For the case of non-uniformed frequency distribution, an envelope of auto-correlation function is useful to find when the of signal starts to increase. The envelope is constructed by connecting absolute values of the peaks of auto-correlation function. Paragraph 3.7.18 of Annex 4 to the Explanatory Notes suggests using the value of auto-correlation of 0.05 to determine limits valid duration of a record.

If the auto-correlation function begins to increase outside of this interval, then the model shows dependence where the real stochastic process should not have it. This limitation of validity is the essence of self-repeating effect leading to partial self-repetition of the constructed wave elevation time series (Belenky, 2011; Tsoumpelis and Spyrou 2023).

The reason of the self-repeating effect is rooted in an oscillatory nature of the integrand $s(\omega_i)\cos(\omega_i \tau)$. The appendix A of the developed procedure explains the nature of the self-repeating effect.

5.2 Procedure of Estimation of Frequency of Random Events by Direct Counting (TOR 4 B)

Item 4 of the Terms of References for the Stability in Waves Committee contains a task to develop new ITTC recommended procedures in support of direct stability assessment (DSA) with the SGISC. In particular, the task calls for devotement of the procedure for Estimation of Frequency of Random Events by Direct Counting.

The DSA is intended to employ the latest technology in time-domain numerical simulation of ship motion. The output of the time-domain simulation is a time series, from which stability failures are detected and counted. The developed procedure of Estimation of Frequency of Random Events by Direct Counting provides a detailed guidance for these calculations.

There are three approaches to DSA, described in the Interim Guidelines: full probabilistic assessment (section 3.5.3.2 of the Interim Guidelines), assessment in design situation using probabilistic criteria (section 3.5.3.3 of the Interim Guidelines), and assessment in design situation using deterministic criteria (section 3.5.3.4 of the Interim Guidelines). The direct counting is applicable to the first two approaches to DSA as the output of the assessment in design situation using deterministic criteria is deterministic, as its name suggests.

The probabilistic criterion, used for DSA, considers time of exposure i.e. accounts for dependence between time spent at severe see conditions and probability of stability failure. Poisson flow of random events is used as a mathematic apparatus to relate the probability and the time of exposure. The Poisson flow application allows computing probability of at least one failure P during any given time interval T as:

$$P = 1 - \exp(-rT) \tag{5.1}$$

where r is rate of failure that is used as a probabilistic criterion in DSA. It is essentially a probability of stability failure per unit of time. Theoretical background on relationship between the time and the probability through application of the Poisson flow is available from section 2 of SDC-8/INF.2 (IMO, 2021).

One of the principle requirements for application of Poisson flow is that the random events must be independent. At the same time, due to self-dependence of ship motions, large roll angles or large values of lateral accelerations do appear in groups, referred in statistics as “clusters”. In order to use the Poisson flow, only one event per cluster can be counted, thus clusters need to be identified and each cluster needs to be substituted by a single event. This process is commonly referred as “declusterization”.

The Explanatory Notes provides three different techniques for direct counting in Section 3 of Appendix 4 to MSC. 1/Circ.1652 (IMO 2023).

These three techniques differ on their approach to declusterization, using:

- Exponential distribution of the time before the first event occurs; a simulation runs before the first failure occurs, time before-the-first event is recorded and averaged; the reciprocal of the average time before the event is used as an estimate of rate of failures;
- Estimation of probability of failure over the duration of a simulation record; the rate of failures is estimated from the equation above;
- Binomial distribution of the number of independent failures encountered; declusterization is performed with decorrelation time using an estimate of autocorrelation function, following section 3.8 of Appendix 4 to the Explanatory Notes as well as the ITTC recommended procedure 7.5-02-01-08.

Benchmarking of all three techniques have shown statistically identical results (Shigunov et al. 2022; Wandji et al. 2023). Thus, the choice on, which technique to use, depends on which one fits better to simulation technology, used at a particular organization. The developed recommended procedure contains step-by-step guidance on all three techniques as well as on constructing confidence interval for the estimates. An example of application of all three techniques is included for the same ship configuration, demonstrating equivalency of all the techniques. The test configuration is ITTC-A1 (Umeda et al. 2000), 150 m long containership.

Theoretical background of all three techniques, including formal study of properties of the estimators is available from Wandji et al. (2024). The IMO sub-committee on Ship Design and Construction (SDC) has been informed on the development of this recommended procedure by the way of an information paper SDC 10/INF.7 submitted by ITTC: (IMO 2023).

Statistical Validation of Extrapolation Methods for Time Domain Numerical Simulation of Ship Motions (TOR 4 C)

Procedure of Estimation of Frequency of Random Events by Direct Counting.

Procedure 7.5-02-01-11 Statistical Validation of Extrapolation Methods for Time Domain Numerical Simulation of Ship Motions (TOR 4 C).

The purpose of the procedure was to describe a process for the validation of extrapolation methods used for direct stability assessment for the stability failure modes described in section 3.5.6 MSC.1/Circ. 1627. The validation is considered successful if an extrapolation method (including those described in the ITTC Recommended Procedure 7.5-02-07-04.6) captures a “true” value. The percentage of these “successes” should be about accepted confidence probability.

The formulation of the procedure and the acceptance criteria for validation are based on the work of Smith (2019), i.e., the three-tier validation: single extrapolation, single condition and multiple conditions. The validation of the extrapolation is assessed by means of the confidence intervals of the “true” and the “extrapolated estimate. For the tier 1 validation, a single extrapolation is considered as a Bernoulli trial where success (overlap of confidence intervals) is attributed 1.0 and failure (no overlap of the confidence intervals) is given 0.0. The second tier (validation of a single condition with, for instance, 50 extrapolations) is computed through binomial quantiles, where 0.88 was suggested as the standard for passing rate (as in the IMO Interim Guidelines). Finally, the tier 3 validation (multiple conditions), which should account for different ship speeds, relative wave headings and sea states, accepts/rejects an extrapolation method or define limitations for it, for a particular specific intended use. For the tier 3 validation, an assumption allowance is suggested to be introduced in the lower limit of the tier 2 criterion. Based on data from Campbell et al. (2023), a numerical example of partial validation of EPOT extrapolation method has been provided in the appendix A of the procedure.

6. NEW PROCEDURE FOR INSTANTANEOUS GZ (TOR 5)

Historical Background

The roll righting arm (GZ) curve in waves is an important factor in the evolution of ship`s changing stability in waves. For more than a century, naval architects have been aware of the phenomenon of transverse stability change in longitudinal waves (Pollard and Dudebout, 1892). Methods for calculating the change in stability in waves are not considered as a new development by any means. Paulling (1961) proposed a quasi-static approach for accounting for pressure changes while a wave passes a ship. Boroday (1967) developed a method for theoretically predicting the statistical characteristics of restoring moment in irregular waves, taking into account Froude-Krylov pressures

The roll restoring moment is made up of two parts. The nonlinear Froude-Krylov component (GZ_{FK}) is calculated by integrating the wave pressure all the way to the wave surface. The other component is the hydrodynamic effects caused by the radiation and diffraction component (GZ_{RD}).

It is widely agreed that the Froude–Krylov assumption can explain the wave influence on roll restoring moment when assessing roll restoring arm variation in waves. However, a study Hashimoto and Umeda (2004), that include captive model experiments, show that Froude–Krylov assumption may overestimate the magnitude of GZ curve. An accuracy of the instantaneous GZ may be critical for predicting roll response (Vidic-Perunovic and Jensen, 2009). Thus, it make sense to develop more detailed and realistic mathematical model for predicting roll restoring moment.

So far, no consensus has been reached about the contribution of GZ_{RD}. This issue is still unresolved and requires additional experimental and numerical research. In terms of the consequences of GZ_{RD}, certain studies have shown that when the dynamic component is considered, prediction accuracy improves (Umeda et al., 2005; Hashimoto et al., 2007; Lu, et al., 2017). The computation of roll restoring arm variation in these studies is based on a strip theory under the linear and nonlinear assumption of GZ_{RD} with reference to roll angles. The roll restoring moment is particularly crucial when the rolling angle is relatively big at high incident wave steepness, according to a number of research done in the past, using the CFD approach (Sadat-Hosseini et al. 2010; Ma et al., 2018).

The CFD approach, however, makes it exceedingly challenging to discriminate between the effects of various components. The rules of roll restoring moment fluctuation in waves was investigated using a three-dimensional hybrid time domain panel method by Bu et al. (2019, 2019a). By taking into account the radiation and diffraction moments based on the body-exact condition, the nonlinear characteristics of roll restoring arm are studied for varied constant heeling angle, wave amplitudes and ship forward speeds. The results of the studies demonstrate that, particularly at high speeds, the component brought on by radiation and diffraction moments may be important in head or oblique waves. It was also found that the time history of *GZ* curve clearly exhibits the multi-frequency superposition phenomena. Just twice as often as the first resonance frequency, the second peak mostly results from nonlinear radiation and diffraction moment.

Hashimoto and Umeda (2004) found that the lift effect generated by a heeled hull due to asymmetry may have an influence on roll restoring in high speed. Cited research has been performed for a fishing vessel. Studies by Hashimoto and Umeda (2010), Gu et al. (2014), studying influence of different combinations of degrees of freedom, concluded that at least the coupled heave-roll-pitch model should be used for calculations of GZ curve in waves. Belenky and Weems (2008) describe calculation of variation of GZ curve during time-domain simulation with Large Amplitude Motion Program (LAMP, see Shin et al. 2003). That calculations were preformed with 3 DoF (heave-roll-pitch) and included diffraction and radiation forces computed over average waterplane.

Physical Background and Motivation

For ships with significant variation of a shape of the waterplane (such as flared bow or transom and buttock-flow stern), the change of GZ in waves can be particularly noticeable. The waterplane area has a substantial effect on ship stability, which is well known from ship hydrostatic. When the waterplane area is reduced, so is the GZ curve (see Figure 37). The change of stability in waves, is the physical basis for the stability failure modes parametric rolling and pure loss of stability, see, e.g. Appendix 1 of Explanatory Notes.

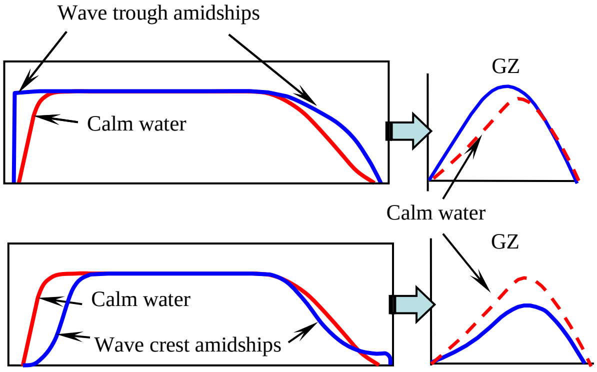

Figure 37: Stability, represented by righting level curves, corresponding to waterplane changed with the midship located on the wave trough (top) and the wave crest (bottom) (Appendix 1 of MSC.1/Circ.1652)

Large roll excursions may be better understood if evolution of the shape of the instantaneous GZ curve in irregular waves is known. Example of application of this analysis can be found in Spyrou et al (2014).

Calculation Procedure

In general, stability in waves is evaluated in the same way as it is done in calm seas. A vessel is rotated (heeled) about its longitudinal axis; the pressure on the hull surface is integrated to get the restoring forces and moments acting on the ship. The uncompensated moment relative to the longitudinal axis is used to derive a restoring arm that represents the value of the GZ curve for the rotation (heel) angle.

Most of commercially available hydrostatic programs are capable to compute the restoring arm as a quasi-static wave-pass problem, so only the variation in the Froude-Krylov and hydrostatic forces is evaluated. To perform the complete analysis similar to described above, actual dynamics of the ship in wave needs to be considered: i.e. the ship's hydrodynamic forces (including radiation, diffraction, influence of forward speed, appendages, etc. need to be included. However, Belenky and Weems (2008) have assumed these hydrodynamic forces do not to change with heel angle.

In the righting arm calculation, the heel rotation disturbs the ship's static or dynamic equilibrium in pitch and heave – in other words, the heave force and pitch moment also change. These changes may influence roll moment and need to be excluded. To exclude the pitch and heave influence, balancing is performed relative to instantaneous forces and moments acting on the ship. This is a direct result of application of the d'Alambert principle, as the instantaneous attitude in waves is a result of action of inertia forces and moments.

It makes sense to perform the instantaneous curve calculation in irregular waves in conjunction with time-domain numerical simulation for a preselected interval of time. The calculation also can be incorporated into a post-processing routine. The main steps of the calculations are listed below:

1. The ship is heeled through a range of angles relative to its instantaneous position.
2. At each heel angle, forces and moments acting on the ship are computed for the heeled position.
3. The ship's heave position and pitch angle, expressed relative to a global coordinate

system, are iteratively adjusted until the dynamic equilibrium in these degrees of freedom is achieved

4. The net roll moment defines the instantaneous GZ value corresponding to current heel angle.

The calculation procedure is detailed in the draft ITTC recommended procedure "Computational procedure for instantaneous GZ curve during time-domain numerical simulation in irregular wave".

Belenky and Weems (2008) describe a technique for checking self-consistency of calculation. A simulation is set when a ship is placed on a wave and sails with the celerity of this wave and heeled by an external moment. Angle of heel is recorded and compared to the value from the GZ curve computed for this wave. This process can verify the values of the GZ curve in wave before the maximum, as the equilibrium above the maximum of GZ curve is unstable. A similar procedure is used in section 2.3 of Appendix 4 of Explanatory Notes for qualitative validation of mathematical model of ship motions in waves.

7. DAMAGED SHIP IN WAVES (TOR 6)

Investigate the current state of the art on flooding dynamics of damaged ship in waves, including EFD and CFD.

Mauro et al. (2021) proposed three methods to identify the critical scenarios for the assessment of damaged passenger ships. The first method is based on preliminary static calculations, the second on the energy absorbed by the ship during an impact, the third on a purely dynamic approach. The authors compared their differences based on two sample passenger ships, showing their respective advantages and disadvantages.

Zhang et al. (2021) introduces a method using AIS data to estimate collision frequencies and scenarios for use in ship damage stability, Figure 38.

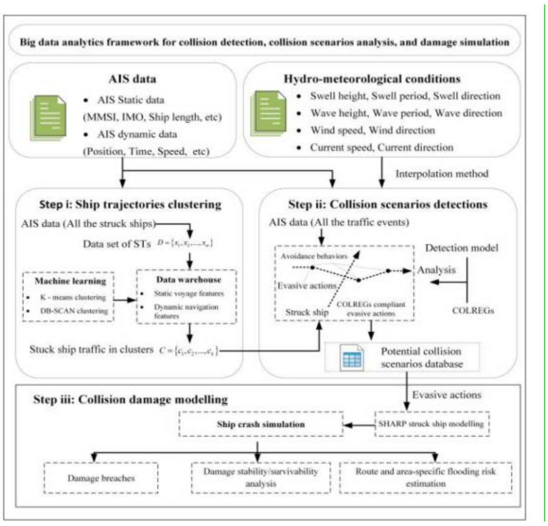

Figure 38: A framework for collision risk estimation using big data analysis

Vassalos, et al. (2021) presents the new developments in the H2020 FLARE project, especially the quantitative risk models pertaining to ship flooding. They also proposed a new risk-based method for the direct assessment of flooding risk estimation using numerical tools with support from datasets. Efforts has been made to build more suitable model for cruise ships than current high level risk models, Figure 39.

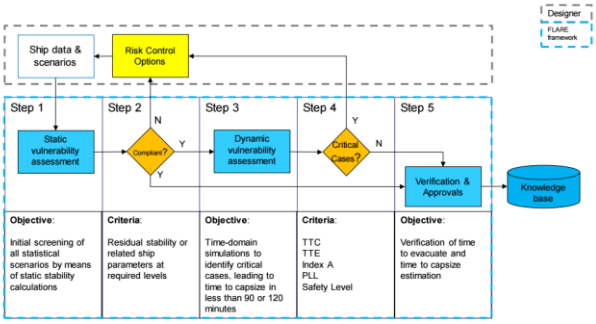

Figure 39: H2020 FLARE framework for direct flooding risk estimation

Krüger et al. (2021) extend the Monte Carlo principle for the computation of ship damage stability over the whole ship design process, with a focus on how to obtain the missing information through a sort of reverse engineering method and how the identified problems can be solved numerically. Traditionally, Monte Carlo simulation was used in the early stages of ship design.

van‘t Veer, et al. (2021) proposed a new flooding model for ship internal flooding. It has two modes of operation: one that uses the traditional steady Bernoulli equation and the other that includes a flow-averaged momentum term in each floodable region.

Bu et al. (2021) describe a viscous and potential prediction method for damaged ship motion. The method combines floodwater and motion in waves, see Figure 40 for the definition of the two domains. The three-dimension time domain potential method is coupled with CFD method. The described method can significantly improve computational efficiency while ensuring computational accuracy. Results are compared to the ITTC benchmark and to full CFD calculations.

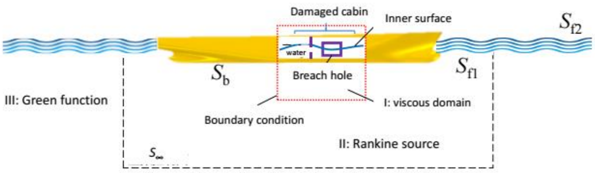

Figure 40: Diagram for the filed domains in the prediction method, from Bu et al. 2021a.

Valanto and Schumacher (2021) investigate the roll damping of intact ship with varying draughts and heeling angles to study the effect of the ship floating position on these coefficients. Then further study the roll damping of damages ship with different damaged cases was conducted. They studied the influence of the roll amplitude, installed bilge keels and ship speed on the roll damping behavior of the intact vessel. They also studied the influence of different floating condition, raking damage and collision damage on roll damping of the damaged vessel. From their first test simulation of damaged cases, they found that the transient flooding in calm water with a damage rapidly opening at the ship side, the use of draught and heel dependent roll damping coefficients can led to better results than using constant roll damping coefficients. However, the situation in a gradual flooding case in irregular beam seas is complicated, and the internal flooding models should be improved. The roll excitation is generated by a gyroscopic machine using gyroscopic controlled by a dedicated software, see Figure 41.

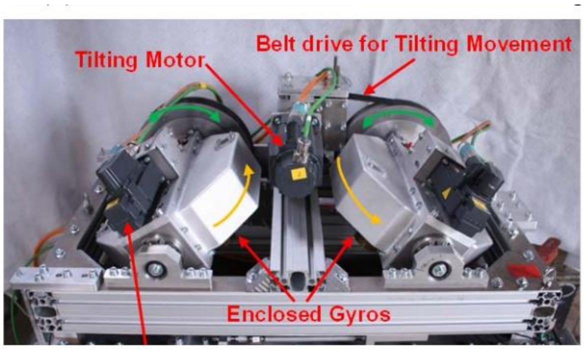

Figure 41: Gyroscopic roll excitation machine.

Predicting the motion responses of a damaged ship under various incoming waves is important. Vidić and Bačkalov (2022) investigated the present intact and damage stability requirements intended for Large Inland Passenger Ships, LIPS. They offer a critical analysis of the present stability regulations, highlight the need for a global harmonization of regulations, and probe into the hierarchy of the stability requirements for LIPS.

Hu et al. (2021) investigated the seakeeping performance of a DTMB 5415 model by focusing on its roll motion under beam wave condition, aiming to analyze the damaged ship motion performance under this rarely studied condition.

Bu et al. (2023, 2023a) investigated the motion and flooding process of a damaged passenger ship in regular and irregular beam waves experimentally and numerically at zero forward speed.

Pineau et al. (2022) present a numerical tool based on analytical formulations for rapid assessment of damage in ship grounding accidents. Through a step-by-step solution, the ship resistant force is assessed by the super-element method and transferred to a 6-DoF external dynamics solver, which updates the global ship motion by taking into account the action of hydrodynamic forces.

Dong et al. (2023) simulated the free-running turning maneuvers of a surface combatant with a damaged bow compartment numerically using an in-house unsteady RANS solver, coupled with the dynamic overset approach. Liu et al. (2022) predicted extreme roll motions with large amplitudes, induced by the pure loss of stability, for a benchmark combatant ONRTH running in stern quartering waves by CFD simulations. It is observed that ship capsizing occurs coupled with a rapid increase of yaw angle.

To assess the survivability of damaged ships, Kawamura and Hino (2023) developed a numerical method to simulate the motion of a floating body with partially filled tanks. The present method couples MPS and the Finite Volume Method (FVM), which are developed at the National Maritime Research Institute of Japan, by using peer-to-peer file exchange to retain the advantages of each discretization technique. The computational results are encouraging in that the Response Amplitude Operators (RAOs) of sway and roll motion show good agreement with the data measured in incident regular waves with various wave lengths.

Gao and Tian (2021) investigated the roll phenomena of a damaged ship in head waves using CFD. A series of head wave scenarios where the frigate was in a damaged condition and in an intact condition were simulated to highlight the main factors that affected the ship loads and motion response.

Pertaining to s-factor, according to SOLAS, a hybrid two-level framework for the stability of damaged ships was proposed (Mauro et al., 2023): Level-1 assessment based on static damage stability simulation and Level-2 assessment based on dynamic flooding simulation. The p-factor in SOLAS is calculated based on the dedicated marginal distribution functions of breaches in collision damage, which is commonly referred to as “zonal” approach. In order to calculate the p-factor of different damage types, the “non-zonal” approach is proposed (Krüger and Aschenberg 2021; Bulian et al. 2023). Duan et al. (2023) proposed an improved method within probabilistic framework for the survivability assessment of damaged ships in waves. To calculate s-factor, a fast dynamic numerical model to compute the motion of damaged ships under design sea states is put forward. Additionally, the p-factor is calculated based on the “non-zonal” approach.

Focused on the probability of occurrence of a certain breach, Vassalos et al. (2022) explained associated probabilistic content as p-factor, including pertinent assumptions and limitations. For a better understanding, a detailed statistical analysis on new damage breach distributions for passenger ships was undertaken according to the new database developed in the project H2020 FLARE. During the probabilistic damage stability calculation, concerning characteristics are illustrated, such as derivations of the breach distributions, sampling methods for numerical simulation, crash-worthiness considerations, and so on.

Aimed at enhancement of ship safety pertaining to flooding risk, Bae et al. (2023) suggested a quantitative risk assessment methodology (Figure 42), with the application of crashworthy structural designs as Risk Control Options (RCOs). The method provides equivalent damage stability criteria to the current SOLAS regulations within the IMO framework in a cost-effective way, which consist of seven steps. The first step is to calculate the damage stability of the target ship using standard damage stability analysis according to current SOLAS 2020, and select one or two high-risk zones for RCO application. The next step involves conducting ship collision simulations for the target vulnerable zone. The third step involves the implementation of alternative design arrangements as RCOs, to the target zones identified in the first step. After completing Step 3, the cumulative transverse breach distribution function of the target zone can be adjusted to obtain the corresponding PDF, after which the damage stability can be recalculated. The subsequent step involves conducting a cost-benefit analysis to determine the optimal RCO solution, utilizing the Gross Cost of Averting a Fatality (GCAF).

Based on above 6 steps, the final decision will be made after thorough discussion.

When evaluating ship damage stability, almost all pertinent parameters are calculated to extreme accuracy, except permeable volume and its distribution. Over the years, some generalized approximations have been adopted for principal ship spaces without differentiating between ship types. To demonstrate the impact of such approximations, Vassalos et al. (2022a) selected several passenger ships and undertook a sensitivity analysis addressing the main ship spaces and their contribution to permeable volume. Damage stability calculations (A-Index) are conducted to provide indicative measures on the impact of permeability. As a general remark, permeable volume plays a vital role in either case as it affects dramatically the slope of change of the A-Index to changes of permeability.

Figure 42: Overall methodology for quantitative risk assessment

Vassalos et al. (2022a) conducted a study about influence of life-cycle damage stability requirements on the internal ship layout, emergency response. Taking constraints and conflicting requirements into consideration, a framework of optimal configuration is presented, related to design, operation, and emergency response on a large passenger ship.

Take the existing failure probability calculation method on intact ship stability provided by IMO for reference, the application of the direct stability procedure and the direct counting method is investigated (Bu et al., 2023a), for calculating failure rate of damaged ships. Four methods are used to obtain failure rate in different sea states: a piecewise linear method on the GZ curve; a probabilistic method with first stability failure occur; a probabilistic method with fixed specified exposure time; and a deterministic method. All of them have a certain range of application for calculating the capsizing probability of damaged ships.

Forensic level flooding analysis is traditionally rooted in accident investigation. Nowadays, a great deal of process has been made, with more contemporary examples including the work conducted in Karolius et al., (2020), Vassalos et al., (2021) and Valanto, (2023). Paterson et al. (2023) developed a clear and rational methodology for conducting flooding forensic analysis, which is consisted of 9 distinct stages as shown in Figure 43. A transient capsize scenario and a progressive flooding loss scenario are selected as examples for elaboration.

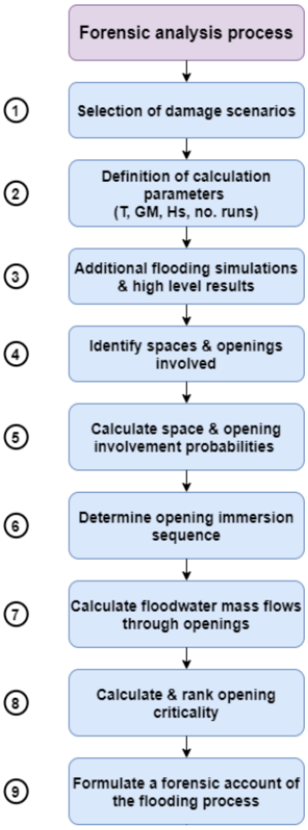

Figure 43: Process of forensic analysis

Bu et al. (2022, 2023, 2023a) adopted the experimental method to investigate motion and internal water height of a damaged passenger ship, which is compared with that under the intact state. The time history of the ship motion in regular and irregular beam waves are presented.

With the adoption of the self-designed electrically operated valve (Figure 44), the size of the opening can be controlled. The flooding into the side-damaged opening increased the period of ship's roll and the roll amplitude increased with increasing wave steepness in both ship states. Under testing damaged conditions, the roll amplitude of the damaged ship is smaller than that of the intact one. More nonlinear effects throughout the flooding process, as well as unsteady effects in irregular waves, should be added to improve the accuracy of the numerical method.

Figure 44: Self-designed electrically operated valve for control-ling the opening's size

ML/AI tools have started to be used in the damage stability area. Examples can be found in Section 2.1 of this report (Louvros et al. 2023; Mauro et al. 2023a; Vassalos et al. 2023a).

Lee et al. (2023, 2023a) describe work of 27th ITTC Stability in Wave Committee on handling inertia of floodwater. Three cases were identified in (Lee et al. 2023): water entering a ship, partially and fully flooded compartment. Approach to account for inertia of floodwater is different for each case. Lee et al. (2023) considers influence of trapped air in flooded compartment, comparing with a case of the vented compartment.

8. BENCHMARK (TOR 7)

The collection of benchmark data has always been a very important work of ITTC. This year, the members of ITTC SiW mainly collected benchmark data in the following aspects. The first one is about the GZ curve in wave for intact ship provided by the CSSRC. The test cases include mainly the change of the GZ curve in different wave conditions under a fixed heel angle for a container ship. The second one is about damage stability. H2020 FLARE presents an international benchmark study on flooding and motions of damaged ROPAX and cruised vessels. The 2023 ITTC procedure 7.5-02-07-04.4 "Simulation of Capsize Behaviour of Damaged Ships in Irregular Beam Seas" introduce the pertinent details. The dataset is located at the shipstab website: shipstab.org/index.php/news/98-added-flare-benchmark-study-damaged-cruise-ship).

Kapsenberg et al. (2020) describes benchmarking of numerical simulation tools for parametric roll, including comparison to a model test in irregular waves. The difference was actually not very much, considering how large roll motions were.

Marine casualties can give some good benchmark data for evaluation of stability tools if they can reproduce or estimate the risk of the realistic cases described. Example of complete documents came from EMSA but many countries have also interesting data and document. EMSA document gave the list of national investigative bodies in EU (see appendix 6 of EMSA 2023). National investigative bodies usually make available very detailed information about marine casualties in their geographical areas. Also many papers, particularly in ISSW, STAB and STAB&S conferences, describe some disasters with scientific point of view, for example, for one event as in Taguchi and Kuroda (2018), or analyzed for a type of ship as Mughadar-Palliparambil et al. (2021) for passenger ships.

9. ITTC LIAISON

SiW committee addressed the question put forward by SKC on wind loads. SiW committee emphasized that transverse loads for stability purposes must be considered alongside the longitudinal force (as mentioned in the proposed procedure focused on resistance evaluation). It was also noticed that the influence of heel angle on loads should be present.

10. IMO LIAISON

Per a request from ITTC secretary, the committee has prepared an information paper for the 10th session of IMO subcommittee on ship design and construction on ITTC support of the trial application of direct stability assessment within the second generation intact stability criteria. Following proper review and approval from ITTC governing bodies the paper has been submitted to SDC-10 under agenda item 16 “Any other business” identified as SDC 10/INF.7. The document gives a brief review of relevant ITTC recommended procedures, noting the status: existing, being updated or development-in-progress.

11. CONCLUSIONS

Technical conclusion

(1) A survey of literature has been conducted, including books, journals and proceedings of international conferences.

(2) The highlight of the reporting period is publication by IMO of the Explanatory Notes for the Interim Guidelines on the Second Generation Intact Stability Criteria with MSC.1/Circ. 1652 in April 2023. The Interim Guidelines was published in December 2020 (MSC.1/Circ. 1627). Direct stability assessment (DSA) is the most innovative part of the Second Generation Intact Stability Criteria (SGISC), where most advanced numerical simulation technology are being applied. As the trials of the SGISC has began, ITTC member-organizations may be interested in providing the DSA as one of their services.

(3) In support of the trail application of DSA, the committee has updated the ITTC recommended procedure 7.5-02-07-04.6 "Extrapolation for Direct Stability Assessment in Waves” one extrapolation over wave height in addition to already described Envelope Peak over Threshold (EPOT) and split-time /motion perturbation methods (MPM). The committee has tested all three method by running them with same input data, obtaining statistically identical output, favorably compared with a “true” values, estimated from a larger dataset.

(4) The committee has developed three more procedures, specifically aimed to aid the member- organizations in application of DSA: “Avoiding Self-Repeating Effect in Time-Domain Numerical Simulation of Ship Motions”, “Estimation of Frequency of Random Events”, and “Statistical Validation

of Extrapolation Methods for Time Domain Numerical Simulation of Ship Motions". The committee believes that those procedures are compliant with IMO Interim Guidelines can be also useful to general numerical simulation work.

(5) Another highlight of the reporting period was publication of the book "Contemporary Ideas on Ship Stability – from Dynamics to Criteria" by Springer in 2023. The book has 43 chapters, covering the entire development in the field of stability in waves over last 10 years, including an extended summary /overview of these chapters. The book is themed over the technical background of the SGISC, but contains all other topics too. The committee has reviewed the book, reporting the result is in Section 2.

(6) One more highlight of the reporting period is the publication of virtual special issue of Ocean Engineering "Extreme Stochastic Dynamics of Ships". Publication of this special issue was inspired by long-term research program "A Probabilistic Procedure for Evaluating the Dynamic Stability and Capsizing of Naval Vessels" run by the US Office of Naval Research. Most important results of this program were published in the special issue along with other papers focused on extreme ship motions. Totally, the special issue contains 17 full-length research papers, relevant to this committee. Review of these papers by the committee can be found in Section 2.

(7) One of the papers of the Special Issue contained the information that was necessary for updating the ITTC recommended procedure 7.5-02-01-08 Single Significant Amplitude and Confidence Intervals for Stochastic Processes. The information concerned account for self-dependence of a stochastic process constructing confidence interval. In fulfilment of Task 3 of the Terms of References, the committee has updated the procedure.

12. FINAL REPORT AND RECOMMENDATIONS TO THE 30TH ITTC

The 30th ITTC Stability in Waves Committee recommends the following:

- Adopt the updated ITTC Recommended Procedure 7.5-02-01-08 "Single Significant Amplitude and Confidence Intervals for Stochastic Processes".
- Adopt the updated ITTC Recommended Procedure 7.5-02-07-04.1 "Model Tests on Intact Stability"
- Adopt the updated ITTC Recommended Procedure 7.5-02-07-04.3 "Predicting the Occurrence and Magnitude of Parametric Rolling".
- Adopt the updated ITTC Recommended Procedure 7.5-02-07-04.4 "Simulation of Capsize Behaviour of Damaged Ships in Irregular Beam Seas".
- Adopt the updated ITTC Recommended Procedure 7.5-02-07-04.5 "Estimation of Roll Damping".
- Adopt the updated ITTC Recommended Procedure 7.5-02-07-04.6 "Extrapolation for Direct Stability Assessment in Waves"
- Adopt the new ITTC Recommended Procedure "Avoiding self-repeating effect in time-domain numerical simulation of ship motions", QSG suggested number is 7.5-02-01-09.
- Adopt the new ITTC Recommended Procedure "Estimation of Frequency of Random Events by Direct Counting", QSG suggested number is 7.5-02-01-10.
- Adopt the new ITTC Recommended Procedure "Statistical Validation of Extrapolation Methods for Time Domain Numerical Simulation of Ship Motions", QSG suggested number is 7.5-02-01-11.
- Adopt the new ITTC Recommended Procedure "Computational Procedure for Instantaneous GZ Curve during Time-domain Numerical Simulation in Irregular Waves", QSG suggested number is 7.5-02-07-04.8.

- Develop a new ITTC Recommended Procedure "Evaluation of Dynamical Characteristics of a Ship" to support application of Direct Stability Assessment within the framework of the Second-Generation Intact Stability Criteria (IMO, 2020).
- Further update ITTC Recommended Procedure 7.5-02-07-04.6 "Extrapolation for Direct Stability Assessment in Waves" to include two more extrapolation methods: Critical Wave Method and Linear Superposition Method, as described in the Explanatory Notes to the Second-Generation Intact Stability Criteria (IMO, 2023).

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Nomenclature

AIS	Automatic Identification System
BR	Broaching-to
CFD	Computational Fluid Dynamics
CRNAV	Cooperative Research NAVies
CTO	Centrum Techniki Okrętowei - Maritime Advance Research Centre
Circ.	IMO Circular
DoF	Degree of Freedom
DSA	Direct Stability Assessment
EA	Excessive Acceleration
EFD	Experimental Fluid Dynamics (or model experiments)
EMSA	European Maritime Safety Agency
EPOT	Envelope Peaks over Threshold
EU	European Union
FORM	First Order Reliability Method
FTA	Fault Tree Analysis
FVM	Finite Volume method
GEV	Generalized Extreme Value
GCAF	Gross Cost of Averting a Fatality
GPD	Generalized Pareto Distribution
HERM	Harmonic Exciting Roll Motion
IMO	International Maritime Organization
IS Code	Intact Stability Code

ISOPE	International Society of Offshore and Polar Engineers and International Ocean and Polar Engineering Conference
ISSW	International Ship Stability Workshop
IT	Inclining Test
ITTC	International Towing Tank Conference
LIPS	Large Inland Passenger Ships
LNGC	Liquefied Natural Gas Carrier
LSTM	Long-Short Term Memory
MPM	Split-time/ Motion Perturbation Method
MPS	Moving Particle Simulations
MSC	IMO Maritime Safety Committee
NSC	Naval Ship Code, published by NATO as ANEP-77
OMAE	International Conference on Ocean Offshore & Arctic Engineering
ONR	US Office of Naval Research
ONRTH	ONR Tumblehome Hull form
ORV	Oceanographic Research Vessel
OMAE	International Conference on Offshore Mechanics and Artic Engineering
PCC	Pure Car Carrier
PL	Pure Loss of stability
POT	Peak-Over-Threshold method
QoI	Quantity of Interest
QSG	ITTC Quality System Group
RAO	Response Amplitude Operator
RANS	Reynolds Average Navier Stokes
RCO	Risk Control Options
RPS	Revolution per Second
RNG	Renormalization Group (related to CFD)
ROPAX	Roll on Roll off Passengers
SDC	IMO Sub-Committee on Ship Design and Construction
SKC	ITTC Seakeeping Committee
SGISC	Second Generation of Intact Stability Criteria of IMO
SOLAS	International Convention for the Safety of Life at Sea
SSA	Single Significant Amplitude
SST	Share Stress Transport (related to CFD)
STAB	International Conference on Stability of Ships and Ocean Vehicles
STAB&S	International Conference on Stability and Safety of Ships and Ocean Vehicles
TOR	Terms of Reference
TTC	Time to Capsize
TTE	Time available to Evacuate
VCG	Vertical Centre of Gravity
VLCC	Very Large Crude Oil Carrier
VOF	Volume of Fluid method