The Seakeeping Committee

Final Report and Recommendations to the 29th ITTC

1. GENERAL

1.1 Membership and meetings

The Committee appointed by the 29th ITTC consisted of the following members:

- Pepijn de Jong (Chairman), Maritime Research Institute Netherlands (MARIN), Wageningen, The Netherlands;
- Christopher Kent (Secretary), Naval Surface Ship Warfare Centre Carderock Division (NSSWC-CD), West Bethesda, USA;
- Benjamin Bouscasse, École Centrale de Nantes (ECN), Nantes, France;
- Frederick Gerhardt, SSPA, Göteborg, Sweden;
- Ole Andreas Hermundstad, SINTEF Ocean, Trondheim, Norway;
- Toru Katayama, Osaka Prefecture University, Osaka, Japan;
- Munehiko Minoura, Osaka University, Osaka, Japan;
- Bo-Woo Nam, Seoul National University, Korea;
- Yin Lu (Julie) Young, University of Michigan, USA.

Three committee meetings were held at:

- Osaka University, Osaka, Japan, Decem-ber 2018
- Maritime Research Institute Netherlands (MARIN), Wageningen, Netherlands, January 2019
- University of Michigan, Ann Arbor, USA, June 2019

Following the onset of the COVID-19 Pandemic no further in-person meetings were held. A series of regular video teleconferences were held to continue the work of the committee. These covered the time period of February 2020 to June 2021. The video conferences were found to be an effective way of replacing the face-to-face meetings, and by keeping a regular pace, helped the committee to continue its work.

1.2 Terms of Reference given by the 27th ITTC

The Seakeeping Committee is primarily concerned with the behaviour of ships underway in waves. The Ocean Engineering Committee covers moored and dynamically positioned ships. For the 29th ITTC, the modelling and simulation of waves, wind and current is the primary responsibility of the Specialist Committee on Modelling of Environmental Conditions, with the cooperation of the Ocean Engineering, the Seakeeping and the Stability in Waves Committees.

1. Update the state-of-the-art for predicting the behaviour of ships in waves, emphasizing developments since the 2017 ITTC Conference. The committee report should include sections on:
    1. the potential impact of new technological developments on the ITTC;
    2. new experiment techniques and extrapolation methods;
    3. new benchmark data;
    4. the practical applications of numerical simulation to seakeeping predictions and correlation to full scale;
    5. the need for R&D for improving methods of model experiments, numerical modelling and full-scale measurements.

2. Review ITTC Recommended Procedures relevant to seakeeping, including CFD procedures, and:
    1. identify any requirements for changes in the light of current practice, and, if approved by the Advisory Council, update them;
    2. identify the need for new procedures and outline the purpose and contents of these.

3. Update ITTC Recommended Procedure 7.5-02-07-02.5, Verification and Validation of Linear and Weakly Non-linear Seakeeping Computer Codes to include the verification and validation of ship hydroelasticity codes in response to any comments from the ISSC Loads and Response Committee.

4. Update 7.5-02-07-02.1 Seakeeping Experiments. The procedure should be extended to include the measurement of added resistance in waves with emphasis placed on the uncertainty in the measurement. Review procedures 7.5-02-07-02.2 and the new procedure on the calculation of the weather factor fw in the EEDI formula to ensure that they are consistent with the proposed update.

5. Update Recommended Procedure 7.5-02-07-02.8 “Calculation of the weather factor fw for decrease of ship speed in waves” to bring it in line with the terminology in the EEDI guidelines and submit to MEPC 72 (Spring, 2018). The submission should state that the procedure is applicable mainly for large ships and that additional work is required for smaller ships, and state the limit between large and smaller ships.

6. Expand Recommended Procedure 7.5-02-07-02.8 “Calculation of the weather factor fw for decrease of ship speed in waves” to include the uncertainty associated with each method.

7. Update 7.5-02-07-02.2 Prediction of Power Increase in Irregular Waves from Model Tests should be modified to make it more comprehensible for the wider community outside of the ITTC.

8. Update ITTC Recommended Procedure 7.5-02-07-02.3 Experiments on Rarely Occurring Events to include the measurement and analysis of impulsive loads, peaks in pressures and maximum accelerations.

9. Liaise with SIW Committee on the updates to the guideline 7.5-02-07-04.3 for the prediction of the occurrence and magnitude of parametric rolling.

10. Develop a procedure for undertaking inclining tests at full scale include estimates of the measurement uncertainty. Liaise with the Stability in Waves Committee, as required.

11. Develop a procedure for conditioning a model for seakeeping tests, e.g. CG position, GM, moments of inertia. Include in the procedure estimates for measurement uncertainty.

12. Survey and/or collect benchmark data for ship structural hydroelasticity in waves and for added resistance in waves tests.

13. Continue the collaboration with ISSC committees, including Loads and Responses and Environment Committees.

14. Undertake a complete review of the procedures related high speed marine vehicles (HSMV) and update according to recent advances in testing techniques, in particular,
    1. Update the seakeeping related HSMV procedures:

        - 7.5-02-05-04 Seakeeping tests;
        - 7.5-02-05-06 Structural loads;
        - 7.5-02-05-07 Dynamic instability.

    2. Develop a new procedure for motion control of HSMV during seakeeping tests.
    3. Use as a basis the reports of the various committees to undertake a review the state-of–the-art in seakeeping of HSMV.

2. STATE OF ART REVIEW

2.1 New Experimental Facilities

A worldwide survey identified a handful of new experimental seakeeping facilities that have been built or commissioned during the last three years.

2.1.1 Flanders Maritime Laboratory

In May 2019 Flanders Maritime Laboratory (FML) was officially opened in Ostend/Belgium. The laboratory is operated by Flanders Hydraulics Research, Ghent University, and KU Leuven University. It consists of two facilities, a Coastal & Ocean Basin (COB, Figure 1) and a Towing Tank for Manoeuvres in Shallow Water. It is planned that both become fully operational during 2020-2021. The COB is a midsize wave basin (30 x 30 m²) with a maximal water depth of 1.4 m (adjustable between 0.4 and 1.4 m), and a deeper (4.0 m), central pit. Its principal aim is to study the influence of waves, winds and currents on coastal defences and blue energy applications. The towing tank will mainly focus on ship behaviour in shallow water, see Delefortrie et al. (2019).

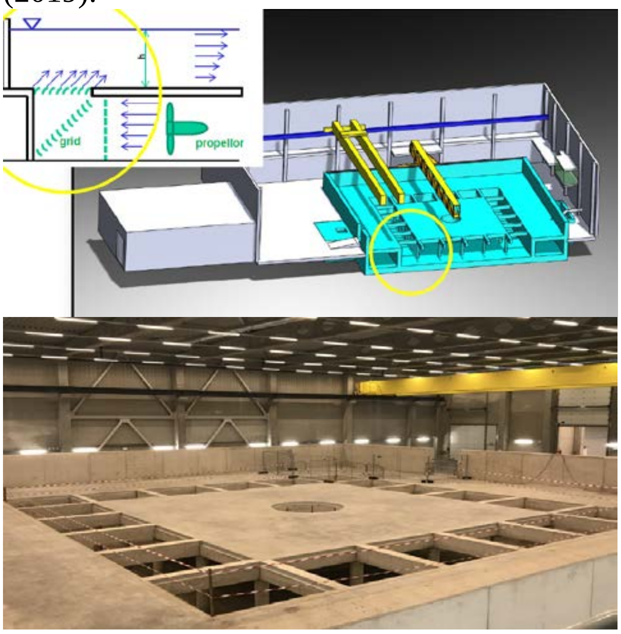

Figure 1: Coastal & Ocean Basin in Ostend. http://cob.ugent.be

2.1.2 Deep Ocean Engineering Basin at KRISO

The world biggest deep-water offshore basin was built at the Korea Research Institute of Ships and Ocean Engineering (KRISO), Sung et al. (2016). It has a floor area of 100 m x 50 m with a water depth of 15 m (50 m in the 12 m diameter pit), as shown in Figure 2. The basin was successfully commissioned during 2020 and is now operational. It has generation systems for wind, waves, and currents.

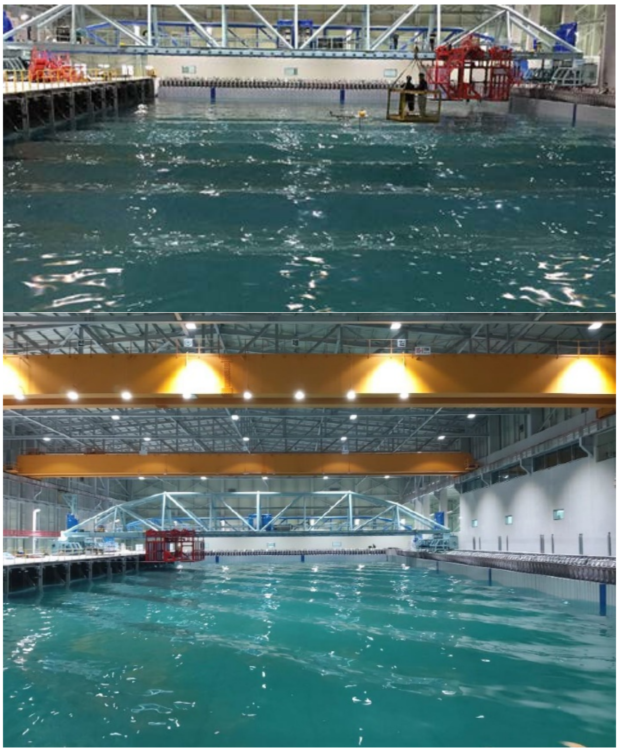

Figure 2: KRISO Deep Ocean Engineering Basin (DOEB). kriso.re.kr

2.1.3 Technology Centre for Offshore and Marine Singapore (TCOMS)

Another large deep-water basin with a 50 m deep centre pit is under construction in Singapore. The facility is slated to be operational by 2021.

2.1.4 University of Southampton Towing Tank

The recently constructed 138 m x 6 m towing tank at the University of Southampton's Boldrewood Innovation Campus is equipped with a 12-element wavemaker on one end. Straight and oblique waves of up to 0.7 m height can be produced. Malas et al. (2019) report on early sports engineering investigations in the facility (Figure 3). The tank (including carriage) became fully operational in late 2020, see Malas (2020) for more details.

Figure 3: Sports engineering in the Boldrewood tank. www.southampton.ac.uk/engineering/research/facilities/towing-tank-news

2.2 Experimental Techniques

2.2.1 Measurement of added resistance

The accurate measurement of "added resistance in waves" continues to be a hot topic. Added resistance is obtained by measuring the small difference between two large quantities (calm water resistance and mean resistance in waves) consequently demands on the quality of the experiments are high.

Park et al. (2019) show that the uncertainty of added resistance measurements is particularly high in short waves.

Kjellberg and Gerhardt (2019) discuss an improved evaluation method for free-sailing model tests. The method is quasi-steady in nature and can take the small unwanted model accelerations into account that almost always occur during "real life" testing. They also explore the idea of towing a model in waves using a modified "soft-mooring" setup that consists of long lines and soft springs. Compared to the "free-sailing" technique such an approach reduces the number of tests that need to be re-run because the target speed was not achieved.

2.2.2 Instrumentation and measurement technology

Tukker et al. (2019) discuss the measurement quality of electrical resistance-type wave gauges. They point out, that especially thin wire gauges can show a non-linear behaviour. The common assumption of linearity will therefore result in systematic measurement errors. The authors present a way of quantifying the resulting errors and show that the size of the non-linear errors can easily be reduced by about 40% if stainless steel wires are replaced with titanium wires.

Zeraatgar et al. (2019) analysed the effect of sampling rate on slamming pressure measurements. A range of prismatic wedges with deadrise angles of 5°–35° were dropped into a small tank and impact pressures recorded at different sampling rates. Based on the results minimum sampling rates are recommended. For wedges with deadrise angles of 25° and higher, a sampling rate of 25 kHz is sufficient while, for deadrise angles smaller than 20°, higher sampling rates are required. For very small deadrise angles of 5° an acceptable sampling rate is 600 kHz at a water entry velocity of 3.13 m/s.

Mutsuda et al. (2019) used a combination of particle image velocimetry (PIV), high speed video cameras and pressure measurements to investigate the characteristics of stern slamming. Water entry tests with a prismatic wedge model and a 3D ship stern model were performed to examine nonlinear interactions between a body and the free surface with splashing and droplets. Especially the PIV results provide an interesting insight into the detailed flow field some distance away from the body. Tests with a complete ship model in following seas where also performed.

Fukushima et al. (2019) used “optical strain gauges” of the “Fiber Bragg Grating” (FBG) type to simultaneously measure the pressure at 146 points on the hull surface of the KVLCC2 tanker.

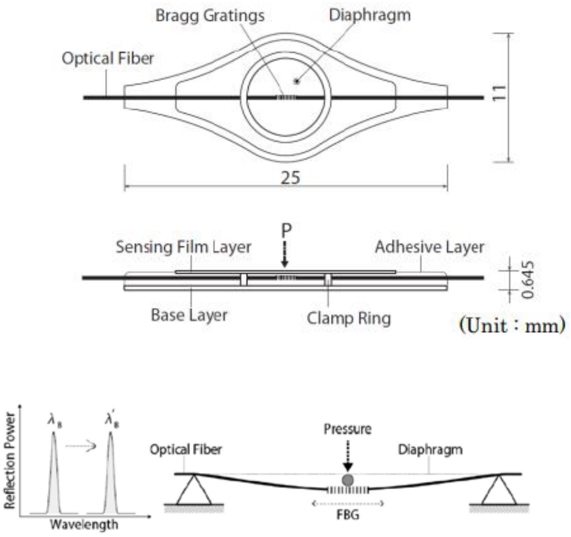

Figure 4: Schematic of the FBG sensors used by Fukushima et al. (2019)

Several of the 0.6mm thick glue-on sensors (Figure 4) were connected in series and arranged along different water lines (Figure 5). Measured pressures from the FBG-sensors compare well to more traditional tube-sensor arrangements and LES-CFD simulations. The advantages of the new sensors are a) low cost and b) short installation time (compared to traditional pressure tabs and tubes). The authors point out that the thickness of the sensor is sufficiently thinner than the boundary layer thickness over the hull. However, the thickness of the viscous sublayer is about the same as the sensor thickness. Results and a comparison to the pressure-tap and LES results however indicate that this does not seem to affect the measurements. So far the system seems to have been used to study ship behaviour in calm water only. However, using the sensors to measure pressures during seakeeping tests appears to be a possibility.

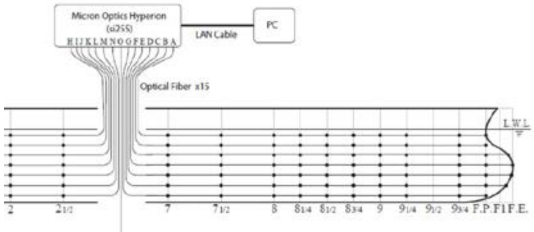

Figure 5: Arrangement of FBG sensors on KVLCC2 hull from Fukushima et al. (2019)

The use of cameras and optical systems to record ship motion in waves continues to increase across the industry, see e.g. Malas et al. (2019) or Mathew et al. (2018).

Mathew et al. (2018) describe an investigation into Replenishment at Sea (RAS) operations. They experimentally studied the influence of lateral and longitudinal separation on the wave induced motions of two vessels operating in close proximity to each other. While the actual testing technique is similar to single ship testing the simultaneous measurement of the motions of two models adds an additional level of complexity. Results show, that there can be significant interaction between the two vessels and that even in head seas substantial rolling can occur.

Silva et al. (2017) used a large number of wave probes and load cells to study green water impact on a Floating Production Storage and Offloading unit (FPSO). Considering the large number of monitored green water events, identification of critical regions near the deck edge and the water on deck propagation are characterized, including the influence of a riser balcony along the side hull.

Tsukada et al. (2017) describe the development of a “Wind Load Simulator” for free-sailing seakeeping model tests. The device consists of three pairs of ducted fans that are mounted on the ship model, one pair parallel to the centreline, the other two athwartships. The fan units are mounted on load cells and can be individually controlled to simulate the effect of wind on the above water part of a ship. During a seakeeping test ship motions due to waves are recorded and used in combination with wind-load coefficients to predict longitudinal and lateral wind forces and yawing moment in real time. The fans are then controlled to produce these target forces and moments. Feedback control from the load cells under the fans ensures that the target values are achieved.

2.2.3 Hydroelastic ship models

Studying the effects of hydroelasticity on global loads and fatigue of ships continues to be of interest to researchers. At the 8th International Conference on Hydroelasticity in Marine Technology (2018), a number of papers specifically addressed experimental techniques and focused on the design and construction of for hydroelastic models for seakeeping tests.

Houtani et al. (2018) describe the construction of a flexible container ship model where the vertical bending and torsional vibration modes of the full-scale ship are replicated. To achieve similarity in torsion the height of the shear centre of the model needs to be located below the keel. This is because the real ship has large deck openings. The resulting ship model is of similar construction and manufactured from urethane foam, without backbone and non-segmented, Figure 6.

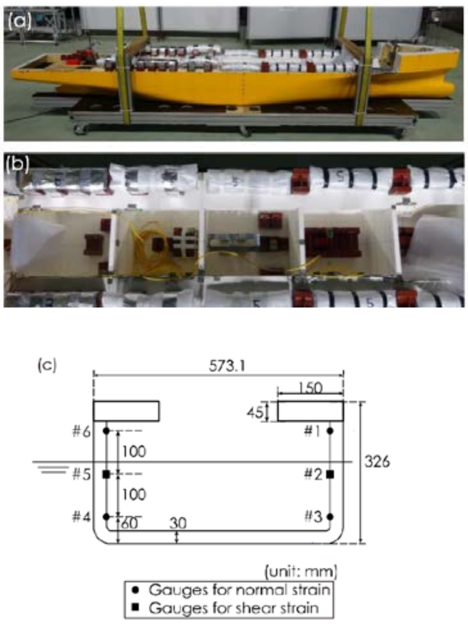

Figure 6: Continuous i.e. non-segmented hydro elastic container ship model designed by Houtani et al. (2018).

Grammatikopoulos et al. (2018) report on the design and manufacture of a barge-like hydroelastic model using 3D-printing techniques. The model design was inspired by the S175 container ship combined with the cross-sectional geometry of a realistic container ship. In contrast to most other ship models the inner details of the full-scale construction were also replicated. The study focused on structural and manufacturing issues and was aimed at demonstrating the possibilities and challenges of "additive manufacturing" when building hydroelastic models.

2.2.4 Seakeeping testing of wind assisted ships

The development of experimental techniques to study the seakeeping and manoeuvring behaviour of wind propelled/assisted ships is of significant current interest. Several alternative methods are currently investigated. These include:

a) Construction of a simple "wind tunnel" under the carriage of a seakeeping basin and equipping the model with scaled-down sails, Eggers and Kisjes (2019);
b) Simulation of sail forces by towing via a rope attached to a short mast (see Gauvain 2019 for examples);
c) A "hybrid approach" where the sail forces are simulated by rpm and azimuth-controlled fans/airscrews. See Gauvain (2019) and Gerhardt and Santén (2021).

Figure 7: "Wind tunnel" in MARIN's seakeeping basin, from Eggers and Kisjes (2019)

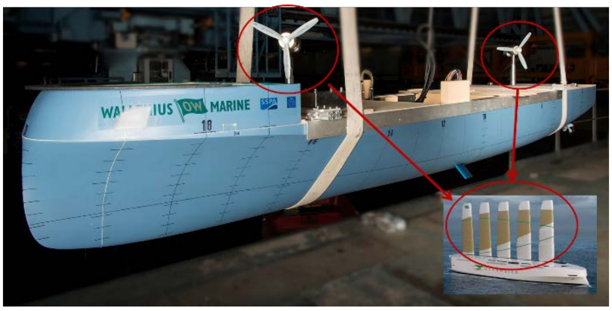

Figure 8: Simulation of sail forces via rpm azimuth-controlled fans, from Gerhardt and Santén (2021)

Due to this increased interest, there seems a clear need, and therefore an opportunity for ITTC, to develop guidance for performing model tests for wind assisted vessels.

2.3 Numerical Methods

2.3.1 General

This section gives an overview of recent developments within potential theory methods for ship motions predictions. The related topic of added resistance assessment is covered in Section 2.7. Moreover, developments within combined seakeeping and manoeuvring are covered by the Specialist Committee on Manoeuvring in Waves, while papers on stability in waves are dealt with by the Stability in Waves Committee.

2.3.2 2D and 3D methods

Despite the massive developments within methods solving the Navier-Stokes equations, the CFD methods are still not practical for routine seakeeping calculations. Hence, potential theory methods, with simplified models to account for viscous forces in e.g. roll motions, are the workhorses when it comes to ship seakeeping assessment. Even classical linear 2D strip theory methods are still widely used in practical applications. They are easy to use, robust and computationally very efficient; and for conventional seakeeping analyses they have shown to give sufficiently accurate results in most cases.

For higher forward speeds, non-slender structures, or for cases where the flow field and pressure distribution near the ship ends is of concern, 3D potential theory methods are used. Linear 3D methods for stationary floating structures are standard tools today. For ships at low and moderate speeds, "speed-correction" methods, where the forward speed is treated in the same manner as in classical strip theory, are efficient methods. More computationally demanding are the methods where the effect of forward speed is included in a more consistent manner, and the methods where nonlinearities are handled. Most of the recent developments in potential theory methods focus on 3D methods.

2.3.3 Boundary methods and field methods

The boundary methods, which require discretization of the domain boundaries only, are by far the most common in seakeeping analyses based on potential theory. When discretization of the whole computational field is avoided, the number of unknowns will normally be significantly reduced.

As an alternative to the popular boundary methods, some interesting developments with field methods using a high-order finite difference technique have been presented by Amini-Afshar and Bingham (2017, 2018) and Amini-Afshar et al. (2019). They are motivated by the fact that the finite difference method leads to a very sparse system of equations, as opposed to the boundary methods, which produce dense matrices. This allows for an optimum scaling of the computational effort with increasing resolution. This, combined with the high-order accuracy of the discrete operators, makes the approach competitive with boundary methods, especially for nonlinear problems. The method can be well suited for calculation of the second-order wave drift forces from the computed first-order results. The forward speed radiation problem is dealt with in Amini-Afshar and Bingham (2017), while Amini-Afshar and Bingham (2018) focus on the forward speed diffraction problem. A stability analysis of the solution scheme and application to the steady wave resistance problem is presented in Amini-Afshar et al. (2019). Comparison with results from experiments and other numerical methods show good agreement for spheres and ship-like structures.

2.3.4 Boundary element methods

The main advantage with the Green function method (GFM) is that the source function satisfies the free surface boundary conditions, and only the wet surface of the floating body needs to be discretized. One problem with the GFM is the presence of cavity resonance, or irregular frequencies, that correspond to eigenfrequencies of a fictitious inner problem, and cause the solution of the outer problem to break down at these frequencies. For the zero-speed problem there are efficient ways of removing the irregular frequencies, e.g. by the lid method, while this is much more challenging with the forward speed Green function. Moreover, the forward speed Green function (translating-pulsating source) is substantially more complex to evaluate than the zero speed Green function, and it displays a highly oscillatory behaviour for field points near the free surface.

Assuming that the encounter frequency is high and the speed moderate, the forward speed only occurs in the body boundary condition, and the solution can be separated into a zero-speed solution and a correction due to forward speed; just like in the classical strip theory. With this approach, the robust and efficient zero-speed Green function can be used.

Due to the complexity of the forward speed Green function, the Rankine Panel Method (RPM) has become more popular for the forward speed seakeeping problem. The RPM, using the simple Rankine source, is generally easier to implement and more robust. It avoids the problem with irregular frequencies, and implementation of nonlinear free surface boundary conditions is easier. Disadvantages are that the free surface must be discretized, and special care must be taken to ensure that waves are not reflected at the outer boundary of the surface mesh. The discretized surface may need to be large and with high resolution, due to the different wavelengths involved in the wave systems generated by the ship. A time domain RPM is presented by Chen et al. (2018a) and applied to four different ship types. Yao et al. (2017) present a frequency-domain RPM for finite water depth. The method is used to study the influence of water depth on the hydrodynamic characteristics of two ship types at forward speed in water depths down to about twice the ship's draft.

As a logical consequence of the drawbacks and merits of the GFM and RPM, the hybrid, or multi-domain methods have evolved. In these methods the RPM is used in an inner domain, including the ship and a limited surface area surrounding it, while the GFM is used in the outer domain. The solutions for the two domains are matched at their common boundary.

A 3D multi-domain BEM is presented by Chen et al. (2018b). The boundary value problem is solved directly in time-domain with a RPM in the inner domain and a transient GFM in the outer domain, as shown in Figure 9.

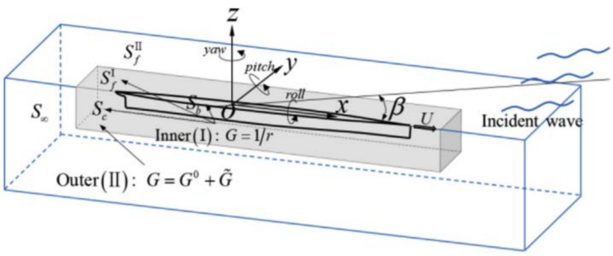

Figure 9: Principle sketch of the multi-domain BEM method (Chen et al. 2018b).

A new 3D multi-domain method for the linear and second order mean wave drift loads on floating bodies was presented by Liang and Chen (2017). The control surface, separating the inner and outer domains, is mesh-free and the quantities on it are expressed analytically. The method has been generalized to the ship motion problem with forward speed by Chen et al. (2018c). Frequency and time-domain formulations are presented, and comparisons are made with results from experiments and from the Hydrostar code.

Nwogu and Beck (2017) extend the FFT-accelerated method of Nwogu and Beck (2010) to simulate the 6 DOF motions of vessels moving in multidirectional waves. This is a variant of the mixed spectral-panel method, in which the kernels of the free surface boundary integrals are expanded in a wave steepness parameter and evaluated with FFT. A velocity-based boundary integral method is used to solve the Laplace equation at every time-step for the fluid kinematics. Comparisons with semi-analytical results for a floating oscillating hemisphere show good agreement. Good agreement with experimental results is also demonstrated for a self-propelled ship in oblique waves.

2.3.5 Acceleration techniques and higher order methods

Several techniques have been applied to speed up the computations required to solve the dense matrix of equations that results from the boundary element methods. Two examples are the sparsification techniques based on the multipole expansion method and the pre-corrected FFT method. Desingularization is another popular acceleration technique. The sources are then distributed slightly above the calm water surface rather than on the surface itself. The source distribution over each panel can then be replaced by an isolated source, which greatly reduces the computational complexity of the influence matrix. The technique is recently used by e.g. Yao et al. (2017) in their RPM for finite water-depth.

The FFT-accelerated boundary integral method of Nwogu and Beck (2017) reduces the cost of evaluating the free-surface convolution integrals from $O(N^2)$ to $O(N\log N)$, where N is the number of grid points on the free surface. They report that the method is an order of magnitude faster than non-accelerated boundary integral methods.

Shan et al. (2019) present algorithms for more efficient evaluation of the zero-speed Green function (pulsating source) in the frequency-domain. Both infinite and finite depth are studied. Parallelization of the serial code with the OpenMP library is also discussed.

Zangle et al. (2020) present three new techniques to improve boundary element methods. Triangular B-splines are introduced as an alternative to four-sided NURBS, which cause problems when modelling three-sided surfaces at e.g. bulbous bows and waterline cuts (Figure 10). They also present a mixed-order BEM, which allows body patches to be represented as meshes of low-order bilinear panels, while the free surface is represented as high-order NURBS. This simplifies the calculation of influence coefficients over the body patches and increases the efficiency of the method. Finally, a near field influence approximation with flat panel influence calculations is introduced to reduce the number of recursive calculations of the high-order near-field influence coefficients.

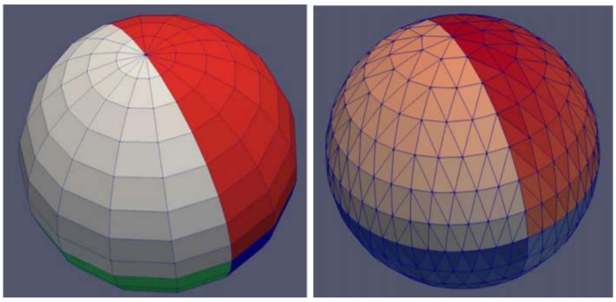

Figure 10: Quadrilateral NURBS (left). The degeneracy at the pole is removed when using triangular B-splines (right) (Zangle et al. 2020).

2.3.6 Forward speed effects

It is well known that the forward speed, *U*, and the steady flow field around the hull influences the seakeeping behaviour of a ship, and this must be accounted for in seakeeping prediction methods. One may distinguish three levels of refinement in representing the steady flow field:

- The Neumann-Kelvin approximation, where the steady flow is approximated by a uniform flow with velocity *U*;
- The double-body approximation, where the steady flow is approximated by that obtained by using a mirror condition on the calm water surface;
- The complete method, where the “exact” steady flow and wave elevation is used.

For ships at moderate speeds, the Neumann-Kelvin approximation is commonly used. With this simple approach one avoids the calculation of spatial derivatives of the steady potential. The double-body approximation is also only accurate for low speeds.

A recent study on the effect of the different flow representations was presented by Chen et al. (2018a). A time-domain RPM with higher order panels is used, so that second derivatives of the velocity potential and m_j-terms can be evaluated directly. They compared hydro-dynamic coefficients and motions obtained with the three formulations and with model tests for four different ship types: Series 60, Wigley-1, S-175 and a full-form tanker at various speeds. The conclusion was that the Neumann-Kelvin approximation gives less accurate results compared to the two more refined methods, and that for ships with complex and full-form hulls, the complete method gives the most accurate motion predictions.

Yao et al. (2017) use a frequency-domain RPM to compare excitation forces and heave and pitch motions, obtained with the Neumann-Kelvin and the double-body approximations, of two modern hull forms at Froude numbers between 0.13 and 0.27. Results were compared with model tests. For these cases, the double-body approximation did not show any significant improvement over the simpler Neuman-Kelvin approximation.

2.3.7 Nonlinear Froude-Krylov and hydro-static forces

In evaluation of seakeeping performance and hull girder load effects, nonlinear Froude-Krylov and hydrostatic forces are usually the first non-viscous nonlinearities to be considered. In the so-called weakly nonlinear (or body-nonlinear) methods, this is done by considering the instantaneous position of the ship hull relative to the incident (undisturbed) wave surface. Simulations are performed in time-domain, and a common approach is to obtain linear motion time-series by inverse Fourier transform of frequency-domain results. Then the nonlinear modifications of the Froude-Krylov and hydrostatic forces can be calculated, either by section-wise 2D calculations or by using a 3D mesh on the hull.

Rodrigues and Guedes Soares (2017) use the above approach to consider motions of the US Navy Destroyer Hull DTMB-5415 at zero speed. They use a newly developed adaptive panel mesh on the hull surface, where the Froude-Krylov forces are calculated analytically. Chen et al. (2018a) use B-spline interpolation to obtain a mesh on the instantaneous hull. Weems et al. (2018) express the Froude-Krylov and hydro-static forces in terms of the instantaneous submerged volume of each ship section, by assuming that the waves are longer than 2-3 times the section beam. The forces are then found in a section-wise manner without having to evaluate the pressure under the incident wave for a large number of wave components.

Sugimoto et al. (2019) apply an existing 3D body-nonlinear method and compare motions and hull girder loads with experimental results for a ship with pronounced bow flare. The results confirm that nonlinear Froude-Krylov and hydrostatic forces contribute significantly to the hull girder load effects, while their influence on heave and pitch motions is relatively small.

Another 3D body-nonlinear method is used by Park et al. (2017) and compared with experimental results for a tumblehome vessel, where the width of each section decreases from the waterline and up. Comparisons are also made with existing experimental results for the S175 containership. Whereas the heave and pitch RAO's for the conventional S175 ship decrease with increasing wave steepness, the opposite was the case for the tumblehome hull. The body-nonlinear method captured these trends with quite good accuracy.

Pollalis et al. (2018) applied a 3D body-nonlinear method to study heave and pitch of the KVLCC2 tanker. No significant influence of the nonlinearities was observed for the investigated cases.

Two levels of nonlinear methods were used by Van Walree et al. (2020) to study the motions of an appended version of the DTMB-5415 destroyer hull at high forward speed in extreme stern quartering seas. Comparisons were made with results from free-running model tests and CFD simulations. The first method is body-nonlinear. The second is body-exact, meaning that also the radiation and diffraction forces are found for the instantaneous position of the hull beneath the incident wave surface. Maneuvering, resistance and propulsion forces are included in the simulations. Viscous forces are added for roll damping and cross flow drag. Both methods gave fairly good predictions for heave, roll and pitch motions as well as forward speed variations. Sway velocity, yaw motions and deck edge immersion heights were more difficult to predict accurately with these methods. For a validation case involving large resonant roll motions, the simpler body-nonlinear method performed slightly better than the more time-consuming body-exact method. For another case the situation was the opposite. The CFD (URANS) results compared very well with the experiments, but the required computational efforts prohibit simulation of long time-series.

Rajendran et al. (2016) also present results from a body-nonlinear and body-exact method. Their simulations are based on precalculated 2D hydrodynamic coefficients. In the body-exact method, interpolation between coefficients for different drafts is used. Results were compared with experimental data for heave, pitch, relative motions and the vertical bending moment of a container ship at forward speed in extreme head seas. The agreement was generally good, and it was found that the body-exact method gave significantly better predictions for the peak sagging bending moment. These peaks were largely overpredicted by the simpler body-nonlinear method.

Gkikas and van Walree (2017) apply a body-nonlinear/body-exact time-domain forward-speed GFM to simulate drifting of a cruise ship in large waves. The second order forces are evaluated in the mean wetted body surface, while the Froude-Krylov and hydrostatic forces are evaluated on the exact wetted surface. In conventional seakeeping analyses, the forward speed is input to the BEM, but in this case it is a priori unknown. The problem is solved iteratively, by estimating the initial drifting velocity. Results were compared with model tests. Cross flow drag forces and a constant wind force were also included in the simulations. Since the drifting speed was dominated by the constant wind force, which was the same in model tests and simulations, it seems difficult to conclude on the method's ability to predict drift forces and speeds.

In the recent years there seems to have been less focus on the high-fidelity potential theory codes, where “fully” nonlinear formulations are pursued. The developments within RANSE-solvers may be one possible reason for this trend. Instead, activities within potential theory seakeeping seem to have shifted towards combined seakeeping and maneuvering codes. There has also been an increased interest in assessment of added resistance.

2.4 Rarely Occurring Events

Rarely occurring events for ships can usually be categorised into three aspects: (1) slamming, with the hull (bow, bottom or stern) of the vessel impacting onto the wave surface, (2) green water events, where a mass of water flows onto the deck, possibly impacting on the superstructure or cargo and (3) emergence events of propellers or other equipment, sometimes associated with ventilation. Other rarely occurring events, related to dynamic stability are the topic of the Stability in Waves Committee and not included here.

2.4.1 Water entry

Water impact problems of wedge type shapes are often considered as a basic model for bow and stern slamming or flat plates for bottom slamming or green water impact problems. Studies can be experimental, looking into two- or three-dimensional impacts at model scale, or numerical, with methods ranging from semi-empirical and analytical, incompressible (potential flow and Euler methods) to fully compressible and two-phase CFD approaches.

2.4.1.1 Experimental.

Guo et al. (2017) performed wedge drop tests and compared the results against CFD simulations and the simplified analytic Wagner solution. They discussed the design of the drop test device (Figure 11), the measurement of the impact loads, the test procedure and data analysis. They highlighted that measuring space averaged forces during impact may be more relevant from a structural perspective than measuring local pressures, while local pressures can be very sensitive to randomness due to entrapped air. They designed a force panel to measure the impact force and used a Frequency Response Function to overcome the effect of the load cell’s own dynamic response on the measured loads.

Hasheminasab et al. (2020) presented an experimental study on the water entry of a catamaran section. Their section consisted of identical asymmetric twin wedges connected with a wet deck structure. The wedges were vertical on the inboard side and non-vertical on the outboard side. They performed drop tests of a set of twin wedges with deadrise angles of 7, 15 and 20 degrees. They studied the effect of tank depth, three-dimensional effects, sampling rate and repeatability. The results showed that the demi-hull spacing did not have a considerable effect on the peak pressure on the bottom of the wedges. They found air entrapment on the vertical side of the twin wedges and below the wet deck.

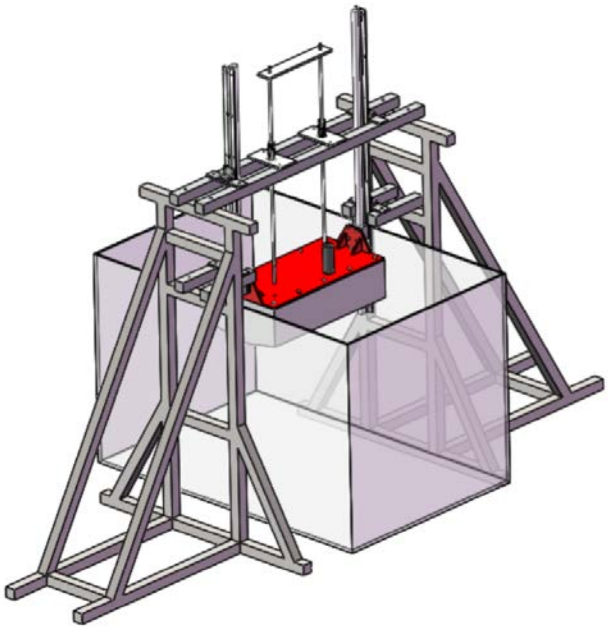

Figure 11: Drop test setup (Guo et al., 2017)

Kim et al. (2017a) studied the characteristics of various pressure sensors for measurement of wave impact loads. They used drop tests with a free-falling wedge to study peak pressures, rise times and pressure impulses measured by the different types of pressure sensors. On the basis of these results, the characteristics and reliability of the pressure sensor for the measurement of the water impact load were discussed.

Zeraatgar et al. (2019) discussed the effect of the sampling rate on the impact pressure of wedge water entry tests. Also they used drop tests, and showed that although 25 kHz sampling rates were appropriate for deadrise angles of 25 degrees and higher, for lower deadrise angles higher sample rates should be used, of up to 600 kHz for a deadrise angle of 5 degrees.

2.4.1.2 Numerical

Where a decade ago analytical or empirical Von Karman or Wagner based approaches and two-dimensional potential flow solutions were still commonplace for water impact problems, over recent years a shift has taken place towards more advanced CFD methods and meshless methods such as the Smoothed Particle Hydrodynamics (SPH). Many studies focus on the effect of compressibility.

Bašić et al. (2017) presented a meshless Langrangian method for the hydromechanic loads during water entry of a rigid body. They based an unsteady incompressible solution on the Pressure Poisson Equation reformulation of the Navier-Stokes equations. They applied a novel meshless discrete Laplacian avoiding the need for a volumetric mesh. Validation against wedge section water-entry results from literature (Figure 12) showed that pressure and velocity fields during the water entry were well-reproduced. Numerical damping near walls and the free surface still needs further improvement.

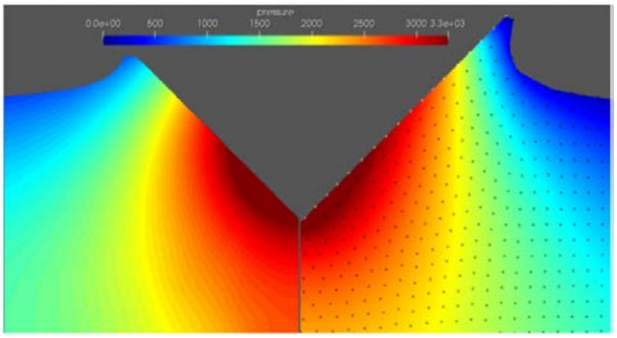

Figure 12: Comparison of numerical results (right) with PIV pressure contours (Bašić et al., 2017)

Falahaty et al. (2018) proposed a fully-Langrangian computational method for the simulation of incompressible fluid-nonlinear structure interactions, based on an enhanced Incompressible Smoothed Particle Hydro-dynamics (ISPH) solver combined with a SPH-based Hamiltonian structure model (HSPH). Validation included a dam break problem with an elastic gate as well as elastic wedge impact (Figure 13) and hydroelastic marine plate slamming.

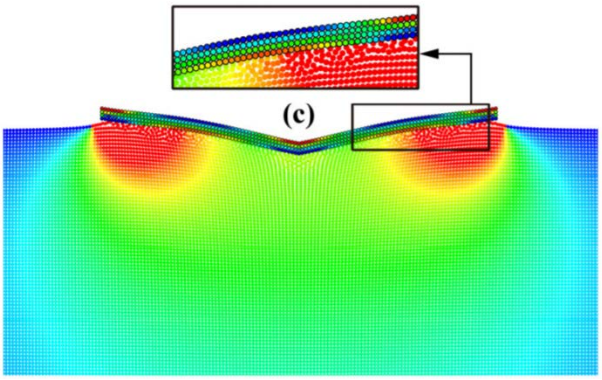

Figure 13: Hydro-elastic wedge impact with ISHP-HSPH method (Falahaty et al., 2018)

Sun at al. (2019) used a mixed mode function-modified MPS (Moving Particle Semi-implicit) method to simulate slamming on the cross deck of a trimaran with rigid and flexible arches. The water was considered as an incompressible inviscid fluid and the “conceptual particle” model was used to enhance the stability of the intense free surface interaction during the “filling-up” process under the cross deck. The results for rigid arches obtained with the use of an improved free surface condition show good improvement, in comparison to the experiment data. From the study of flexible arch cases with different flexibilities, it was found that the flexible structure can reduce the local pressures and slamming loads. In another study Sun et al. (2020) applied an incompressible CFD approach to study the pressures and load characteristics of a very similar trimaran section. They investigated three different motions: free fall, constant vertical velocity and harmonic vertical velocity, with all three motions having the same entry velocity of 1.7 m/s. The constant velocity case produced a significantly larger pressure compared to the other motions.

Jiang et al. (2018) also applied a RANS-based CFD method to the problem of water entry of a rigid body with a low deadrise. Both water and air were included in the computations, allowing to study air-cushioning effects. They found that the average impact force coefficient was constant as function of entry depth and that the oscillation period of the impact force decreased after the air-cushion was formed.

2.4.1.3 Comparative Study

A comparative study of a water-entry problem was conducted as a focused session of ISOPE-2016 in Rhodes by the International Hydrodynamic Committee (IHC) of ISOPE (Hong at al., 2017). Thirteen institutions participated, and twenty different numerical results were investigated and compared with one another and with model test data. Some promising results were obtained even though arriving at general conclusions is still a long way away.

The experimental results consisted of two-dimensional triangular wedge drop with a 30 degree deadrise angle and a ship section drop. The test results were provided by the WILS JIP-III. The wedge results included a symmetric impact case and a 20 degree inclined asymmetric case (Figure 14). Instrumentation included two pressure sensors, two impact force transducers and a high speed camera.

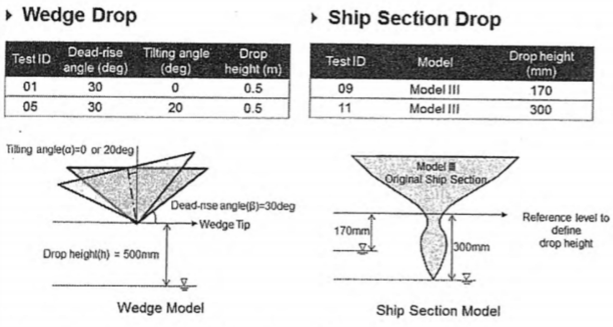

Figure 14: Wedge and ship section used for the IHC comparative study (Hong at al., 2017)

The numerical methods included potential flow Boundary Element Methods (BEM(based on Generalized Wagner Method and the Modified Logvinovitch Method, CFD methods based on the Finite Volume, Finite Element and Finite Difference Methods (FVM, FEM and FDM) and particle based methods (Langrangian methods such as SPH and MPS). In some cases compressibility was considered.

With the limited number of cases and participants it was not possible to arrive at general conclusions, but some important observations were made. CFD results were found to be very promising for symmetric impact, but there remained quite some uncertainty for the asymmetric impact case. The ship section drop case showed a larger spread in the results than the wedge drop, especially for the potential flow results. This is most likely related to the formation of air pockets for the ship section drop case. Peak pressures showed a better agreement than rise and decay times. The results were found to be very sensitive to grid generation and prone to human error, emphasizing the need for grid convergence studies. The use of filtering to remove oscillations in the time traces should be carefully considered and explained.

Yang et al. (2017b) applied an incompressible Immersed Boundary Method (IBM) to both the wedge and the ship section. Besides the incompressible IBM, they also performed numerical simulations with OpenFOAM that included compressibility and compared against experimental results. They found that the IBM performed reasonably well considering that compressibility was ignored and the results were sensitive to mesh and grid sizes.

Kim et al. (2017b) present the results of potential-based methods and computational fluid dynamics (CFD) for the water-entry impact of the wedge and ship-like section (Figure 15). In the potential-based computation, a Generalized Wagner Model (GWM) and a Modified Logvinovich Model (MLM) were used. In the CFD computations, a constrained interpolation profile (CIP)-based method and commercial software were used for the prediction of fully nonlinear slamming phenomena. The grid convergence index for the peak pressure was analyzed for both CFD computations. Accuracy was investigated in terms of the peak pressure, pressure distribution, local hydrodynamic force, and free-surface shape.

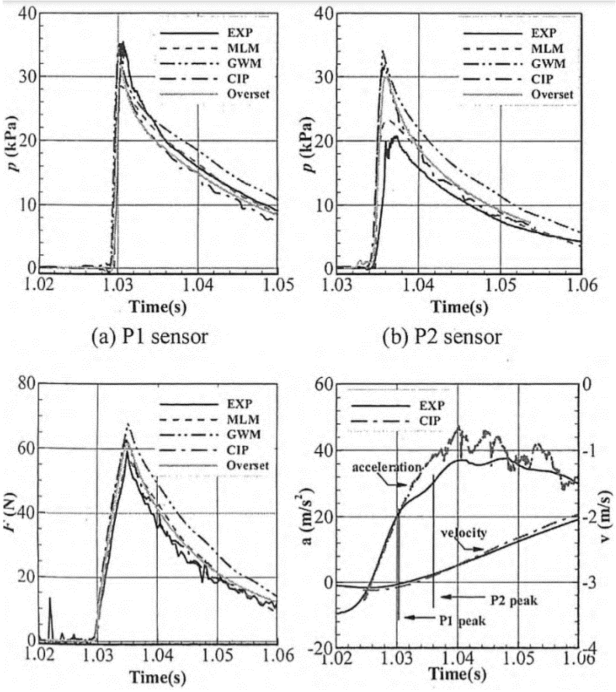

Figure 15: Comparison of experimental and computational results for wedge drop (Kim et al., 2017b)

Ma and Liu (2017) used a two-phase Smoothed Particle Hydrodynamics (SPH) method. From a comparison of the numerical results and the measured data, it was found that good agreement can be achieved. The later stage of the cavity evolution for the wedge water entry and the formation of the entrapped air cavity for the ship-section water entry were simulated well by the two-phase SPH method.

Monroy et al. (2017) compared two different classes of methods to the experimental cases: potential theory based on a Wagner model and computational fluid dynamics (CFD) based on a finite volume method with a volume-of-fluid (VOF) interface. They stressed the importance of finding a compromise among the wide range of available methods for slamming impacts related to CPU time, setup time (i.e. engineering time) and accuracy.

2.4.2 Slamming

Slamming assessments are focused on quantifying the occurrence rates of bow slamming and stern slamming, as well as quantifying the magnitude of the impact loads. In recent years there is an increased focus on oblique wave impact, with multiple sources reporting larger impact loads than in head seas in particular cases. This highlights the need for carefully considering the influence of wave heading on slamming.

Most computational approaches employ a combination of calculation methods of different levels of fidelity. Lower fidelity methods such as 2D or 3D potential flow methods are used to quantify the overall motions, slam occurrence rates and relative impact velocities. Individual impacts are then investigated in further detail by using dedicated computational approaches. These approaches vary from considering water entry of two-dimensional ship sections, as described in section 2.4.1 to considering a three-dimensional impact of larger sections of the vessel.

Various methods are applied to obtain the structural response, from simple beam models to 3D FEM methods. In many cases hydroelastic coupling is considered. This section focuses on the quantification of occurrence and magnitude of slamming. Hydro-elasticity is treated in more detail in section 2.6.

2.4.2.1 Bow slamming.

Ge et al. (2018) performed CFD computations to predict slamming loads for a moving ship (Figure 16) in head waves and in oblique waves. They used an in-house code based on OpenFOAM. The CFD results for the head-sea case showed excellent agreement with the corresponding model experimental data (see for instance Figure 17). For oblique seas, the CFD results showed good comparisons with the model test data for the heaving, pitching motions, the hull pressure patterns, and the vertical forces on the ship segments. Higher discrepancies were evident in the comparison of rolling motions and transverse forces on ship segments as well as the peak values of the pressures, highlighting the need for further improvements for oblique sea cases.

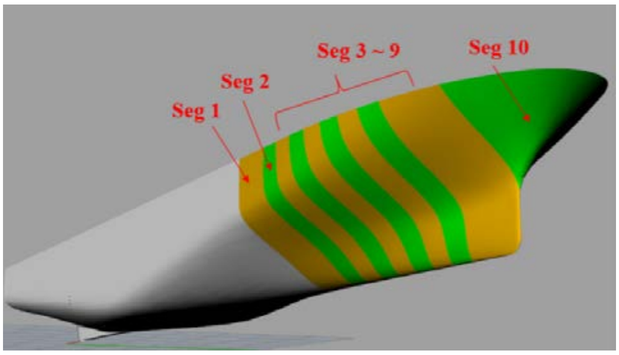

Figure 16: Forebody of the model split into 10 segments (Ge et al., 2018)

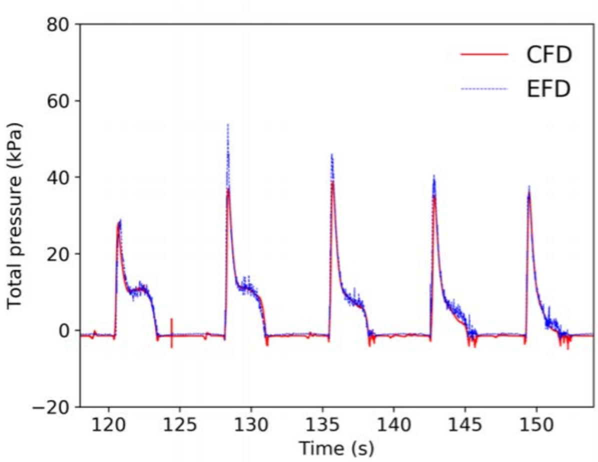

Figure 17: Pressures time histories for CFD vs EFD in head seas (Ge et al., 2018)

Kim et al. (2019a) conducted an experimental study on the spatial distribution of bow flare slamming loads of ultra-large container ships. They used a 1/60 six segmented scale model of a 10,000 TEU container ship, with 15 force transducers on the bow flare surface to measure impact loads. They found that in regular waves the slamming pressures were higher for oblique directions compared to head waves. In an irregular wave test, extremely large slamming loads were measured at the centre line at the bow, influenced by the horizontal relative velocity such as the ship speed and surge. They noted that in an analysis of the slamming load of the ship, the direction of the wave and forward speed of the ship should be carefully considered, which is difficult to achieve with two-dimensional analysis.

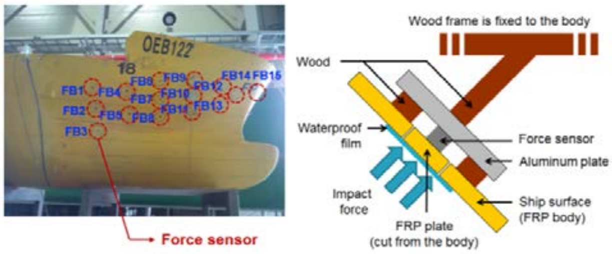

Figure 18: Setup for force sensors for measurement of impact loads (Kim et al., 2019)

Lin et al. (2018) proposed an approximate prediction method for slamming loads in parametric rolling conditions for large container vessels. They combined a weakly nonlinear time domain model for prediction of the ship motions with a Wagner model for asymmetric impact. They validated the approach with model tests with a segmented model of a 10,000 TEU container vessel. Their results indicate that while the bow flare slamming pressure is smaller than for bottom slamming, the pulse duration is longer and the occurrence of bow flare slamming is associated with the cycles of parametric rolling motions.

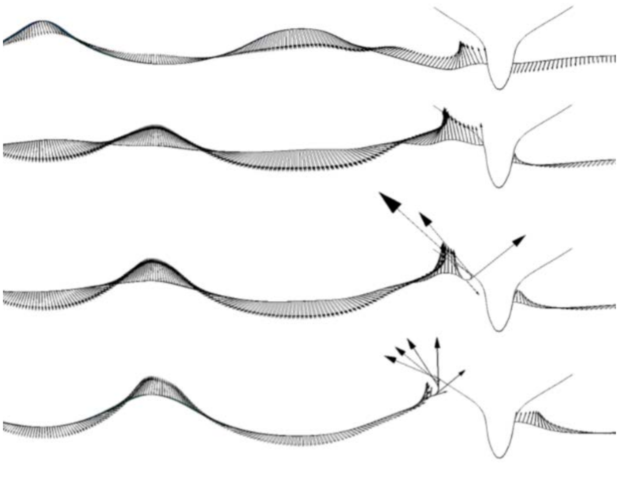

Figure 19: Free surface profiles and surface velocities of short waves (Sun and Helmers, 2020)

Sun and Helmers (2020) studied the influence of short wave components on the bow slamming loads. They developed a nonlinear numerical wave tank based on a Boundary Element Method and carried out simulations for a bow-flare section in short beam waves modelled with a nonlinear Higher Order

Spectral Method (Figure 19). Their results imply that the nonlinear characteristics of the incident short wave components can lead to higher peak pressures.

Wang et al. (2018) investigated the bottom slamming at the bow and stern of a chemical tanker and an LNG carrier advancing in irregular waves numerically and experimentally. They applied a simplified method to include the effects of body nonlinearity by evaluating radiation and diffraction forces in the time domain as function of the instantaneous wetted surface. They determined the relation between relative wave height, impact velocity and peak slamming pressure at the stern and at the bow for both vessels from the experiments and combined this with the slamming probability obtained from the numerical simulations.

Xie et al. (2018) also systematically studied the bow-flare slamming loads of an ULCS in oblique waves. They combined a frequency domain Boundary Element Method to predict the relative motions at the bow and CFD on the oblique water entry of two bow sections to predict the slamming loads. Their results showed that transverse and roll motion cannot be ignored in oblique waves. Pressure characteristics in different wave directions were discussed and also their results showed that slamming loads in some oblique wave cases were larger than that in head seas.

Yang et al. (2017a) considered the dynamic response of the bow structure of a large container ship subjected to slamming pressures. They derived a simplified slamming pressure pulse characterized by its amplitude, duration, shape, spatial distribution and travel duration over the hull. Using this they studied the dynamic response of the bow structure as function of the pressure pulse characteristics. They found that for symmetric load shapes (i.e. the pulse rise time equals the duration of load decrease) led to lower stress responses compared to more realistic asymmetrical load shapes (i.e. the rise time is smaller than the duration of load decrease). The position of the maximum slamming pressure was found to be an important parameter for the dynamic response of bow structure under slamming pressures.

2.4.2.2 Stern slamming

Mutsuda et al. (2018) investigated the characteristics of stern slamming pressures, such as occurrence mechanism, space-time distribution and influence of the local deadrise angle and relative vertical velocity by performing water entry tests of a wedge model and a stern section (Figure 20). Besides water entry tests they also performed model tests in irregular seas and numerical computations based on the Smoothed Particle Hydrodynamics method. They presented an extensive comparison of the results.

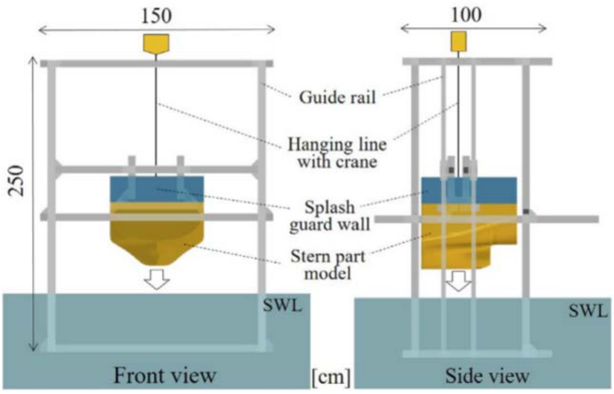

Figure 20: Experimental setup for the water entry tests of a stern model (Mutsuda et al., 2018)

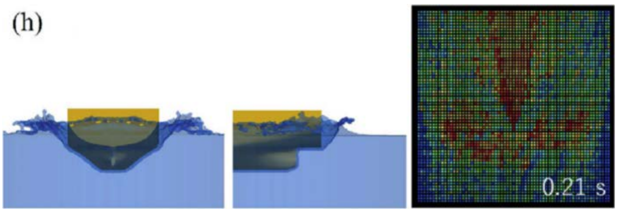

Figure 21: Numerical results of stern impact using SPH (Mutsuda et al., 2018)

Wang and Soares (2016) applied an Arbitrary Lagrangian Eulerian (ALE) algorithm implemented in LS-DYNA and a Modified Logvinovich Model (MLM) to predict the stern slamming loads of a chemical tanker. They used a nonlinear time domain strip theory program to compute the ship motions for a range of irregular sea states and used the relative vertical velocity in the ALE and MLM methods to simulate the water entry of 2D stern sections. A comparison of the results of both methods was made with results from model tests.

2.4.3 Slamming on High-Speed Craft

For high speed craft operating at sea slamming becomes an event that occurs almost every single wave encounter – hardly a ‘rarely occurring event’. For this reason slamming of high speed craft is an integral part of the assessment of its seakeeping performance with respect to structural integrity as well as human safety. This topic is included in section 2.9 on High Speed Marine Vehicles (HSMV).

2.4.4 Green Water

Green water and impact due to green water on the deck is associated with very complex three-dimensional water flow. Enclosed air pockets can have a large effect on the magnitude of the impact loads. Similar to slamming, in many cases multiple fidelity levels are combined to make a full prediction of green water loading, with more standard and efficient potential flow methods employed to compute the overall motions and high fidelity multi-phase CFD computations for the green water problem itself. The well-known dam break problem is still an important validation case for these high fidelity tools.

2.4.4.1 Numerical

Van der Eijk and Wellens (2019) extended a volume of fluid method for simulations of extreme wave interaction with maritime structures with a Continuum Surface Force (CFS) model for surface tension to improve gas-water interaction after free surface wave impacts. The method was applied to a dam-break simulation in which the impact on a wall leads to an entrapped air pocket. Surface tension was found not to have an influence on entrapped air pocket dynamics of air pockets with a radius larger than 0.08 metres. For wave impacts it was found that the effect of compression waves in the air pocket dominates the dynamics and leads to pressure oscillations that are of the same order of magnitude as the pressure caused by the initial impact on the base of the wall.

He et al. (2017) performed time-domain simulations on green water of a Wigley hull sailing in regular head waves, using multiphase-flow CFD (Figure 22). They developed a solid-liquid-gas three-phase flow coupling model by adopting the BRICS compressible discrete scheme to reduce numerical diffusion near the free surface. By using this numerical model, impact loads on deck and hull, ship motions and hydrodynamic characteristics during the green water process were investigated.

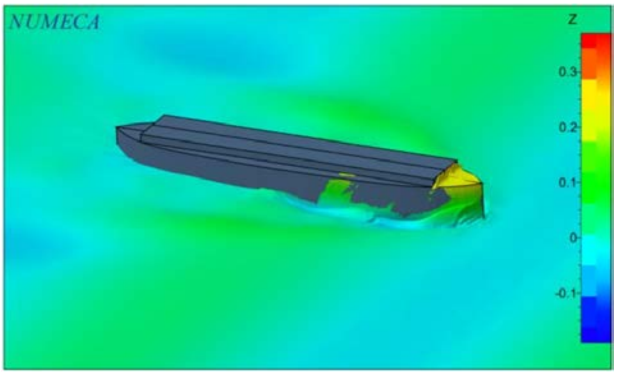

Figure 22: Green water on a Wigley hull (He et al., 2017)

Hernandez-Fontes et al. (2017) studied an alternative approach for isolated green water events by using a wet dam-break to generate the incoming flow. Tests were carried out in a rectangular tank with a fixed structure. Different freeboard conditions were tested for one aspect ratio of the wet dam-break (h0/h1=0.6). High speed cameras were used to investigate the initial phases of green water. The results demonstrated the ability of this approach to represent different types of green water events.

Kudupudi and Datta (2017) modelled green water loading on an oscillating body using CFD. The vessel motion was calculated a priory using time domain panel method code, before computing green water impact based on the pre-calculated motion. A Finite Volume Method was used to capture the green water impact combined with a Volume of Fluid Method to capture the free surface. They demonstrated that impact loading phenomena are significantly affected by the ship motions compared with results obtained from fixed vessel cases.

Kudupudi et al. (2019) used a similar approach combined with a Finite Element Method to study the effect of green water loading on the global structural response. They applied the approach to a large container vessel with and without forward speed in waves. They concluded that the proposed three-step (time domain simulation for motions, green water loading with CFD and FEM for the structural response) model is a useful practical tool to predict green water loading.

Liao et al. (2017) presented a 3D hybrid Eulerian-Lagrangian method for simulating green water on a ship. They considered three benchmark cases: dam-breaking, wave impact on fixed structure and green water on ship, showing reasonable comparison between experimental data and numerical results.

2.4.5 Emergence and Ventilation

Emergence is usually studied by obtaining the relative wave height at locations of interest. These locations can include propellers, rudders, stabilizer fins as well as sonar apparatus. Experimentally usually relative wave probes of various types are applied at such locations and counts where the relative wave height exceeds a threshold are used to identify emergence events. Numerically, usually a direct computation of the relative wave height at locations of interest can be made. Depending on the fidelity of the numerical approach, the disturbance of the local wave profile can be included with various degrees of accuracy.

Experimental measurements of the variation of the lift, drag, and moment coefficients on a rigid and a flexible surface-piercing hydrofoil at different submergence levels, angles of attacks, and speeds across a range of flow conditions ranging from fully wetted, partially cavitating, partially ventilated, and fully ventilated can be found in Harwood et al. (2016, 2019). The results show that the lift and moment coefficients reduce rapidly with reduce submerged aspect ratio (e.g. as the rudder or propeller emerges) because of increased 3-D effects and pressure relief at the free surface. In theory, the 2-D lift coefficient reduces by 75% in fully ventilated (FV) flow compared to fully wetted flow (FW). For 3-D bodies, the lift coefficient generally reduces by ~50%, but the moment coefficient can reduce by 70% or more because of reduction in lift compounded with move of the center of pressure to near the midchord. The change in hydrodynamic load coefficients due to transition from FW to FV flow can occur gradually or very rapidly (in less than a second) depending on the ventilation mechanism.

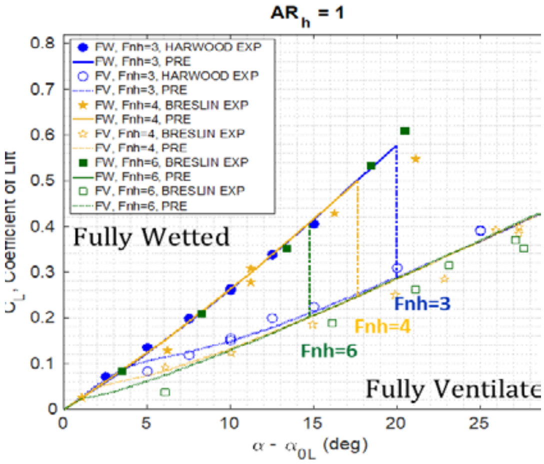

Figure 23: Hysteresis response of the lift coefficient as function of incidence angle and chord Froude number (symbols: experiments, lines: predicted, Damley-Strnad et al., 2019)

The hydrodynamic response is also highly hysteretic, as illustrated in Figure 23. The sudden and drastic load changes and hysteretic response can significantly challenge design of controllers and auto-pilots. To facilitate design and control of lifting devices subject to ventilation, semi-empirical equations of the hydrodynamic performance can be found in Damley-Strnad et al. (2019), which showed good comparison with experimental measurements, as demonstrated in Figure 23.

A series of experimental studies of ventilation of marine propellers can be found in Kozlowska et al. (2017, 2020), along with empirical equations to predict the steady and dynamic propeller performance in different flow regimes. Similar to a hydrofoil or strut, ventilation can lead to significant reduction in thrust and torque (as demonstrated in Figure 24), which will lead to rapid increases in propeller rpm to maintain thrust, or reduction in vessel speed. Scaling of the hydrodynamic performance of marine propellers in ventilated flows, and discussion of the hysteretic response can be found in Kozlowska et al. (2017, 2020). A recent review of the physics of ventilation can be found in Young et al. (2017).

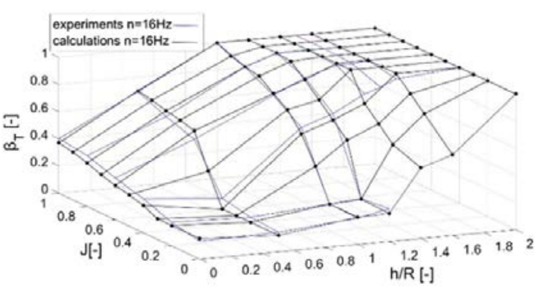

Figure 24: Comparison between calculation and experimental values of thrust loss (β_T) due to ventilation and out of the water effects for shaft submerged depth to propeller radius ratio, h/R, and advance coefficient, J. (Kozlowska et al., 2017)

Recent reviews of the hydroelastic response of propellers and hydrofoils can be found in Young et al. (2016, 2017) and Young (2019). The topics discussed include the effects of emergence, cavitation, ventilation, hydroelastic performance and instability mechanisms. In general, for a hydrodynamic lifting device made of solid and homogeneous material with the center of pressure upstream of the elastic axis, elastic deformations will lead to bending towards the suction side and nose-up twist, which will act to increase the lift and moment, and accelerate cavitation, ventilation, stall, and may lead to static divergence instability. However, these effects can be countered by taking advantaged of material anisotropy and geometric bend-twist coupling provided by sweep (Liao et al., 2019).

The influence of changing submergence (such as caused by emergence) and ventilation on the hydroelastic response of a surface-piercing strut/hydrofoil was studied experimentally in Harwood et al. (2019,2020) and Young et al. (2020). Examples of the measured variation of the measured modal fully wetted (FW) and fully ventilated (FV) modal frequencies as a function of the submerged aspect ratio (AR_h) are shown in Figure 25. They found that, in general, as submergence decreases (body emerges), the system modal frequency increases because of reduction in added mass. The modal frequencies also tend to be higher in FV flow compared to FW flow because the replacement of dense water to light air on the suction side of the body. In addition, since added mass depends on the direction of motion and/or deformation, mode switching and modal coalescence can occur (such as shown for the surface-piercing strut at $AR_h = 2$ shown in Figure 25). The measurements also showed significant dynamic load amplifications caused by modal coalescence (Young et al., 2020; Young, 2019).

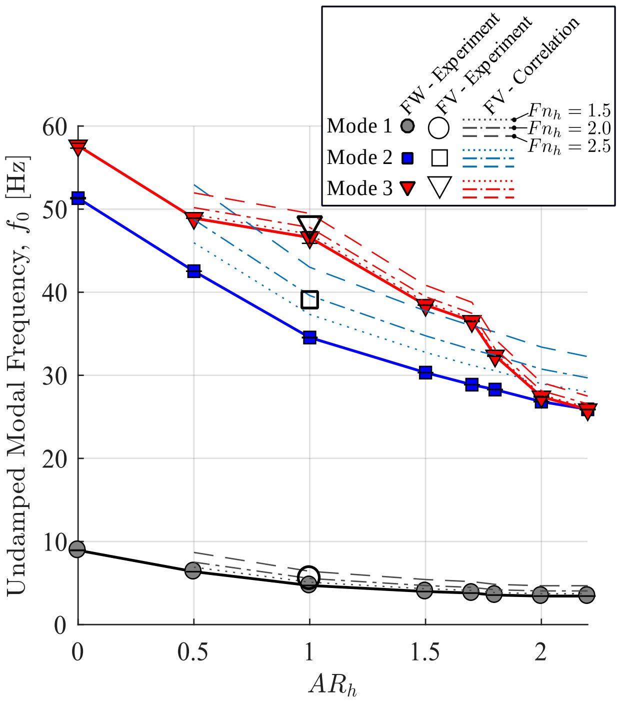

Figure 25: Measured variation of the fully wetted (FW) and fully ventilated (FV) modal frequencies as a function of the submerged aspect ratio (AR_h). From Harwood et al. (2020) and Young et al. (2020).

2.5 Sloshing

Assessment of sloshing loads for LNG tanks has been an issue of significant interest by the shipbuilding industry owing to the recent renewed interest into the transportation of LNG. Until now, it has been believed that only experiments can provide reliable data to evaluate the impact load for the sloshing problem. Malenica et al. (2017) reviewed recent approaches to assess sloshing loads describing the industrial experiments as well as numerical simulations. The study concluded that performing model experiments has been the most frequently used and relatively reliable approach.

Ahn et al. (2019a) described details of sloshing experiments in an industrial site and investigated the possibility to adopt a machine learning scheme. They developed an artificial neural network (ANN) to predict the sloshing load severity. They showed the ANN model has an acceptable performance considering the highly nonlinear and complex nature of the sloshing problem, by comparing against experiments that have not been part of the training process (Figure 26).

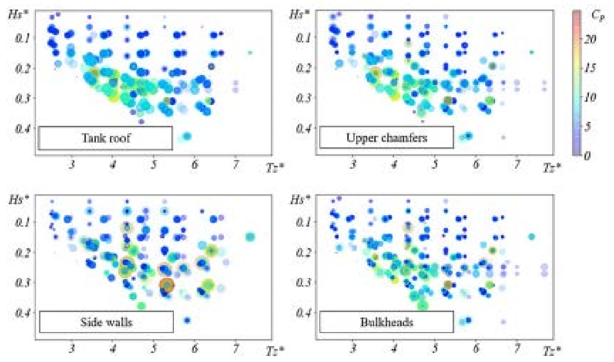

Figure 26: Scatter diagram of sloshing impact pressure coefficient with respect to environmental conditions (Ahn et al., 2019a)

Fluid-structure interaction (FSI) is an important topic for the sloshing tank. Taian et al. (2019) showed a numerical study on the influence of elastic baffles on the sloshing loads. Zhang et al., 2018 performed numerical simulations of the sloshing flows inside an elastic wall tank (Figure 54). An analytic model was developed to assess the effectiveness of a porous elastic baffle on liquid sloshing by Cho (2021). He applied the matched eigenfunction expansion method (MEEM) with the Green function for the liquid sloshing interaction with the porous elastic baffle.

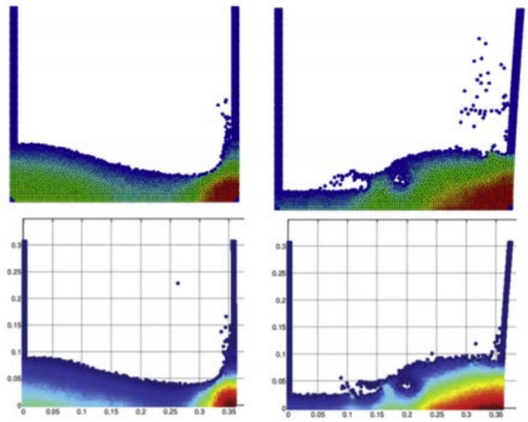

Figure 27: Numerical simulation for sloshing flows in an elastic tank (Zhang et al., 2018)

The most profound issues in violent sloshing flows are related to the effects of density ratio and bubbles on the sloshing impact. Ahn et al. (2019b) carried out a sloshing model tests considering gas-liquid density ratio. They proposed an experimental procedure for handling an alternative gas mixture to match the density ratio. Through a series of experiments, they showed that the density ratio clearly affected the sloshing impact pressure. It appears that the sloshing impact pressure decreases with the increase of density ratio, which means the conventional sloshing test using air-water may give more significant sloshing impact pressures compared to the model test based on the density ratio of an actual LNG cargo hold.

Kim et al. (2017c) observed the effects of the phase transition and bubbles on the impact pressure through a small scale drop test. On the basis of this experiment, it was confirmed that the existence of bubbles decreases both the peak pressure and the impact duration. In addition, it was found that the amount of vapour trapped in the gas pocket was important to generate the phase transition effect which is related to the damping effect.

Sloshing is induced by the ship motion but in return, the ship motion is also affected by the sloshing-induced load. There have been various research efforts on the coupled dynamics between the ship motions and sloshing problem. (Huang et al., 2018, Bulian et al., 2018, Saripilli and Sen., 2018, Lyu et al., 2019). Figure 28 shows snapshots of a coupled numerical simulation of an LNG carrier in waves with sloshing LNG tanks. In addition, Seo et al. (2017) studied the effect of internal sloshing on added resistance of ship applying numerical approaches. They showed the sloshing flows inside the inner tanks may significantly influence not only the ship motion, but also the added resistance, especially near the resonance frequency of the sloshing flow.

Figure 28: Numerical simulation of coupled ship motion and tank sloshing of an LNG carrier in head wave (Lyu et al., 2019)

Kwon et al. (2018) investigated the sloshing load for a single-row arrangement system into a midscale floating production unit of liquefied natural gas platform. Through the sloshing experiments, they evaluated the significant wave height limit for the offloading operation. Also, a sloshing severity index was calculated and compared with the sloshing model test results.

2.6 Hydroelasticity

There has been much progress over the last five years on the experimental and numerical modelling of the hydroelastic response of marine vessels at sea. A brief summary of representative literature concerning experimental modelling is presented first, followed by theoretical and numerical modelling.

2.6.1 Experimental

2.6.1.1 Full-scale studies

Full-scale measurements of slamming loads and structural responses of a 9.6 m high-speed planning craft in different sea conditions and at different speeds and headings can be found in Camilleri and Temarel (2018). They found that the ISO standard and DNV rules predicted pressures that are significantly lower than the measured values, while the LR rules predicted pressures that are higher than the measured data for high forward speeds and lower for moderate speeds.

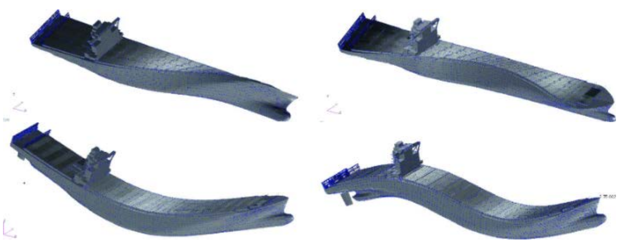

Figure 29: Predicted torsional and vertical bending modes of an 8,600 TEU container ship (Miyashita et al., 2020).

Miyashita et al. (2020) presented full-scale measurements of an 8,600 TEU container ship taken over four years and two months. The focus was on the influence of sea states and navigational conditions on the whipping response of hull girder. Vibration analysis, including the added mass on the hull surface, was used to derive the vibration modes related to vertical bending and torsion, such as shown in . They found that the vertical bending stress is dominant and accounts for 81% of the total stress. Whipping response on the vertical bending stress was significant in head seas, while it was not observed in beam seas or following seas. They also found that higher ship speed will lead to a higher whipping factor in head seas.

2.6.1.2 Operational Modal Analysis

Multiple full-scale studies were conducted to investigate the modal characteristics of marine vessels via operational modal analysis (OMA). One of the early works of OMA for marine vessels was conducted by Kim et al. (2016), who used OMA to extract the modal parameters (vertical and torsional mode shapes and damping ratios) to characterize the hydroelastic response of a 1/60-model scale segmented container carrier subject to head waves and oblique waves. They later extended the method to determine the modal characteristics of a full-scale 9400 TEU container ship by POD analysis of acceleration signals in Kim et al. (2018). They found that the natural frequencies and damping ratios vary with loading conditions, where the 2-node vertical bending varied from 0.45-0.6 Hz, and the damping ratio varied between 1-3%. They also noted that fatigue damage increased by ~70-85% due to vibrations.

Hageman and Drummen (2019) presented a time-domain Auto Regression Moving Average (ARMA) method for Operational Modal Analysis based on Stochastic Subspace Identification (SSI). The method was found to be able to determine the frequencies, mode shapes, and damping characteristics of the system based on acceleration and strain measurements. Hageman and Drummen (2020) later extended the method for in-service measurements of the operational mode and damping characteristics of a frigate type vessel. They found that the added mass changed with operations in confined waters, heading, and speed, with variation in natural frequency as high as 10%. Moreover, they found that damping depended on speed and wave height, with values ranged from 0.6 to 2.5%.

Shakibfar et al. (2020) presented full-scale measurements of the damping characteristics of an 8400 TEU container ship obtained using operational modal analysis. They found that the natural frequencies of all the modes, except for 2-node vertical bending, decrease with increasing speed, and the damping factors to increase with increasing speed for both the vertical bending and the torsion mode.

Operational modal analysis was also used in Harwood et al. (2020) to determine the change in modal frequencies and damping coefficients of a cantilevered surface-piercing strut with operating conditions. They found that the modal frequencies reduced with increasing immersion, and increased with increasing cavitation and/or ventilation, due to changes in the fluid added mass. The damping ratios generally increased with increasing immersion and with forward speed, and is a nonlinear function of the reduced resonance frequency. A later work by Young et al. (2020) also showed that changes in modal characteristics with immersion can lead to frequency coalescence, which resulted in significant dynamic load amplification.

2.6.1.3 Scaling of Vibrational Response

A new design procedure for model-scale testing of flexible containership was proposed in Houtani et al. (2018) to ensure similarity of the vertical-bending and torsional vibration response between the model and the prototype. They noted that the height of the shear center of the model must be located below the hull bottom, like that of an actual container ship with a large open deck, to achieve similarity in the torsional vibration mode. They met the design conditions by using urethane foam to build the hull and without a backbone, and demonstrated the ability of the method in measuring the dynamic elastic response in waves.

2.6.1.4 Slamming and Whipping

Wang et al. (2020) presented experimental data on the calm water slamming impact of a series of three aluminium plates with different thicknesses. The results showed that the peak force and moment increased, the time of the peak force increased, and spray height increased, with reduction in the plate thickness.

Javaherian et al. (2020) presented experimental study of calm water entry of flexible bottom panels, and towing tank test of a rigid composite planning hull. Compared to a rigid aluminium panel, the measured peak pressure of the flexible aluminium and composite panels dropped by 4% and 10%, respectively.

Spinosa and Iafrati (2021) presented experimental studies of the fluid-structure interaction of the high-speed water impact of varying thickness aluminium plates. They found that plate deformation lead to reduction in the pressure peak, a subsequent pressure rise, and a change in the direction and shape of the spray root. The structural deformation lead to an increase in the total loading by up to 50%. They also discussed the challenges with scaling the fluid-structure interaction response.

Full-scale measurements, as well as model-scale measurements and numerical simulations of a segmented model of wetdeck slamming on a wave-piercing catamaran can be found in Lavroff et al. (2017). The 2.5 m segmented model was designed to match the scaled first longitudinal modal (whipping) frequency and damping ratio measured for the 112 m full-scale INCAT vessel. Good general agreement is observed between the model-scale experiment and predictions using CFD and FEA analysis, but there were some deviations in the peak slamming load and location. Full-scale measurements were complicated by uncertainty of the sea state, but the full-scale slam impulses were generally less than those measured at the model-scale. The authors suggested that the differences are probably due to a difference in the identification of the slam duration.

Slamming induced whipping computations were conducted for a large database of 17 post-Panamax container ship models in Lauzon et al. (2020). The calculations include 1-way and fully-coupled hydroelastic computations for long term wave vertical bending moments in full irregular sea states, with and without whipping, to get the global whipping factor for each ship. The results are summarized in Figure 30. They showed that 1-way coupling method always gave a large overestimation of the whipping factor for both hogging and sagging. The reason for the overestimation is because the slamming loads do not influence the rigid-body motions in the 1-way coupled simulations, which lead to over-prediction of the pitch motions, and hence higher slamming loads. The results also showed that using a low-pass filter of the measured response to extract the rigid-body moment, lead to negligible difference in the hogging, but a large overestimation of the whipping factor for bending due to under-estimation of the nonlinear rigid-body moment in sagging. The results also showed that both regular and irregular equivalent design waves (EDW) give acceptable precision in sagging, but there was a large scatter in hogging for regular design waves.

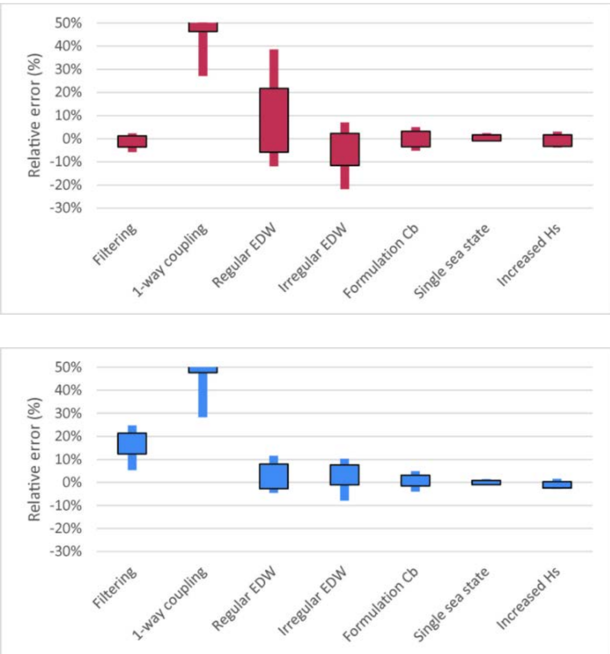

Figure 30: Relative error in the evaluation of the whipping coefficient in hogging (top) and sagging (bottom) (Lauzon et al., 2020).

2.6.1.5 Wave statistics of hydroelastic response

The short-term statistics of hydroelastic loads of an ultra large containership in head and oblique seas was investigated using combined numerical and experimental techniques in Rahendran and Soares (2018). A 2D body nonlinear time domain method was used for the numerical model, which showed good agreement with experiments of a container ship at low Froude numbers. The results show that the ship encountered the largest hogging and sagging peaks in oblique waves instead of head seas because the larger high frequency waves with shorter period was in proximity to the first natural period, i.e. dynamic load amplification due to near resonant condition.

The statistics of extreme hydroelastic response of large ships was examined using the ACER (Average Conditional Exceedance Rate) method in Gaidai et al. (2018). The results showed that the method can capture extreme tail statistics for sagging and hogging. The method also accounted for the effect of data clustering, which played an important role in whipping.

2.6.2 Analytical/Numerical

2.6.2.1 Analytical models

Sun et al. (2021) presented a semi-analytical model for hydroelastic slamming predictions. The method is based on analytical Modified Logvinovich Model of the hydrodynamic loads coupled with modal description of the elastic deflections. The analytical predictions were compared with experimental measurements of the forces and deflections for wedge water entry and cylindrical shell drop problems. The method provided efficient predictions at the initial slamming stage, but not the deep penetration stage with large flow deformation.

Yu et al. (2019) performed a hydroelastic analysis on water entry of a constant velocity three-dimensional wedge with stiffened panels, assuming incompressible flow while applying potential flow theory. Based on the Wagner theory, they developed a semi-analytical hydrodynamic impact theory for the analysis of elastic wedges. They coupled two-dimensional impact in the cross sectional fluid domain to modal analysis of the three-dimensional structure, making the model suitable for complex three-dimensional shapes. The new method incorporates the effect of flow separation on the responses and follows more detailed CFD results better than more traditional Wagner based approaches. Through the comparison between coupled and decoupled results of a 3D wedge, it is shown that the effect of fluid-structure interaction and the oscillatory response after flow separation are important for predicting the structural responses.

2.6.2.2 BEM-beam models

Riesner et al. (2018a) presented a linear frequency-domain hydroelasticity method to predict the wave-induced global hydroelastic ship response. They used a coupled 3-D boundary element method with a Timoshenko beam element model, and the method was designed to be suitable for both short and long period waves.

Heo and Kashiwagi (2019) used a time-domain higher-order boundary element method coupled with a generalized mode expansion model for the structure to predict the springing response of an elastic body. They used the method to demonstrate the importance of second-order velocity potential on wave-induced vibrations for different flexural rigidity and forward speed.

Bakti et al. (2021) coupled a discrete-module-beam structural model with a potential flow model based on slender body theory and low forward speed approximation. The predictions compared well with experimental and other computational results of a Wigley hull with and without forward speed. The results showed significant difference between dry and wet natural frequencies, and change in the first bending mode shape with forward speed.

Zhang et al. (2017) presented a 3-D nonlinear time-domain hydroelasticity method that combines a 3-D dynamic Timoshenko model with a 3-D nonlinear hydrodynamics model based on Green's function. Good comparisons of the predictions were observed with experimental measurements of the nonlinear effects on the vertical motions and loads on a container vessel advancing in irregular waves. The method was later extended in Jiao et al. (2019, 2020) to predict the motions and loads of a large bow-flared ship advancing in irregular seas. The effects of nonlinear Froude-Krylov force, radiation force, and slamming loads were considered. Good comparisons were observed with experimental measurements of the frequency spectra and statistics of the ship motions, deformations, and loads in regular and irregular waves of a 1:50 segmented model with large flare-bow.

2.6.2.3 BEM-FEA models

Im et al. (2017) used a fully coupled 3-D FEM-3-D BEM method to compare the hydroelastic performance of two design concepts for a 19,000 TEU large container ship. The new design with higher loading capacity achieved via a mobile deckhouse structure on a special railing system lead to slightly lower natural frequencies compared to the conventional ship design. Although the extreme structural responses of both designs are safe, the conventional design performed slightly better with respect to fatigue because of higher torsional frequencies, which lead to lower local stress concentrations.

Chen et al. (2019) presented a 3-D nonlinear time-domain method to study the hydroelastic responses of high-speed trimaran in oblique irregular waves. The method is based on Green's function for the hydrodynamics and the commercial FEM solver MSC.Patran for the structural dynamics, together with a Proportional, Integral and Derivative (PID) autopilot model. The predictions compared well with experimental measurements from segmented model tests of a high-speed trimaran in oblique waves.

2.6.2.4 RANS-FEA models.

Moctar et al. (2017) used RANS simulations (COMET and interDyMFoam) together with rigid body ship motion and Timoshenko beam model to determine the wave-induced structural loads for three containerships in regular and irregular waves. Good agreements were observed between predictions and measurements.

Takami et al. (2018) used a one-way coupled model with RANS CFD (STAR-CCM+) and dynamic FEA (LS-DYNA) to simulate hydroelastic response of a model-scale POST PANAMAX size container ship under severe wave conditions. Good comparisons of vertical bending moment were reported with experimental measurements and with weakly nonlinear method predictions. Some difference in natural frequencies were observed, which the authors attributed to the neglection of added mass effects.

Pellegrini et al. (2020) presented single and two-phase simulations of the hydroelastic response of vertical and oblique flexible plate slamming. The simulations used 1-way and 2-way coupling between CFDShip-Iowa and ANSYS finite element method, and the results were compared with experimental measurements presented in Wang et al. (2020a). Good agreements were observed for the forces and moments, but large errors for the strains and deformations, where the later was attributed to differences in assumed versus actual boundary conditions and material properties.

Takami and Iijima (2020) presented coupled CFD-FEA methods utilizing STAR-CCM+ and LS-DYNA to predict the global vertical bending moment and the local double-bottom bending moment of a 6600 TEU containership. The predictions were compared with towing tank test of a segmented model. Predictions with strong coupling compared better with measurements than one-way coupling, but discrepancies associated with hydroelastic vibrations were observed.

Lakshmynarayanana and Temarel (2020) presented two-way coupled RANS-FEM simulations using STARCCM+ and ABAQUS to predict the wave-induced loads of a self-propelled model-scale flexible containership. The predictions were compared with towing tank studies at CSSRC. The method was able to capture the nonlinearities in the wave-induced bending moments, and resulting hogging and sagging response.

2.6.2.5 Particle models

Khayyer et al. (2018) compared several full-Lagrangian fluid-structure interaction solvers for the simulation of hydroelasticity problems, including slamming impact of an elastic beam and tank sloshing. The methods considered included projection-based MPS (Moving Particle Semi-implicit), and ISPH (Incompressible Smoothed Particle Hydrodynamics) fluid models coupled with Newtonian SPH/MPS or Hamiltonian MPS/SPH structural models. They found that Hamiltonian methods have the advantage of preserving conservation laws, but Newtonian structural models provide more stable pressure/stress fields. The Enhanced Multi-resolution MPS-based FSI solver was found to yield relatively accurate results in terms of deflections.

Andrun et al. (2020) presented a coupled Lagrangian meshless Finite Difference Method (Rhoxyz) and Finite Element Method (CalculiX) for prediction of hydroelastic slamming during water entries of a deformable symmetric wedge with low dead rise angle. Validations were shown for rigid body slamming and dam break with a flexible wall, and numerical results were presented for hydroelastic slamming.

2.7 Added Resistance in Waves and Power Requirements

2.7.1 Development of Numerical Methods to Predict Added Resistance in Head Waves

The mainstream numerical methods in head waves are the Reynolds-averaged Navier-Stokes (RANS) solver for CFD and the Rankin panel method (PRM) for potential flow. Several papers have shown that after checking the convergence CFD calculations provide results that shown that ship motions and added resistance in regular head waves are in good agreement with the experimental results. Lyu and el Moctar (2017), Sigmund et al. (2018), Zhang et al. (2019) systematically performed numerical calculations of both CFD and RPM and experiments with each method and publishes a series of results. After confirming the reliability of the regular head wave calculation, Yoo et al. (2020) verified the added resistance by the spectral method and the direct calculation method, and showed that the spectral method underestimated the added resistance. In addition, Crepier et al. (2020) showed with CFD that the quadratic assumption of wave height to the added resistance is not always satisfied depending on the wave steepness. The details are summarized in the following paragraphs.

Sigmund et al. (2018) systematically conducted CFD calculations and tank experiments for four different ship types, such as a post-Panamax containership (DTC), a KVLCC2, a medium-size cruise ship, and a Wigley hull, in regular head waves to investigate in detail the influence for added resistance due to ship speed, viscosity, interaction between the radiation and diffraction problem in a nonlinear regime, wave quadratic correlation in higher wave steepness. The friction added resistance in waves is shown to increases for short waves, but it was concluded to be less pronounced at full-scale ships (Figure 31).

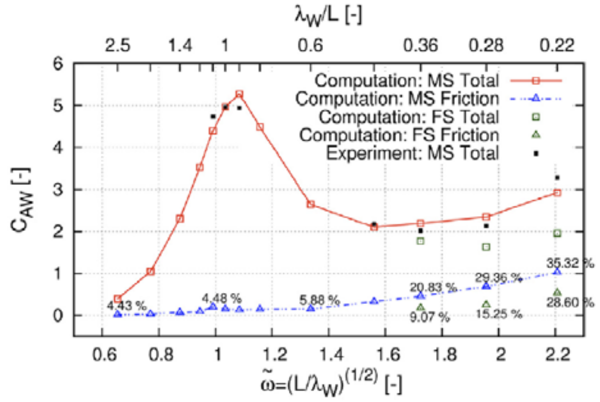

Figure 31: Computed and measured coefficients of total and frictional added resistance at model scale, $Re=6.1x10^6$, and full scale, $Re=2.9x10^9$, of the containership at Fn=0.14 in regular head waves.

Liu et al. (2018) discussed the motion and resistance of DTC ship at Fn=0.058 and 0.138 in short and long head waves using by in-house CFD code naoe-FOAM-SJTU. Predicted added resistance is underestimated by 6% compared with experimental data at Fn= 0.138, while the error can be up to 30% at lower speed. The second harmonic resistance and pressure distribution obtained by the Fourier analysis increases as ship speed increases and varies nonlinearly with wave amplitude. It is concluded that the bow region is critical to the seakeeping performance of DTC ship in moderate speed.

Yao et al. (2020) have predicted the motions and added resistance for KVLCC2 models in head regular waves by using the expanded RANS solver on OpenFOAM platform. The computed added resistance is decomposed into that due to pure hydrodynamic effect and the mean inertia forces due to the surge acceleration and the coupled motion of heave and pitch. The influences of ship speed, wave height, scale ratio, and spring stiffness on the components of added resistance and motions are analysed. When comparing CFD with experiments, it is suggested to be important to consider the effect of inertia forces.

Cakici et al. (2017) applied CFD to predict the motions and added resistance of DTMB5512 models at Fn=0.41 in head regular waves. The pitch and heave response calculated by CFD are in excellent agreement with those of experiments in the entire frequency range. CFD is confirmed to be effective for vertical motions.

Kim et al. (2019b) presented the numerical simulations for the prediction of added resistance in waves for KVLCC2 at three ship speeds which are the design speed (Vs = 15.5 knots), operating speed (Vs = 12 knots) and zero speed (Vs = 0 knots). These are calculated using RANS CFD and 3-D potential methods, both in regular head seas, and compared with those of experiments. It is concluded that vessels in stationary condition should be carefully operated in heavy weather conditions because the transient drift forces at zero speed may be larger than the transient drift forces of a vessel advancing in waves.

Hizir et al. (2019) performed numerical simulations for the prediction of added resistance for KVLCC2 with varying wave steepness using a CFD (STAR-CCM+) approached by RANS method and a 3-D linear potential method (PRECAL) developed by MARIN, and then investigated the non-linearities of added resistance and ship motions in regular short and long waves. It is concluded that CFD results have a reasonable agreement with the experimental data and estimate the non-linearity in the prediction of the added resistance and the ship motions with the increasing wave steepness in short and long waves. It is emphasised that the non-linearity of the added resistance and ship motions around the resonance period is larger than in short waves.

Seo et al. (2017) predicted the added resistance with the motions of KCS in head waves using OpenFOAM and compared with those of model experiments. Unstructured grid using a hanging-node and cut-cell method was used to generate fine grid around a free-surface and ship. When the wavelength was similar to the ship length, the ship moved against the waves, and thus the added resistance was greater compared with other wavelengths. Large vortices structures were shown to be occurred under the transom and ship bottom due to the large ship motions (Figure 32).

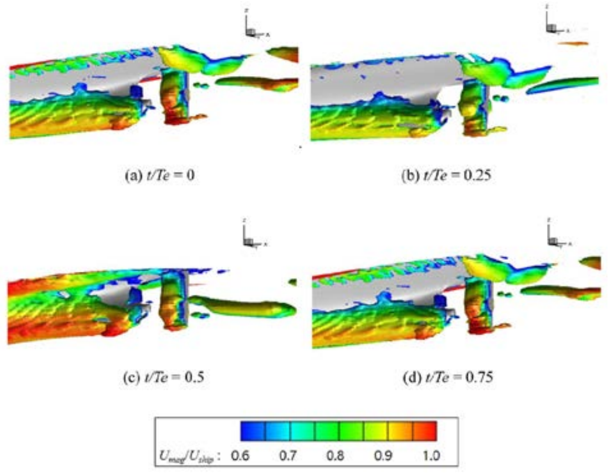

Figure 32: Vortices structures around stern for one encounter period (λ/L_{PP}=1.15) (Seo et al, 2020).

Yoo et al. (2020) investigated the added resistance in an irregular head sea using CFD. The reliability of results was confirmed by with those from model tests conducted in Samsung Ship Model Basin. The added resistance obtained by the spectral approach was reported to be underestimated by 20-40% over the direct estimate, suggesting that the direct estimation is required.

Crepier et al. (2020) compared the added resistances and pressure distribution on hull in head waves obtained by CFD, RPM and experiments conducted by MARIN. A very important result of this work is that it demonstrates that the traditionally assumed quadratic relationship between the wave amplitude and the added resistance is only partly valid. CFD results as well as the results of experiments show a clear relative decrease in higher waves. The effect of the temporary high steepness of individual waves in an irregular wave train may play a significant role.

In waves, CFD simulation can cover several effects such as viscosity, full nonlinearity, interactions of propeller-hull-rudder motions including some devices, however, still less time efficient compared to a potential flow method. Hence, a potential flow method is still indispensable in covering many operational conditions required for a complete assessment of the operational performance. Since there is almost no ship motion in the relatively short wavelength region, the component caused by diffraction is dominant, but in RPM, the discrepancy with the experiment is assumed by the fluid viscosity, and an empirical viscous drag equation is added. As a result, there are examples of improving the calculation accuracy, where developments of RPM in head waves are summarized below.

Riesner et al. (2018b) presented a partially nonlinear time-domain Rankine source method (nonlinear TDIR) to calculate the wave induced added resistance of ships advancing at constant forward speed in regular head waves according to Cummins approach. This nonlinearity comes from nonlinear Froude-Krylov and hydrostatic forces induced by wet area changing by undisturbed incident waves. In addition, the viscous component of wave added resistance was added empirically. Compared with CFD and EFD, the nonlinear TDIR with viscous effect (Figure 33) is concluded to provide more accurate predictions in waves of almost every wave length than frequency domain approach. In particular, this is remarkable in short wave length. Quadratic assumption of wave height and wave steepness are also discussed in detail.

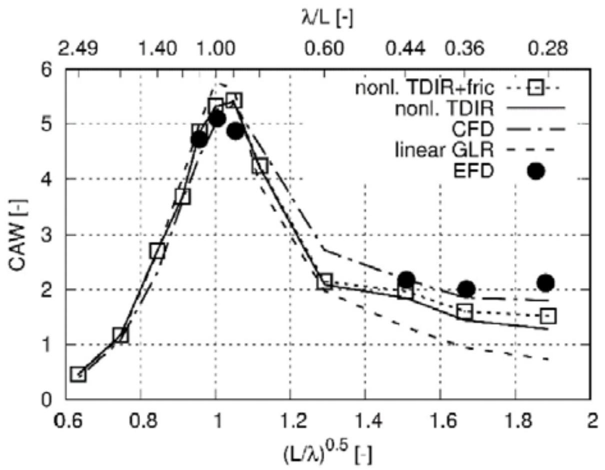

Figure 33: Wave added resistance coefficient including viscous effects for the DTC containership (Fn=0.139), EFD denotes experiments (Riesner et al., 2018b).

Zhang et al. (2019) developed a time domain Rankine panel method based on the double-body linearization with empirical viscous effect and a flow field described by the quadratic B-spline basis function. Through comparing with the motion and added resistance by experiment and CFD simulation for a Wigley hull, the S-175 container ship, and the KVLCC2 tanker, the effectiveness of the developed code is reported. The importance of the interaction between radiation force and diffraction force is shown.

2.7.2 Steady Force and Moment for Oblique Waves

Reliable prediction of second order forces and moments acting on ships in oblique waves is useful to assess the actual operational aspects, such as drifting angle, minimum power requirements, manoeuvring capabilities, and towing forces. However, the mean forces and moments is less studied so far in oblique waves than in head waves. This has resulted in only limited data on oblique sea conditions. Currently there is a trend to collect such data by numerical simulations and tank(basin) experiments. Through these studies, it is pointed out in several papers that ship motions appear to be significant even in short wavelengths and the radiation problem comes to be important. Research on oblique waves are summarized below.

Lyu et al. (2017) presented computational methods to reliably predict second order forces and moments acting on ships in waves using a Rankine source method and an extended RANS solver. Comparative results from model experiments by a DTC, a KVLCC2 and a medium-size cruise ship validated these methods to reliably and predict first and second order wave-induced ship response in different headings and wave lengths. Investigations systematically dealt with the influence of ship speed, hull shape, and encounter wave angle on second order forces and moments.

Park et al. (2019) experimentally and numerically estimated the added resistance of a large tanker in oblique waves by the self-propulsion test for seven wave directions between 0 and 180 degrees. The added resistance was estimated from the difference between the thrust of the propeller in calm water and waves. Experiments were performed in the SSPA seakeeping basin and compared with two numerical simulations: the strip method and the 3D Rankine panel method. Calculated results by the Rankine panel method agreed well with the experimental results, where viscous roll damping was accounted for by taking 3% of the critical roll damping (estimated from roll decay tests). The maximum added resistance is observed at wave headings between 180 deg and 150 deg. In the oblique sea conditions, the peak frequency of the motion response moves and the radiation-related component of added resistance can increase even in short waves. This means that it is equally important to predict the radiation related component as well as the diffraction component. The literature data of added resistance experiments were also summarized and trends were investigated (Figure 34 and Figure 35).

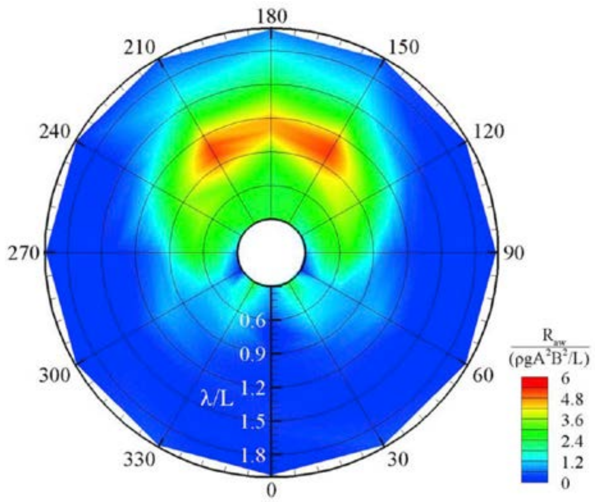

Figure 34: Polar diagram of added resistance, experiment, S-VLCC, Fn=0.137 (Park et al. 2019)

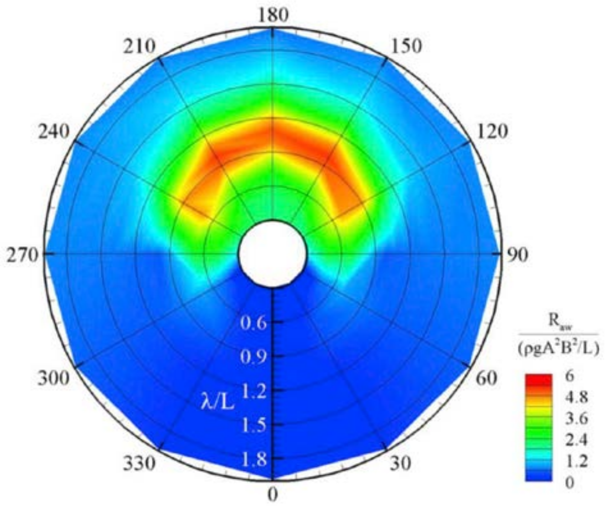

Figure 35: Polar diagram of added resistance, RPM, S-VLCC, Fn=0.137 (Park et al. 2019)

Wicaksono et al. (2018) simulated the mean forces and moments acting on an advancing ship in oblique waves based on the new strip method (NSM) and the enhanced unified theory (EUT) and compared them with published experiments. This experiment was carried out with a JASNAOE-BC084 tanker model for four different forward speeds and four wave directions. An equivalent damping coefficient was based on the component analysis method as formulated by Himeno. It was concluded from the comparison that for short waves such as wavelengths longer than λ/L=1.0, the contribution of the radiation Kochin function becomes important and the radiation Kochin function was rather sensitive to the ship's forward speed. EUT was shown to be able to predict steady force and moment better than NSM.

Zhang et al. (2020) conducted numerical prediction of wave-induced motions and steady drift forces for ships in oblique waves using a time domain Rankine panel method and validated the proposed method using published experiments of KVLCC2 of zero advance speed for six wave directions and S-175 of Fn=0.15 for head and beam waves. The roll damping coefficients were determined by the ITTC's Numerical Estimation of Roll Damping Procedure (ITTC, 2011). It was pointed out that numerical results explain the trend of experiments, but there was room for improvement.

2.7.3 Numerical and Experimental Investigation for Self-propulsion Factor & Power Increase

Added power involves propeller-hull-rudder interactions in addition to the increase in hull resistance in waves including added resistance in waves. These interactions generally add loading to the propeller and impact the wake fraction, advance coefficient, and the thrust deduction factor. As a result, the operating point shifts, requiring higher power, and possibly reducing the efficiency. Papers concerning these issues including benchmarking results are summarized below.

Sanada et al. (2020) benchmarked and assessed the capability of model experiments and CFD for the added power in head and oblique waves using experiments from three facilities and CFD from five facilities including one potential flow code. In experiments three different model sizes of KCS were used, depending on the tank size. The biases of scale and facility are separated and validation data and uncertainties for CFD validation, including capability of predicting the scale effects were provided. It is emphasized to be important and necessary to understand hull-propeller (-rudder) interactions and scale effects, especially for single propeller/rudder ships.

Choi et al. (2020) proposed the modified thrust and revolution method to predict speed-power-rpm relationship along with resistance and propulsion characteristics in regular head waves with varying wave lengths and steepness ratios using the 'calm-water' and 'wave tests'.

Knight at el. (2018) presented a body force propeller model for unsteady conditions in order to train a semi-empirical algorithm, that with proper training data accurately predicts the thrust and torque of the propeller. This algorithm is based on analytical relations with coefficients that are determined from CFD calculations with steady motion and with harmonic surge.

Woeste et al. (2020) presented an efficient means of predicting the added resistance and added power in regular head waves, and investigated the change in added resistance and added power with different wave conditions and model sizes using the KCS model. A RANS solver was used to derive the self-propulsive factor according to RTIM and a potential flow code was used for the added resistance in waves. The added power coefficients were concluded to increase with decreasing model length scale ratio due to a reduction in advance coefficient and an increase in torque coefficient caused by a higher relative contribution of viscous effects. This added power coefficients are not simply proportional to the square of the wave amplitude.

Feng et al. (2020) studied the propulsion performance of a cruise ship with podded propulsion in waves based on model experiment. For podded propulsion, TNM was concluded to be most recommended. It is explained that the modified TNM proposed can avoid unnecessary assumptions on the wake fraction.

Hsin et al. (2018) presented numerical self-propulsion tests in waves by three different approaches of computing the ship resistance and propeller effects. A viscous flow RANS method, a potential flow boundary element method (BEM) and the strip theory were combined for computing. An unsteady body force method was developed for the propeller effect.

Tsujimoto et al. (2018) proposed the practical method to predict self-propulsion factors in waves based on the tank test. It was shown that the wake coefficient generally increases due to ship motion induced by waves, as a result the propulsion efficiency is changed.

Otzen et al. (2018) performed measurements including uncertainty with KCS during self-propulsion in calm water and head seas and experimentally assessed the added powering, and compared EFD and CFD(RANS) results to learn the performance of RANS for this application.

Sanada et al. (2018) conducted free-running tests of KCS to know more detail of added powering and propeller load fluctuations in regular waves during free-manoeuvring by CFD and EFD. The data shown in this paper is to be used as CFD validation data for several workshops.

Sigmund et al. (2017) numerically and experimentally investigated the influence of regular head waves on propulsion characteristics of a twin screw cruise ship and the single screw containership DTC using a RANS based flow solver. Experiment were used for the validation of CFD based on the RANS solver. It was concluded that for the twin screw ship the decrease of propulsion efficiency in waves was mainly caused by the propeller's efficiency and those for the containership was caused by not only the propeller's efficiency but also the ship's hull efficiency.

2.7.4 Impact of Added Resistance in Seaway

Accurately knowing the proportion of the added resistance induced by waves in the total resistance is the basis for designing the optimum hull form based on the added resistance in waves. In addition, when combined with the problem of power estimation, a voyage simulation can be developed that can evaluate the service performance, and the role of the added resistance induced by waves in fuel efficiency performance can be visualised.

Taskar et al. (2020) discussed the impact on energy consumption by added resistance in waves. Voyage simulations were carried out using added resistance RAOs computed using different methods, CFD and potential flow, for four routes and four wave headings for the KVLCC2 and KCS at full load condition. It was concluded that the scatter in voyage energy consumption caused by different approaches and wave headings to added resistance in waves was sizable.

Skejic et al. (2020) calculated the total resistance in a seaway by combing empirical and theoretical formulae, and numerical calculations. The obtained calculation results were compared with published experimental and theoretical results and found to be in good agreement. It was pointed out that surge motion is important for the added resistance in waves.

2.7.5 Semi-empirical Formula of Added Resistance in Waves

To design a vessel that is well suited for the intended operational environment it is important to consider the effect of the main characteristics on the vessel's performance in the early deisgn stage, including added resistance in waves and its effect on EEDI and EEOI. Although resulting in reliable and accurate results, numerical calculations with CFD or Rankine Panel Methods require detailed knowledge on the ships design not yet available in the early design stage and often prohibitively high computation time, cost and effort. Semi-empirical formulae for fast estimation of added resistance in head waves have been improved based recent numerical calculations and experiments, and are much more suited for quick design iterations. Nevertheless, it must be noted that these formulae are not applicable for the design of innovative ships and hull shapes, as they are attuned to existing ships.

Lang et al. (2020) introduced a semi-empirical head wave added resistance calculation formula by combining the further tuned NMRI formula and Jinkine and Ferdinande's method. The results indicate that the proposed formula has achieved reasonable accuracy with fast calculation. Uncertainty and prediction capacity are discussed. This achievement can be expected to help evaluate the voyage optimization system requiring iteratively on millions of grid waypoints.

Lee et al. (2018) proposed a nonlinear approximation function to predict added resistance in waves using genetic programming (GP). In this paper, four Froude numbers and three types of ships (total 12 cases) were used as training data to generate a nonlinear approximation function. Accuracy was better than strip theory when comparing with experiments. It is suggested it is possible to apply GP as an alternative prediction method of added resistance in the early design process due to sufficiently accuracy in less time and at a low cost.

Cepowski (2020) proposed a nonlinear approximation function to predict added resistance in waves using an artificial neural network with basic design parameters of ship. The derived function was showed to provide good correlation with measured data. It could have practical application in ship resistance analysis at the preliminary design stage.

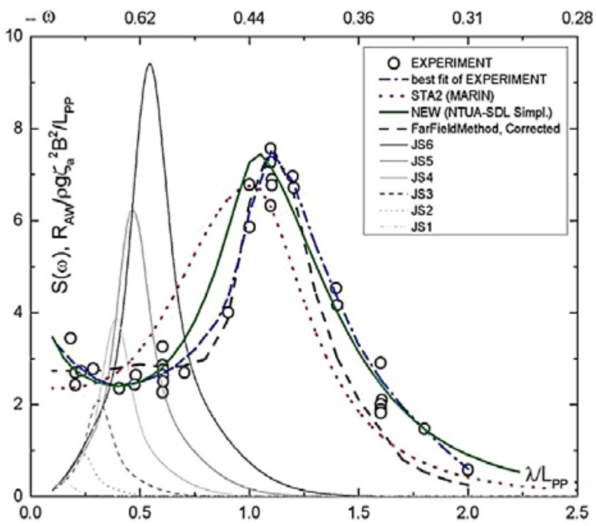

Figure 36: Prediction of added resistance of KVLCC2 ship, in irregular sea ways, Fn=0.142. NEW is proposed formula (Liu et al. 2016).

Liu et al. (2016) developed simple semi-empirical formulations for fast and satisfactory estimation of the added resistance of ships in head waves. New formulations were obtained by extending the approximate formula derived in the past to cover more types (tanker, bulk carrier, containership and cruise ship) of ships, a wider speed range (Fn = 0.0 - 0.3), and the whole range of wave lengths of interest. In short head waves the formulations were originally derived by Faltinsen et al. (1980) and in longer head waves these were proposed by Jinkine and

Ferdinande (1974). Extensive validation of the proposed formula for various ship hulls in both regular and irregular waves were carried out and compared to other comparable methods and more complicated approaches to the determination of the added resistance in head waves (Figure 36Figure 34).

2.8 CFD Applications

Over the period covered by the report, Computational Fluid Dynamics (CFD) popularity has kept increasing amongst researchers and naval architects interested in seakeeping. Where the previous seakeeping committee report reviewed also the basic approaches of CFD, this report section proposes a non-exhaustive review focusing on the applicative part. The significant number of published computations over the last years generally were set up for conditions where other faster methods show limitations. Most common CFD models are built on the Navier-Stokes equations with a turbulence model and discretized with Finite Volume Method, as this what is implemented in the most widely used open source and commercial fluid dynamics solvers.

As CFD allows flexibility in imposing initial and boundary conditions, therefore the topic of CFD studies is often at a crossover of traditional seakeeping applications. CFD is a high-fidelity expensive method from setting up methodology to performing computations, and some studies evaluate its accuracy and added value with respect to alternative traditional solutions.

2.8.1 Added resistance and forces on semi captive models

Wave loads on ship and specifically added resistance has been the subject of several CFD studies.

The influence of trim on the added resistance of the KRISO Container Ship (KCS) is investigated in Shivachev et al. (2020). They showed CFD is reliable enough to optimize the trim angle for added resistance on a set of regular waves. Figure 37 shows a comparison of the added resistance computed by CFD and Potential Flow compared to experiments.

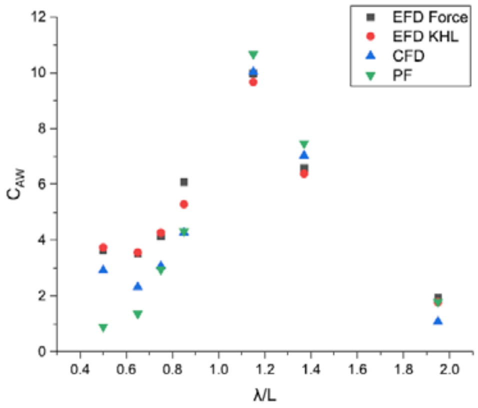

Figure 37: Comparison of CFD to Experiments and potential flow (Shivachev et al, 2020).

Added resistance in an oblique sea is investigated in Gong et al (2020) for a trimaran with forward speed up to Fr=0.47. The paper investigates the effect of wave steepness and Froude number on added resistance and discusses the influence of the numerical setup.

Wave induced forces and motions are compared with a semi captive experiment of ONR Tumblehome in irregular quartering seas in Hashimoto et al. (2019).

2.8.2 Role of shape and appendages in performance

Li et al. (2020) investigated the influence of T-foil appendages on the motions of a fast trimaran in head regular waves with three values for the wave steepness (Figure 38). The loads on the foil and their influence on the ship motions are presented. Liu et al. (2018) presented a similar simulation, investigating the role of the stern flap of a catamaran in regular and irregular sea.

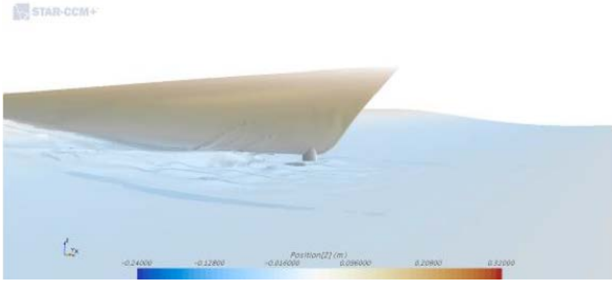

Figure 38: Snapshot of the instant where the T-foil enters the water (Li et al, 2020).

Bhushan et al. (2017) performed URANS simulations with a Surface Effect Ship (SES) in calm water and in head waves using an air cushion model. Niklas et al. (2019) performed advanced CFD full scale simulations to investigate the effect of a X-bow and a V-shaped bulbous bow form on the seakeeping performance.

2.8.3 Self-propulsion and manoeuvring in waves

In Toxopeus et al. (2018) a comparison of RANS, Potential Flow and system-based solvers performance is conducted on the free running self-propelled DTMB 5415 with and without waves. High-fidelity CFD methods are shown to be overall the best prediction tool, though the computational effort is much larger.

A set of simulations of a self-propelled free running KCS under course keeping control in head waves are performed and compared with experimental results in Choudoury et al (2020). Computations of turning circle in waves with a self-propelled Duisburg Test Case ship model are also presented in Liu et al. (2020).

2.8.4 Green water and extreme motions

The demonstration of the capability of CFD to compute loads and wave elevation occurring during a green water event is presented in Rosetti et al. (2019) with a comparison to a dedicated experiment.

The green water event is also investigated on a simplified FPSO shape with comparison to experiments in Gatin et al. (2018). A similar model but with a compressible air-phase is then used with Regular Conditioned Waves and Regular Equivalent Design wave approaches comparing the two in Gatin et al. (2019).

Impact loads exerted by focusing waves on FPSO are computed in Hong et al (2019), where motions and wave elevation and motion are compared with experiments (Figure 39).

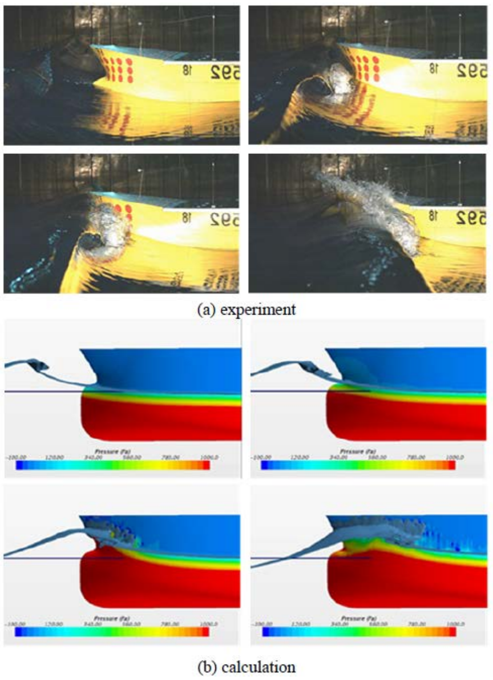

Figure 39: Comparison between experimental and numerical flow field (Hong et al, 2019)

Another simulation of a rogue wave packet impacting onto a containership is performed in O'Shea et al. (2018). The authors in this case use a procedure that incorporates a Higher Order Spectral (HOS) model and the Numerical Flow Analysis (NFA) code.

Zhuang et al. (2020) proposed the coupling of a HOS wave model to generate extreme wave conditions with finite volume CFD to simulate the response of a ship. Deterministic validation using experimental data is proposed in an irregular sea.

Similarly on the topic of design in extreme conditions, Knight et al. (2020) performed a study of a self-propelled ship using the Design-

Loads Generator (DLG) approach to construct a desired seaway over a short time window around an extreme response.

2.8.5 Hydrodynamic coefficients and roll damping

CFD is also used as an intermediate step in a hydrodynamic (seakeeping) assessment. Several works were dedicated to the computation of hydrodynamic coefficients. This is done for the heave and sway motions of several ship hull sections in Gadelho et al. (2018). The roll motion is also investigated, because of the importance of viscosity in this motion and its poor handling by the potential flow model. A detailed study about the role of bilge keel is presented in Irkal et al. (2019) and roll damping is investigated Kianejad et al. (2018) and added mass inertia in Kianejad et al. (2019).

2.8.6 Fluid Structure interaction

In Takami et al. (2018), a one-way coupling between high-fidelity CFD code for the fluid and Finite Element Analysis for the structure is performed to evaluate global and local loads. The results are compared with experiments and with strip methods and panel methods, showing that the gain of accuracy of the fully coupled model is not large for this case (a container ship).

In Lakshmynarayanana et al. (2019) two-way coupling is performed between commercial FEA and CFD solvers to predict dynamic behaviour of a flexible barge.

El Moctar et al. (2017) develop a two-way coupling with a finite element Timoshenko beam method and applied it to three different hulls, showing that the methodology is satisfactory for assessing slamming-induced hull whipping.

2.9 Seakeeping of High Speed Marine Vehicles

Sailing with high speed craft in calm water and in waves is associated with very dynamic behaviour related to dynamic stability and impacts. High speed craft in waves are subjected to significant and frequent impacts with large effects not only on the structural integrity but also on human performance and human safety.

Research is not only focused on model tests and predictions by means of computations, but also full scale recordings play an important role. There is more and more interest in using ride control systems to not only improve passenger comfort, but also in actively reducing slamming itself.

Over the past five years the most investigated types of high speed marine vehicles are monohulls, followed by wave piercing catamarans and trimarans. There seems to be a growing interest in hydrofoiling craft and foil assisted craft, possibly related to the introduction of hydrofoils in high profile sailing matches such as the America’s Cup.

2.9.1 Experimental

Camilleri et al. (2017) performed full-scale rough water trials and drop tests with a 9.6 metre high speed planing craft, measuring rigid body motions, accelerations, pressures and strains. They compared the full scale drop test results to CFD computations and predictions of classification society rules and standards to assess their accuracy. In addition they performed preliminary comparisons between the rough water trails and the drop tests, highlighting the need to further investigate how to relate both.

Davis et al. (2017), Shahraki et al. (2017) Shabani et al. (2018), and Shabani et al. (2019) describe model tests with a 2.5 metre hydroelastic model of a 112 metre fast wave-piercing catamaran fitted with a centre bow (Figure 40) in regular and irregular head waves. They measured loads and pressures on the centre bow and on the hull. Variations of centre bow length showed that for increasing centre bow length the slamming loads increased significantly while the maximum peak pressures varied to a lesser extent. Increasing the height of the centre bow archways (and thus wet deck height) led to a decrease of the slam loads and the vertical bending moment at the cost of larger heave and pitch motions while the peak pressures were less affected. It was also found that wave encounter frequency has a strong effect on the location of maximum pressure along the centre bow.

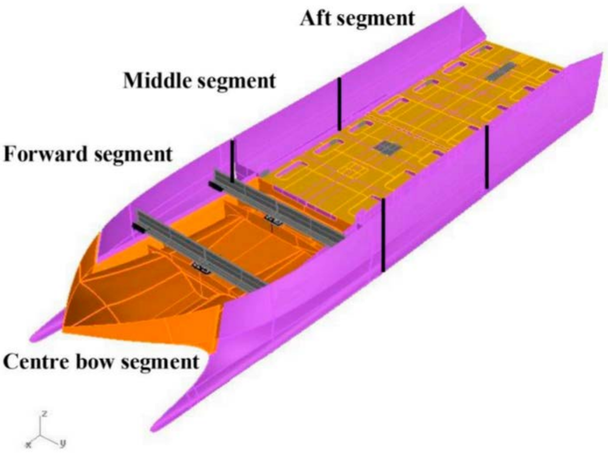

Figure 40: Hydroelastic segmented wavepiercing catamaran model with a centre bow (Shabani et al., 2018)

Katayama et al. (2018) noted the underprediction of roll damping in Ikeda's method for small planing craft due to the absence of lift damping. They investigated roll damping by means of model tests with a model of a small planing vessel forced in roll (Figure 41). They proposed an estimation method for the lift component of roll damping based on previous work by Payne and showed a good comparison with their experimental results.

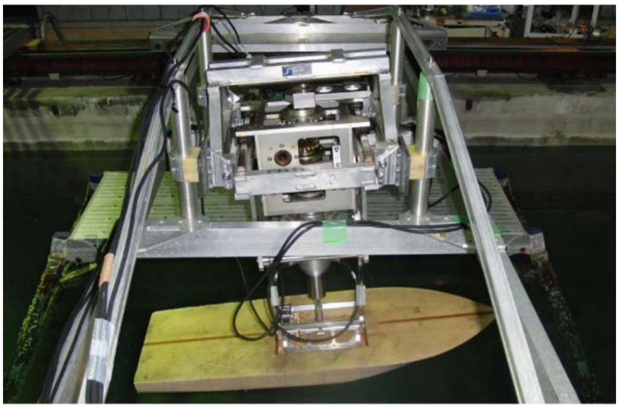

Figure 41: Forced roll test setup (Katayama et al., 2018)

Durante et al. (2020) performed an experimental study of a catamaran in head seas, including uncertainty quantification. The aim of the study was to obtain a statistically-converged experimental benchmark dataset of a catamaran in irregular waves, along with a regular-wave Uncertainty Quantification (UQ) model used to approximate the relevant statistical estimator.

Judge (2020) measured bottom pressures on a model of a high speed planing monohull in regular waves. She applied a pressure reconstruction method to obtain an estimate of the spatial pressure distribution based on point measurements and compared this against empirical formulations.

2.9.2 Numerical

Numerical methods applied for the seakeeping of high speed craft need to cope with highly nonlinear behaviour due to the large variations in wetted surface and impacts. This results in the adoption of nonlinear time domain methods. Besides the more traditional nonlinear 2D+t potential flow methods, nonlinear 3D panel methods have gained significant popularity in recent years. Also CFD methods are slowly gaining terrain. Nevertheless, the highly nonlinear nature of the problem and the importance of obtaining sufficient statistics (and hence requiring significant time durations of simulations) are still difficult to overcome with CFD.

2.9.2.1 Nonlinear 2D+T methods

Ghadimi et al. (2016) proposed a mathematical model based on the 2D+T potential theory and implemented pressure distributions over length of hull in order to compute forces for performance prediction of hard-chine boats which can be used in both semi-planing and planing regimes. Tavakoli et al. (2017a), (2017b) and (2018) extended the 2D+T potential theory to include the prediction of hydrodynamic coefficients of a heeled planing hull in the vertical plane. The accuracy of the method is evaluated by comparing its results against previous empirical methods. The same method is also validated for longitudinal motions without heel in waves for a wide speed and frequency range by Pennino et al. (2018). Allaka and Groper (2020) validated the approach using full scale results.

Consolo et al. (2020) attempted to improve a 2D+T strip theory method for seakeeping of high speed craft to enable the inclusion of roll motions. They treated asymmetric wedge impact by separately considering portside and starboard side wedge parts. Roll damping was estimated based on various methods and successfully validated against captive model tests. Results in waves still showed under prediction of the roll motions.

Garme (2020) studied the modelling implications of various three dimensional geometric variations such as bottom warp in a 2D+T method by comparing simulations with the results of model tests. He concluded that warp can indeed be modelled with the 2D+T method and stressed the importance of combining numerical and experimental methods in research and design.

2.9.2.2 Potential flow methods.

Van Walree and Thomas (2017) and Van Walree et al. (2019) and Bird et al. (2017) developed a nonlinear time domain 3D panel code and validated it with both model scale and full scale test results for a Rigid Hull Inflatable Boat (Figure 42). Van Walree et al. (2018) also applied their nonlinear panel code for predicting the seakeeping behaviour of and hydrodynamic loads on high speed craft operating in a seaway.

Figure 42: Fully free running RHIB model during seakeeping model tests (Van Walree and Thomas, 2017)

Bonci et al. (2017a), (2017b) and (2020) modified the same time domain 3D panel code to include the heel-sway and heel-yaw coupled effects empirically and applied the modified approach to the manoeuvring in following waves of a rescue vessel of the Royal Netherlands Sea Rescue Institution (KNRM) shown in Figure 43. Finally, impulsive loads on the bow door of and water ingress into a landing craft shown in Figure 44 has been investigated by applying the same time domain 3D panel code (Van Walree and Sgarioto, 2019).

Figure 43: Captive model tests with a SAR boat of the Royal Netherlands Sea Rescue Institution (Bonci et al., 2017b)

Figure 44: Model of a fast landing craft used for impact and water ingress model tests (Van Walree and Sgarioto, 2019)

O'Reilly et al. (2017) and (2018) developed a new set of formulations for potential-flow methods that retains the important nonlinear features while maintaining computational efficiency. These formulations include steady and quasi-nonlinear approaches where memory effects are weak. Their initial results are encouraging, with better results in more extreme waves, but still over-predicting for more modest waves.

Kihara et al. (2019) investigated the strength of the cross deck of a trimaran sailing in regular beam and oblique seas by combining pressures obtained from 2D potential flow theory with a Finite Element Method for the whole vessel. They compared the predicted motions with the results of model experiments with reasonable results.

2.9.2.3 Computational Fluid Dynamics.

The field of Computational Fluid Dynamics (CFD) continues to advance with several new accomplishments also in the field of high speed craft design. Ahmad et al. (2017) performed a literature review of the application of advanced CFD simulations over the time period 2007 to 2015 in terms of software tools available and the application to hull form optimization, resistance, and seakeeping analysis and propulsion systems.

Wei et al. (2017) attempted to predict hull hydrodynamics of a semi-planing wave-piercing craft shown in Figure 45 both in calm water and waves by numerical simulations based on CFD. They used a RANS based method and studied various mesh adaptation techniques. Although their calm water results compared reasonably against experimental data, their results for motions showed not a favourable match yet. Yuan and Wang (2018) used commercial CFD software (RANS) to simulate porpoising of a trimaran planing boat shown in Figure 46. They investigated the influence of speed and the centre of gravity location on the vessel motions, resistance, pressures and streamlines during porpoising. They noted the effect of aerodynamic lift on porpoising.

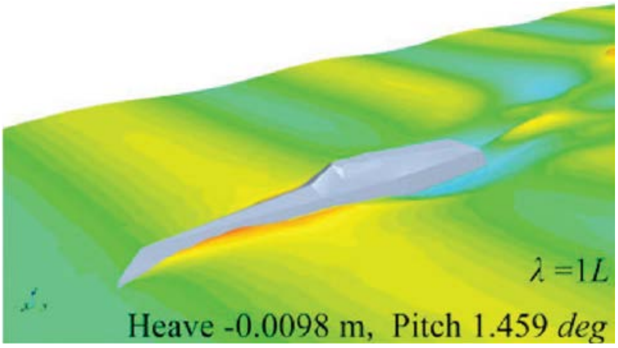

Figure 45: Snapshot of a semi-planing wave-piercing boat in waves using CFD (Wei et al., 2017)

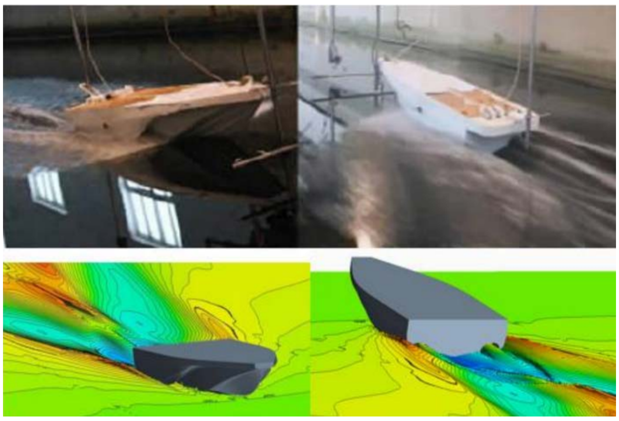

Figure 46: Bow and stern wave characteristics of a trimaran planing craft, CFD versus experiment (Yuan and Wang, 2018)

Yildiz et al. (2017) compared experimental data obtained from forced roll experiments (by Katayama et al., 2018) with CFD results obtained with commercial software, showing good agreement provided that the grid was sufficiently refined.

Ghadimi et al. (2019), through a two-stage approach, simulate the seakeeping and slamming phenomenon of a wave-piercing trimaran vessel by Flow-3D software. In the first stage, the seakeeping of the vessel was investigated in the presence of irregular waves. In the second stage, a water entry problem was simulated for bow section to calculate the slamming pressure for the worst sailing condition based on the relative vertical velocity obtained from the first step.

Diez et al. (2020) performed fluid structure interaction computations for 1-way and 2-way coupled computational fluid and structural dynamics for a bottom panel grillage of a high speed vessel in regular waves. They used an incompressible RANS/DES solver designed for ship hydrodynamics to compute the hydrodynamic loads (Figure 47). Only small differences between 1-way and 2-way coupling were observed in the pressure signals. They showed a good comparison of computational and experimental data, indicating that the accuracy of CFD, rigid-body motions, structural dynamics, and fluid-structure interaction was overall satisfactory.

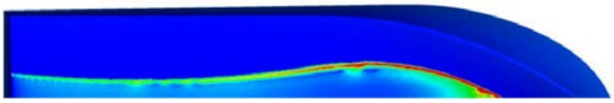

Figure 47: Evaluation of hydrodynamic loads by CFD (Diez et al., 2020)

Judge et al. (2020) presented the results of numerical simulations and model tests for a high speed deep-V planing hull operating in head waves. Both simulation and experimental pressure measurements showed re-entering and emerging peaks (Figure 48). Emerging slams occur as the next wave peak arrives and pushes the boat to go airborne again. They evaluated the effectiveness of the most probably regular wave representation to predict hull performance in irregular waves with mixed results for emerging and re-entering slams and slam duration. The irregular wave comparisons between experiment and simulation indicated that longer run times are required to achieve statistical convergence for the slamming variables. The experimental mount and wave quality, especially for irregular waves, were factors for validation of resistance and slamming.

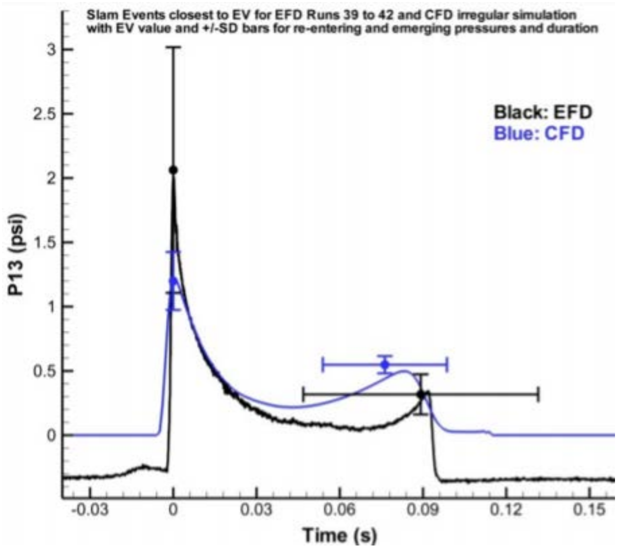

Figure 48: Computed and experimental slamming with emerging and re-entering pressure peaks (Judge et al., 2020)

2.9.3 Statistical analysis

Alwis et al. (2017) investigated the association between working conditions aboard HSC (High-Speed Craft) and its outcomes in terms of acceleration exposure and crew health and systems performance respectively. They collected data through questionnaires tailored to personnel operating high speed craft and by monitoring craft accelerations over longer periods of time. Their results show a promising correlation between the self-reported subjective exposure and the measured objective acceleration. Data indicates a comparatively higher prevalence of musculoskeletal pain in the study population than that of the general population.

Magoga et al. (2017) investigated various methods for identifying slamming impacts in full-scale time records for structural response analysis for an aluminium high speed patrol boat. They discussed an approach to analyse full-scale time records of hull girder stresses, decomposition of the wave-induced and impact components of stress, and definition and detection of slam events. Such knowledge supports informed decision-making in regards to the sustainability and maintainability of the vessel.

For safe operation, it is important to estimate statistical short-term or long-term prediction of occurrence of undesirable large vertical accelerations and avoid its occurrence. Begovic et al. (2016), Katayama and Amano (2016) and Rosen et al. (2018) investigated the statistical characteristics of vertical accelerations and probability distribution of individual acceleration maxima. Begovic et al. (2016) concluded that the Weibull distribution provides the best balance between accuracy and practical use for statistical analysis of vertical acceleration maxima. Rosen et al. (2018) scrutinized the various semi-empirical methods in use by classification societies for the assessment of vertical accelerations. They raise important questions about usage of these semi-empirical methods in high speed craft design and the assessment of safety levels. Figure 22 illustrates how various aspects limit the attainable speed in waves.

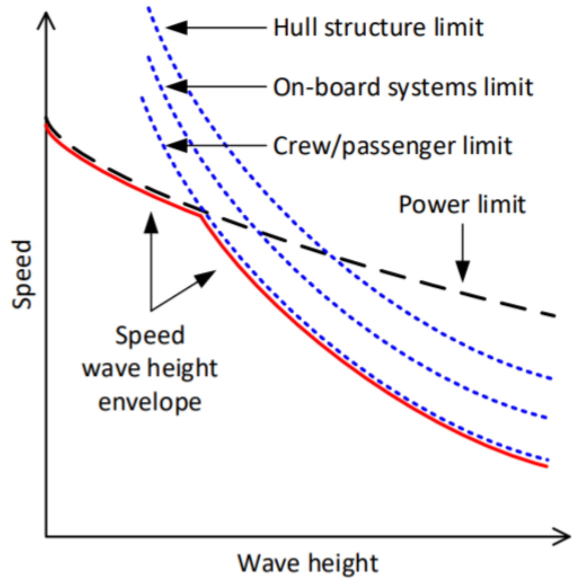

Figure 49: Different aspects limiting the speed in waves and definition of the speed-wave height envelope (Rosen et al., 2018)

2.9.4 Ride control systems

Terada et al. (2017) investigated a time series model for model predictive control to develop a control method for automatic dangerous situations avoidance using an on-board monitoring system of the vertical acceleration. A radial basis function-based state-dependent autoregressive (RBF-AR) model is selected, since it is confirmed that the model is effective to predict nonlinear phenomena. De Castro-Feliciano et al. (2018) applied an ACS (Active Control Systems) to improve seakeeping and propulsive performance.

AlaviMehr et al. (2019) investigated the optimisation of a Ride Control System to reduce the motion, global loads and slamming responses of the same 112 metre catamaran by means of model tests. The ride control system comprised two transom stern tabs and a T-foil beneath the bow (Figure 50). Various control modes were investigated. It was found that the pitch control mode was most effective, reducing the water entry impulse by 40% and the total strain energy by 90% when compared to a bare hull with no control surfaces fitted.

Figure 50: Wavepiercing catamaran model fitted with RCS (AlaviMehr et al., 2019)

2.9.5 Novel and complex concepts

The application of foils to high speed craft is undergoing a revival in recent years. A development that is possibly driven by the adoption of foiling craft in high profile sailing races such as the America’s Cup and the Volvo Ocean Race. Also the advances in material science and the increased adoption of carbon reinforced plastics could play a role in this: making it easier to manufacture light and strong complex structures.

2.9.5.1 Foiling and Foil Assisted Craft

Labat (2017) developed a simplified 2D heave-pitch model of a 45 feet foiling catamaran to study control strategies for the vertical plane dynamic stability. study about evolution of equilibrium of a fast Morace and Ruggiero (2018) performed comparative model tests in calm water and in waves for two surface piercing hydrofoil configurations of a new fast ferry (Figure 51). They touch upon fundamental points such as the wing profile optimization and the structural design and manufacture process to improve both resistance characteristics as ride comfort.

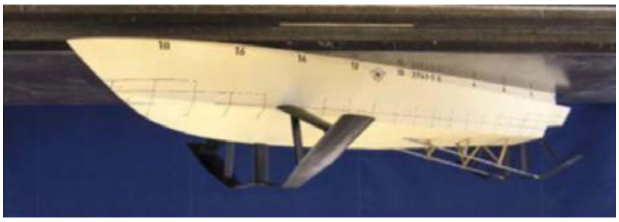

Figure 51: Model of hydrofoil ferry (Morace and Ruggiero, 2018)

Wang et al. (2019) investigated the motions of an unmanned catamaran with fixed horizontal tandem foils to drive the catamaran using a RANS CFD method and a BEM method. Wang et al. (2016a) investigated the vertical plane motion control in rough waves of an S-SWATH (S-type Small Waterplane Area Twin Hull) vehicle equipped with a flapping foil stabiliser. They modelled the fin forces with CFD and the hull forces with strip theory and derived a numerical model and a controller. The concluded that the flapping fins outperformed a conventional fin due to higher lift coefficients and lower drag coefficients.

2.9.5.2 Other Complex Craft

Liu et al. (2019) presented an experimental study of the motions of an ACV (Air Cushion Vehicle) in regular waves. They used customized fans with characteristic curves similar to the ones installed in the ACV to satisfy the laws of similarity. They explored different bag-to-cushion pressure ratios, which usually have a significant influence on the motion. The experiment was carried out with a variety of wave parameters in order to investigate the motions in waves.

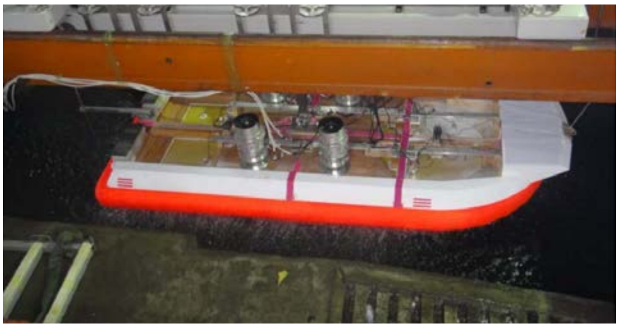

Figure 52: Model of ACV (Liu et al., 2019)

Suspension systems. Han et al. (2018) give an overview of an evolution of cabin suspended ships, called Wave Harmonizer (WHzer). An example is shown in Figure 53. The main focus of this concept is motion reduction and wave energy extraction. The configuration studied were catamaran or trimaran ships with the hulls attached to the cabin by means of suspension systems (passive or active spring-dampers) to isolate the motions of the hulls from the cabin. They developed various passive and active control systems. Model tests in waves were performed to determine motion characteristics and energy production.

Figure 53: WHzer Type 7 (Han et al., 2018)

Li et al. (2018) performed numerical simulation of a trimaran with a deformable (elastic) connection between main and side hulls at design speed in head waves. Their results indicated that the elastic connection helps to reduce heave motions of the main hull and the added resistance in regular waves.

Wielgosz et al. (2020) explored the prospects of using scaled model experiments for capturing the influence of a novel spray deflection concept on planing craft performance in calm water and in waves. Their results give a first indication of the potential for both reduction of the resistance and the accelerations on waves.

3. DISCUSSION OF SPECIFIC TOPICS

3.1 Benchmarks

A review of available benchmark data related to seakeeping issues was performed in relation to Task 12 of the Terms of Reference of the Seakeeping Committee. A discussion of the analysis can be found in Appendix A. A table to the identified benchmarks can be found in Appendix B.

3.2 Uncertainty in Added Resistance

The 'weather factor' f_w for decrease of ship speed in wind and waves is one of the terms in the Energy Efficiency Design Index, EEDI, (IMO, 2014). A key component to determine f_w is the added resistance of a vessel in waves. At this point the relevant ITTC, ISO and IMO procedures leave open many options to determine the added resistance in waves, by model experiments or by various levels of computations. In this section various sources of uncertainties that arise for the various approaches for added resistance in waves are outlined. The details regarding the determination of f_w are outlined in ITTC Recommended Procedure 7.5-02-07-02.8 (ITTC, 2018).

3.2.1 Model Experiments

Experimental methods to determine added resistance in waves rely on the measurement of the total resistance obtained from model tests in either regular or irregular waves R_W and subtracting the total calm water resistance R_T obtained from model tests in calm water.

$$\Delta R_{wave} = R_W - R_T \tag{1}$$

Both total resistance components are relatively large in magnitude compared to their difference: the added resistance in waves. This makes added resistance based on model tests in waves inherently vulnerable to uncertainty. The effect is discussed by Park et al (2019), see also Figure 54 below.

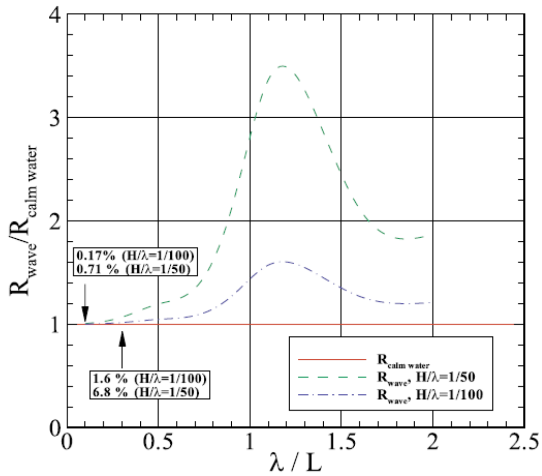

Fig. 2. Approximate ratio of added resistance to calm water resistance, KVLCC2 model (1/100 scale), $Fn = 0.142$.

Figure 54: Approximate ratio of added resistance to calm water resistance KVLCC2 model. (Park et al. 2019)

There are not many papers available that systematically investigate the uncertainty associated with added resistance model tests. One of the more complete attempts is described Park et al. (2015). They performed an uncertainty assessment in accordance with the ITTC Procedures and Guidelines for an added resistance test with the KVLCC2 in regular head waves. They summarized the sources of uncertainty and propagated these to obtain the uncertainty of the heave and pitch motions and the added resistance.

The results of Park et al. (2015) indicate that the uncertainty for added resistance in regular waves is dominated by the measurement accuracy of the resistance in calm water and in waves and the wave amplitude (Figure 55). The uncertainty levels they obtained for short waves, at the RAO peak, and for long waves are indicated in Figure 56. A more detailed assessment showed that this mainly related to the Type B uncertainty of these components, i.e. calibration and measurement uncertainty of these three quantities.

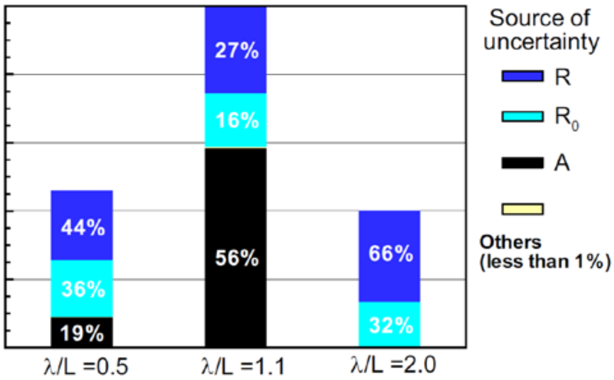

Figure 55: Sources of uncertainty in added resistance (R – resistance in waves, R_0 – resistance in calm water, A – wave amplitude) (Park et al., 2015)

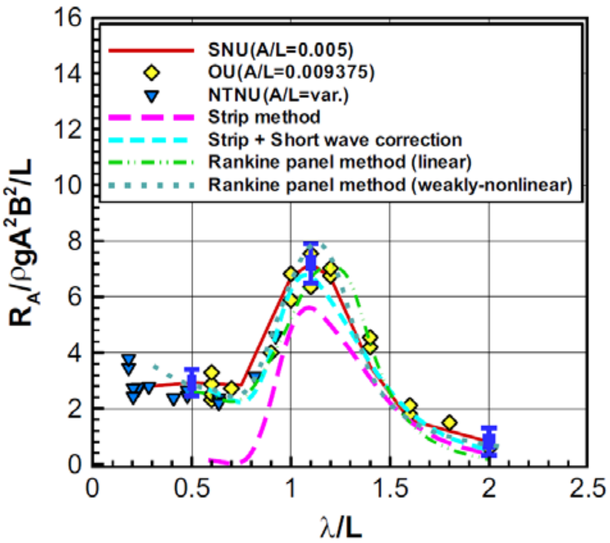

Figure 56: Added resistance with uncertainty bands (at 95% confidence level) of added resistance tests (Park et al., 2015)

These results highlight the need for a focus on accurate measurement of the resistance force and wave elevation. This will be further elaborated below by focusing on the test setup for added resistance tests and the incident waves.

A number of choices are available for the experimental setup of added resistance tests, each with their own advantages and disadvantages. These choices include:

1. Whether to perform tests in regular versus irregular waves,

2. Whether and how to constrain the forward speed,

3. Using self-propelled (and auto pilot controlled) versus unpowered models,

Testing in regular waves is the only way that allows to obtain the Quadratic Transfer Function (QTF) of the added resistance with respect to the incident waves directly. Tests in irregular waves are interesting, as they provide more realistic results, including all possible nonlinearities. When performing tests in irregular waves it is important to allow speed variations of the model to temporarily slow down when sailing in a higher wave group to have realistic motions.

For added resistance tests in general the model needs to, at least, be free to heave and pitch, as these motions are strongly linked to the generation of added resistance in waves. For oblique conditions also the roll and possibly sway and yaw degrees of freedom need to be free. The surge motion can be fully restrained (captive), partly restrained (for instance soft-moored, or using a sub-carriage) or fully free. It is advised to use the same model (with the same loading condition) and test setup for both the calm water tests and the tests in waves to reduce uncertainty e.g. with respect to model building inaccuracies and scaling effects.

Captive setups are easy to implement and allow direct measurement of the surge force at a constant speed. A main disadvantage is the relatively high loading of the force transducers: a relatively high capacity force transducer is needed to cope with large forces during the model acceleration and deceleration phases and with the oscillation of the instantaneous (first order) forces. This reduces the accuracy of the mean force measurement that is required for determination of the added resistance (Park et al., 2015). An advantage of the constant speed is that the interpolation error when obtaining the calm water resistance can be very low, by simply performing the calm water tests at the exact same model speed.

Soft-moored test setups or setups that allow the first order surge motions by using lightweight actively controlled or spring-mounted sub-carriages have the advantage that the transducer loads are reduced by avoiding the first order surge forces. These tests are also referred to as surge free or 'constant thrust' tests (Park et al., 2015), although the latter is only strictly true when using an actively controlled towing device.

Surge free test setups allow the use of more sensitive force transducers and therefore can offer better accuracy. The soft-moored test setup needs to be carefully designed to not affect the magnitude of the first order surge motions and the added resistance by using an appropriately selected spring stiffness. Sadat-Hosseini et al. (2013) describe a test setup using a soft-moored test setup with an external force to avoid too much stretch in the soft springs. Gerhardt et al. (2020) used a similar test setup with soft springs to let the model free to surge, but do not introduce external forces.

Multiple sources indicate that the differences in added resistance due to waves measured with surge free or surge fixed is negligible. Sadat-Hosseini (2013), Park et al. (2018), and Kjellberg and Gerhardt (2019) confirmed this in both experimental and numerical results (for instance in Figure 57 and Figure 58). Surge free setups are necessary when performing tests in irregular waves.

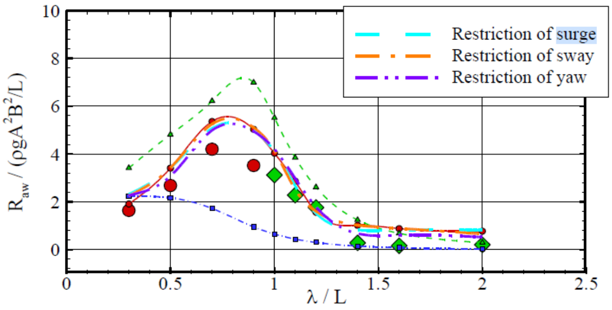

Figure 57: Effect of motion restriction on added resistance in oblique waves (Park et al., 2018)

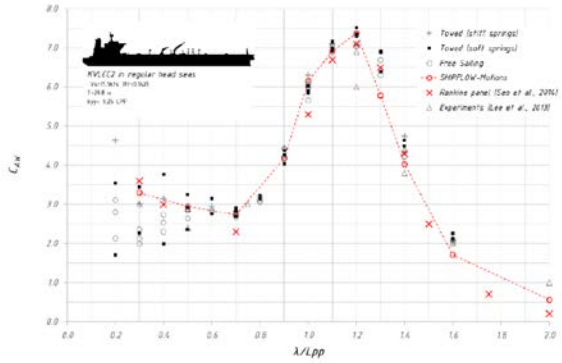

Figure 58: Effect of test setup on added resistance (Kjellberg and Gerhardt , 2019)

An alternative is to perform self-propulsion tests in waves using a fully free-running test setup with a self-propelled model, see for instance Lee et al. (2020). Then the thrust is measured directly on the model propeller and the added resistance is determined by taking the difference between the thrust in waves and the thrust in calm water and using the thrust deduction factor *t*:

$$R_{AW} = \left(T_{wave} - T_{calm}\right)\left(1-t\right) \tag{2}$$

The advantage is that model is allowed to perform completely realistic motions for all possible headings, while avoiding a complex semi-captive test setup. Nevertheless, the added resistance is derived from the thrust under the assumption that the thrust deduction factor remains unchanged in waves. There does not seem to be very much systematic research available to verify this.

Rather than determining the added resistance, self-propulsion tests in calm water and in waves can also be used to determine the added thrust or added power in waves directly. Added power is different than added resistance, as it also involves complex propeller-hull-rudder interactions on top of the hull resistance in waves (Woeste, 2020). To maintain speed in waves the increased propeller loading must be compensated by increased propeller revolutions, torque and power. In experiments care needs to be taken to compensate Reynolds scale effects on the viscous resistance. Tsukada et al. (2013) developed an auxiliary thruster for free running model tests to obtain a correct propeller loading at model scale on a free running model. Otzen et al. (2018) provide a complete uncertainty assessment of captive added powering tests in waves.

A further complication of a surge-free test setup can be that the ship speed now varies over time and the average speed is not exactly controlled. The mean speed is therefore probably slightly different in the test in calm water and in the corresponding test in waves. This may introduce interpolation errors when subtracting the calm water resistance.

Hybrid solutions also exist that combine a captive or soft-moored test setup with a self-propelled model or an additional external force allowing more sensitive and accurate force transducers. Examples can be found in the work of for instance Son et al. (2010), Sadat-Hosseini et al. (2013) and Crepier at al. (2019). The added resistance is then determined by combining the towing force with the additional forces. Again, when using a propeller, the assumption is made that the thrust deduction factor is constant in waves. In some cases clamps are used to temporarily restrain the model during acceleration and deceleration, to allow more sensitive force transducers, similar setups are sometimes used for soft-moored and fully free running tests.

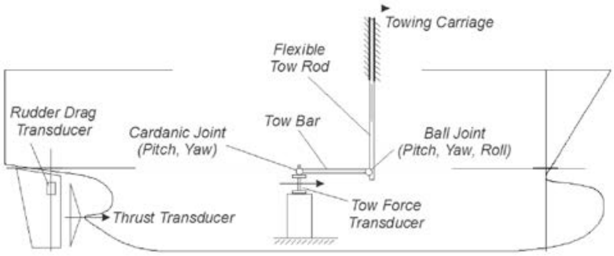

Figure 59: Hybrid test setup for added resistance tests (Crepier et al., 2018)

Regarding the incident waves, these are subject to variability. If the input conditions are accurately repeated (same wave generator flap motions, same location of the wave probe and model, perfectly still starting conditions) then two types of variability can be considered. First, the ‘seed variability’ (Scharnke et al., 2012) related to the finite duration of wave generation, where different random phase distributions of the wave components in the wave spectrum realisation lead to different statistical characteristic values (i.e. standard deviation, significant value) of the wave elevation realisation. Increasing the test duration will reduce this variability; ITTC Procedure 7.5-02-07-02.2 (ITTC, 2014) recommends 1 to 1.5 hours real time equivalent for irregular waves. This is especially important for 2nd order forces such as added resistance forces.

The second variability can be termed ‘basin generation variability’. This variability is related to the repeatability of waves generated in a test basin. This type of variability was studied by Van Essen (2019) and Van Essen et al. (2020), including the effect on the responses of a vessel moving at forward speed in waves. They demonstrated that this variability increased with increased propagation distance from the wave generator, even though the wave generator flap motions and the model location in the basin were very well repeatable. Likely causes are the basin memory effects such as small residual currents after repeated wave generation that die out only very slowly as indicated by Van Essen and Lafeber (2017) and the poorly repeating influence of wave breaking for steeper wave conditions. Variability in ship responses is strongly related to the variability of the incident waves.

Residual basin flows can also have an effect on the calm water resistance. Repetition of calm water tests between tests in waves can be used to obtain the evolution of the calm water resistance of time and monitor or even correct their effect in the added resistance. Residual basin flows and overall turbulence levels in the basin can have a significant effect on the added resistance, especially for low valued added resistance associated with low forward speed and small wave amplitudes. This is again related to the subtraction of two large total resistance values to obtain the added resistance, especially for low wave amplitude conditions, resulting in a very large uncertainty of the added resistance. Crepier at al. (2019) demonstrated the effect of the uncertainty of the calm water resistance as function of wave amplitude on the quadratic transfer function of the KCS (Figure 60).

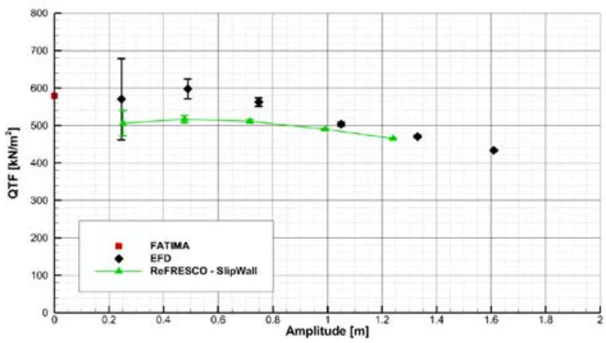

Figure 60: Effect of uncertainty of the calm water resistance on added resistance of the KCS from model tests (EFD), potential flow (FATIMA) and CFD (ReFRESCO) (Crepier et al., 2019)

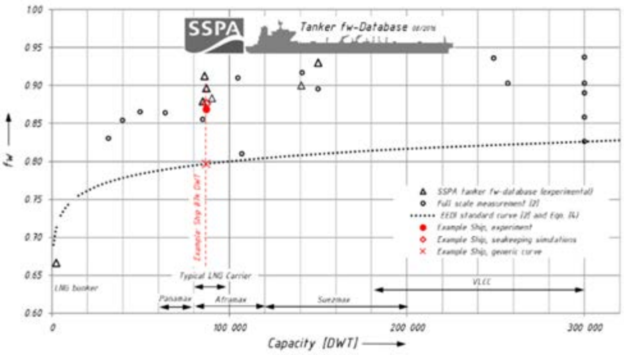

Figure 61: Weather Factor f_w as function of DWT from Gerhardt and Kjellberg (2017)

3.2.2 Numerical Methods

As outlined in ITTC Recommended Procedure 7.5-02-07-02.8 (ITTC, 2018) on the calculation of f_w there exist four categories of prediction methods, with ever increasing fidelity:

1. Empirical prediction methods,
2. Slender body theory (two-dimensional strip theory) frequency domain methods,
3. Three-dimensional panel methods, frequency or time domain,
4. CFD methods, based on the Euler Equations or on the Navier-Stokes equations.

Whereas most of the current numerical methods give very reasonable results for the added resistance for the longer wave length to ship length ratios, the accurate prediction of added resistance for shorter waves is still challenging for many approaches. Liu and Papanikolaou (2016a) give a good overview of the challenges of various numerical methods to capture added resistance in particular in short waves.

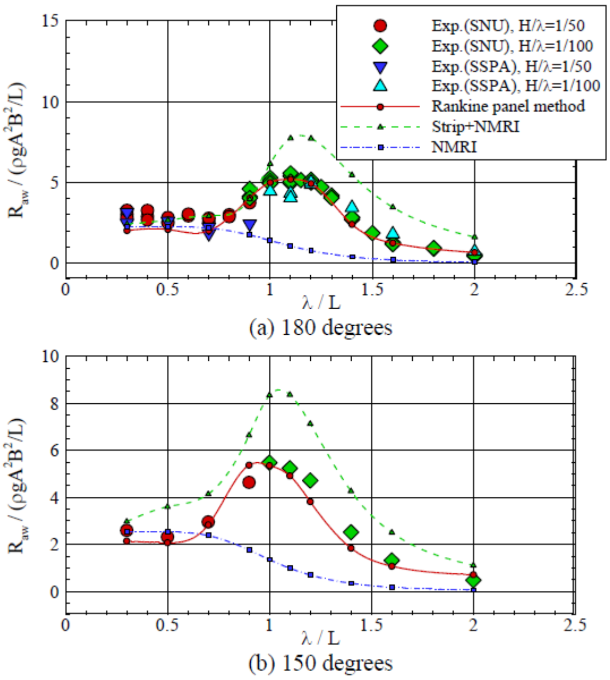

Figure 62: Added resistance of a VLCC by various experiments, empirical correction methods and potential flow methods (Park et al., 2018)

Slender body (or strip) theory does not sufficiently capture abrupt hull form changes in the bow region that drive the generation of added resistance in short waves. This may be to some extent corrected by extensions to slender body theory such as the EUT method (Kashiwagi, 1992). Oblique headings often are even more challenging to predict by slender body theory as illustrated by Figure 62. Three-dimensional panel methods are better at capturing hull form effects, but often underestimate the added resistance.

Forward speed effects are often ignored in both two and three dimensional potential flow methods. Proper wave propagation at forward speed of the radiated and diffracted waves can significantly. Modern advanced panel methods such as Rankine Panel Methods and Green function methods with exact forward speed effects or similar that resolve the potential flow interactions at forward speed show significantly improved results compared to linear zero speed free surface Green function methods (Park et al., 2016, 2018, Bunnik, 1999, Bunnik et al. 2010, Woeste et al., 2020). Often very small fine grids are required on the bow and the free surface around the bow to correctly resolve the flow (Seo et al., 2014).

However, wave-breaking and viscous effects are not captured by potential flow methods. In short steep waves waterline variations due to the changing submerged geometry of the bow and wave-breaking can cause the relation between added resistance and incident wave height to deviate significantly from being quadratic as demonstrated by for instance Crepier et al. (2019) for a wave length to ship length ratio of 1. They showed that the majority of the added resistance is generated in a small region around the waterline at the bow and fore shoulder.

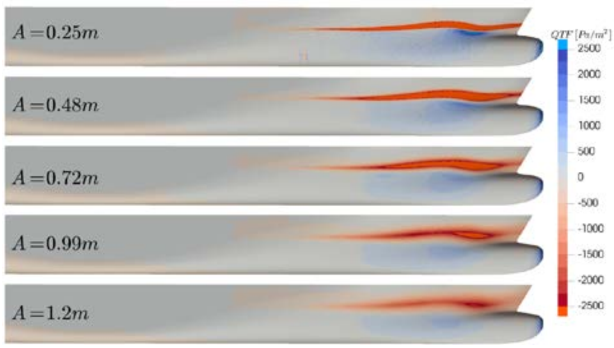

Figure 63: Spatial QTF distributions of pressure over wave amplitude squared for the KCS for various wave amplitudes A, λ/L = 1 (Crepier et al.,2019)

The dynamic waterline variations as function of the ship motions cannot be captured by linear and weakly nonlinear panel methods, breaking the quadratic relation between added resistance and incident wave height. This is illustrated in Figure 60 by Crepier et al. (2019), showing a reduction in QTF as function of wave amplitude. The plot illustrates that CFD results predict a similar trend as the experiments for increasing wave amplitude, and converge to the linear potential flow result for decreasing wave amplitude.

CFD can offer improved predictions of the added resistance that account for these nonlinear effects, viscous effects and wave breaking. This is illustrated by a large number of verification and validation studies, such as Sadat-Hosseini et al. (2013) and Seo et al. (2014) amongst many others. Nevertheless, although nowadays CFD methods can be very useful to validate the added resistance for a few specific conditions, they are still too expensive to compute a full matrix of speed, heading, and wave frequency conditions. Also, it should be noted that currently most CFD work focussed into the wave added resistance, and not the wave added power which is significantly more expensive to simulate. The quality of the outcomes of advanced CFD methods still highly depend on the experience of the user. To obtain satisfactory results requires significant attention to grid generation, grid density and modelling details.

Many semi-empirical methods are proposed to compute or correct the added resistance in short waves, these include the NMRI method (Kuroda et al., 2008), StaWAV I and II methods (ITTC, 2014), Faltinsen's method (Faltinsen et al., 1980). The NMRI method seems to be most widely used. Combined with relatively simple potential flow methods relatively complete and in many cases reasonable estimations of the added resistance can be obtained. Nevertheless, there are also many examples, especially in oblique conditions (Park et al., 2018), where these methods offer less than reasonable agreement with experiments. Also, like strip theory methods, these methods have a larger uncertainty compared to panel methods, CFD and experiments, and have limited capability to distinguish the effect of small design changes (see for instance Park et al., 2016).

At this moment, for modest sea states where nonlinear effects do not play an important role modern panel methods that account for the steady flow interactions seem to offer a reasonable balance between modelling effort and calculation time and accuracy of the results. For these cases the quadratic relation between wave height and added resistance holds. For very short and steep waves and breaking waves, model experiments and/or complex CFD computations currently still seem to be the best options to obtain accurate predictions of the added resistance. Achieving sufficiently accurate predictions of added resistance requires careful attention to the details of the computations or experiments, as well as significant computational resources for CFD.

3.3 Control of High Speed Marine Vehicles in Model Tests

Model tests with High Speed Marine Vehicles are a very common choice for studying their hydrodynamic performance. Phenomena of importance for their operation and safety such as large relative motions, impacts in waves and dynamic stability are highly nonlinear and still difficult to fully and accurately capture in numerical simulations.

Nevertheless, performing model tests with high speed craft comes with its own set of challenges related to scaling of time and model size and weight. To evaluate the hydrodynamic performance the experimental conditions for the model tests are determined according to Froude's similarity law. For a model scale α where the length of the model is $1/\alpha$ of its full value, the weight of the model is a factor $1/\alpha^3$ of its full scale weight, while the time and speed at model scale are $1/\sqrt{\alpha}$ times of the full scale values.

3.3.1 Issues with model size and weight

To keep the model speed and to a lesser extend the wave height within the practical limits of the test basin requires a sufficiently large model scale factor α. A too large model speed leads either to impractically short run duration or a speed beyond the capabilities of towing apparatus. Nevertheless, a larger scale factor α can lead to impractically light models with too little weight margin to setup the correct loading condition and allow installation of drive and measurement equipment.

The high speeds and test conditions of interest can result in violent motions and impacts. Despite their small size and lightweight construction, this poses high demands on structural integrity and water tightness of the models used.

Fortunately, advances in model making techniques using lightweight materials and drive systems, high quality battery packs and miniature computers for data acquisition have made fully free running model tests with remote (auto-pilot) controlled models much more feasible, both in test basins and in outside bodies of water such as lakes. A number of examples of such tests are given in the following paragraphs. Most of the models used are constructed from lightweight material such as Carbon fibre Reinforced Plastics, and a combination of hobby equipment, miniature controllers and computers, wireless technology and custom made parts. The complexities of the instrumentation of these models are illustrated by Figure 64 and Figure 66.

Katayama et al. (2014) developed a free running model test system to safely and easily investigate the occurrence of instabilities as an alternative to full scale trials. They used a 1 metre radio-controlled scale model of a planing hull that included on board measurement devices and its own propulsion and steering system. It was made of thin Fibre Glass Reinforced Plastics and equipped with miniaturized measurement equipment to allow speeds of up to 12 m/s.

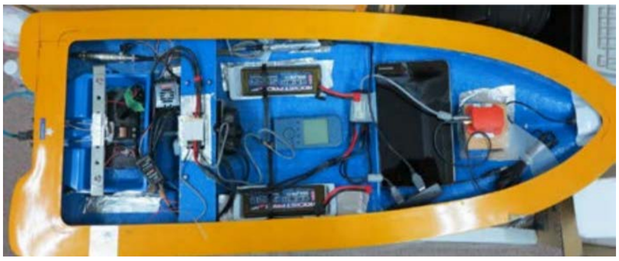

Figure 64: Instrumentation of free running HSMV model (Katayama et al., 2014)

Van Walree and Struijk (2021) carried out model tests and full scale trials for the FRISC-type RHIB of the Royal Netherlands Navy. Due to the high speed and large motions in the horizontal plane of the model the carriage could not always follow the model (Figure 65). The model therefore needed to be fully free running with an on-board position measurement system, autopilot computer, power supply, measurement instrumentation and data storage. The optical motion tracking system functioned when the model was in the measurement window of the carriage, sending position information to the on-board autopilot. When not in the measurement window an on-board inertial (IMU-based) navigation system took over.

Their trial data was obtained with the full scale FRISC under more realistic conditions, with a human in the control loop, with inherently much larger uncertainties on wave conditions. The effect of human course keeping was found to be significant, not only on yaw but also on the other modes of motion: it removes much of the dependency of motions and accelerations on the wave direction.

Figure 65: Fully free running model of the FRISC RHIB (Van Walree and Struijk, 2021)

Wang et al. (2020b) outline a preliminary design and testing plan for a free running (self-propelled, autonomously controlled model) of a high speed craft. The considered the design of the hull, the propulsion system to reach the desired speed and a steering system utilizing IMUs (Inertial Measurement Units) and a proportional derivative (PID) control. Methods for monitoring the outdoor environment using floating wave buoys and/or ultrasonic sensors mounted to the model were explored and specific instrument options were presented. Furthermore, sensor implementation to record necessary performance data was explored and the requirements for eventual testing locations where the model will be used wee detailed.

Figure 66: Instrumentation of free running HSMV model (Wang et al., 2020)

3.3.2 Issues with model scale time and control

Another issue is related to model scale time and control. Due to the small scales also model scale time becomes relatively small (due to aforementioned the laws of similarity). This may result in problems in control systems, as inherent time delays in control systems that may not pose problems for model testing at larger model scales now may introduce unacceptably large time and phase shifts in controller actions. This means that a controller at model scale can act unexpectedly different than intended. This may affect control algorithms and hardware, steering servos, data communication systems, etcetera. Unfortunately, in open literature no previous work could be found on the effects of these phase shifts on HSMV testing.

3.3.3 Scale effects of hydrodynamic forces on hull and control surfaces

Although not exclusively for HSMV model tests, the (Reynolds) viscous scale effects on the hydrodynamic forces have to be considered. As described in the above, due to other scale limitations, models of high speed craft and appendages, tend to be relatively small. Boundary layer effects, such as laminar to turbulent flow transition, flow separation and boundary layer thickness, on hull and appendage forces need to be considered.

The relatively higher resistance at model scale can affect the steering behaviour and therefore the course keeping and broaching, as the steering forces are proportional to the thrust (Van Walree et al., 2004). Applying compensating pulling forces is either impractical due to unintended inertial effects of such setups in unsteady tests or impossible for free running models. Katayama et al. (2012) (in Japanese) try to compensate the viscous effects on running attitude of a free running model by using an air fan on the deck of model to generate compensating forces. Not only friction forces are affected by scale effects, also lift generation can be significantly affected. Katayama et al. (2011) indicated the effect of viscosity on the running attitude of a high speed craft model in calm water.

With respect to controllability the scale effect on lift of control surfaces is of significant importance. Van Walree and Luth (2000) reviewed the scale effects on foils and fins in steady and unsteady flow. The stressed the need of careful turbulence stimulation, and considering the local Reynolds number of each lifting surface. They indicate that for turbulence stimulation to be effective, lifting type control surfaces should not be too small and recommend a Reynolds number of the foil of at least 5 to $7.5 \cdot 10^5$, depending on the foil section type.

Despite using turbulence stimulation, still the lift may be lower at model scale than at full scale. To correct for this Van Walree et al. (2004) suggest the option of using adapted control surfaces at model scale, in size or in foil section. Cavitation is not a limitation at model scale, permitting the usage of higher lift sections at model scale. A priori viscous flow calculations are necessary to assess the lift and drag at low Reynolds numbers to ensure a correct adaptation is done to the model scale appendages.

Still, some results indicate a difference of the lift generated by foils and fins in steady versus unsteady flows. Early results indicate that the lift-curve slope seems to be less affected by scale effects and therefore most of the scale effect on lift may be avoided by choosing an appropriate offset in angle of attack of a lifting surface. More research is needed to further investigate this.

Additional, often secondary, scale effects can be expected due to the surface tension (Van Walree et al., 2004). Spray formation at model scale is different than at full scale. At full scale spray tends to consists of droplets, whereas at model scale more often coherent spray sheets are observed that generally cause a larger spray wetted area.

Combined with the (relatively) too high atmospheric pressure at model scale the incorrectly scaled surface tension may affect ventillation. This can cause thrust breakdown of the propulsor and reduction of controllability due to ventilation of control surfaces. Due to the complexity of the physics involved, no scaling rules or empirical corrections are available to correct for scale effects in spray and ventilation. Young et al. (2017) presented an overview of scaling effects associated with ventilation of lifting bodies. Besides scaling the fluid flow correctly, they also focused on Fluid Structure Interaction and correctly scaling the deformation of lifting surfaces to achieve dynamic similitude in the dynamic hydroelastic response.

4. COLLABORATION

Within the ITTC, the Seakeeping Committee (SKC) has collaborated mainly with the Stability in Waves Committee (SIW). On suggestion of the Seakeeping Committee and after discussion with the AC/EC and the Stability in Waves Committee it was decided to transfer the task (Task 10 of the SKC Terms of Reference) for developing guidelines on the inclination experiment from the SKC to the SIW. The SKC has provided support to the SIW on this task and has provided a review on the draft version of the new procedure on inclining experiments. Various topics have been discussed between the two committees, including various techniques for assessing roll damping from model tests, details of inclination tests, including uncertainty and self-repetition in computationally generated long duration wave elevation time traces.

In response to Task 9 of the SKC Terms of Reference and upon request by the SIW the SKC has provided an extensive review of the Recommended Guideline 7.5-02-07-04.3 on the prediction of the occurrence and magnitude of parametric rolling.

In Task 13 of the Terms of Reference the Seakeeping Committee was requested to continue the collaboration with the ISSC Loads and Responses and Environment Committees. Two members of the SKC were also part of either the ISSC Loads Committee or the Joint ISSC/ITTC Committee. The main result of this collaboration is the 5th Joint ISSC/ITTC International Workshop on Uncertainty Modelling in Wave Description and Wave Induced Responses to organized near the 29th ITTC Full Conference. Three contributions by SKC members on wave modelling, the effect of variability of wave generation in test basins on seakeeping responses such as impact loads and added resistance in waves, and propeller-hull-rudder interaction effects and scaling effects on the added power in waves are to be presented at this workshop. Unfortunately, related to the COVID pandemic, the workshop comes too late to include its results in the 29th ITTC Final Report.

5. ITTC RECOMMENDED PROCEDURES

5.1 ITTC Procedure 7.5-02-07.02.1 Seakeeping Experiments

For the 29th ITTC the Seakeeping Committee was requested to extend this procedure to include the measurement of added resistance in waves, including attention to the uncertainty of added resistance. To maintain consistency between this procedure, procedure 7.5-02-07.02.2 on the prediction of power increase in waves and procedure 7.5-02-07-02.8 on determining the weather factor f_w, details on performing added resistance were transferred from procedure 7.5-02-07.02.2 to this procedure. In this way all experimental test execution is covered in a single procedure on seakeeping experiments, avoiding redundancy between multiple procedures. Procedure 7.5-02-07.02.2 then provides details on how to extract power increase in irregular waves and refers to this procedure for details on test execution of model tests in waves. Procedure 7.5-02-07-02.8 also refers to the aforementioned procedures for details on test execution and data processing and has been checked on using consistent symbols and terminology.

Recommendations for the conditioning of a model for seakeeping tests in terms of required model completeness, model mass properties and the model ballasting procedure were introduced, as requested in the Terms of Reference. Additionally, guidelines on using pre-simulations for the selection of relevant test conditions were added.

The section on measurement of wave loads was brought in line with procedure 7.5-02-07.02.6 on the prediction of global wave loads, by making a distinction between rigid body segmented model tests and elastic (segmented) models and referring to procedure 7.5-02-07.02.6 for more details. Additional remarks on wave generation and the effects of wave steepness on non-linearity, wave breaking and statistical stationarity have been included. The formulation of wave energy spectra have been updated for consistency.

With the above substantial updates were made to procedure 7.5-02-07.02.1. In consultation with the Advisory Council and the Executive Committee it has been decided to include a discussion on uncertainty in added resistance in waves from model tests in this Final Report of the Seakeeping Committee (refer to Section 3.1), in preparation of adaptation of the uncertainty assessment in Appendix A with added resistance in waves by a future committee.

5.2 ITTC Procedure 7.5-02-07-02.2, Predicting Power Increase in Irregular Waves from Model Tests

Recommended Procedure 7.5-02-07-02.2 was updated in conjunction with the previous procedure 7.5-02-07-02.1, by moving the section on execution of model tests for added resistance in waves from this procedure to 7.5-02-07-02.1. A reference was added in this procedure to the new section in 7.5-02-07-02.1.

Furthermore, updates were made to the text of this procedure to enhance readability for a wider audience, as requested in the Terms of Reference. In addition, the formulations and symbols used to describe directional wave energy density spectra were brought in line between this procedure and the previous one, while maintaining consistency with the ITTC Symbols list.

Besides a number of additional editorial corrections, an error was fixed in the formula to compute the power in irregular waves, that incorrectly used a factor associated with Horsepower instead of Watt.

5.3 ITTC Procedure 7.5-02-07-02.3, Experiments on Rarely Occurring Events

The Seakeeping Committee was requested to update this procedure to include the measurement and analysis of impulsive loads, peaks in pressures and maximum accelerations. To address this a number of details on the measurement and recording of extreme impact and green water events were added, with references to useful and more detailed background literature.

Suggestions were added to correctly and completely document the means used to record impact pressures such as sensor type, calibration, sensor arrangement, sampling rate and results of hammer tests to obtain model and sensor eigenfrequencies. Corrections were made to inconsistent suggestions for run durations and outdated usage of expressing wetting event frequencies of occurrence as ‘wets per ship model length’. A statement was included on the effect of air-pocket on the impact loads when applying Froude scaling.

5.4 ITTC Procedure 7.5-02-07-02.5, Verification and Validation of Linear and Weakly Non-Linear Seakeeping Computer

This procedure was revised substantially to minimize redundancies and to use consistent terminology. Improvements were made to the language used to improve clarity and readability. It was made clear that the current procedure is focused on the verification and validation of linear and weakly nonlinear seakeeping computer codes based on potential flow theory. In the future a new procedure may be developed for CFD based methods.

The sections on weakly nonlinear and on hydroelastic seakeeping codes were considerably improved. A note was added to check the natural frequencies and damping coefficients for dynamic simulations and quantification of uncertainties. Remarks on appropriate verification and validation procedures such as definition of model assumptions, checks on numerical convergence as well as quantification of modelling uncertainties were introduced in the procedure.

5.5 ITTC Procedure 7.5-02-07-02.6, Prediction of Global Wave Loads

Besides a number of minor editorial revisions to improve readability more details were added on the usage of elastic segmented models. This includes a discussion on the advantages of using internal rigid structures with instrumented elastic joints that allow better tuning to a specific natural frequency for the two-node bending mode regarding slamming-induced-whipping responses.

5.6 ITTC Procedure 7.5-02-07-02.7, Sloshing Model Tests

During the 29th ITTC only minor changes were introduced into this procedure, that was first introduced during the 28th ITTC. These changes include an update to the data measurement sections with a comment on thermal shock issues of pressure transducers, updated and corrected references, language revisions and an updated figure to improve readability.

5.7 ITTC Procedure 7.5-02-07-02.8, Calculation of the weather factor fw for decrease of ship speed in wind and waves

The Seakeeping Committee was requested to update this procedure in two steps. The first step was to update the procedure very early in the 29th ITTC term to bring it in line with the terminology in the EEDI guidelines and to enable the ITTC to submit it to MEPC 72 (in the spring of 2018). Based on the discussion during the Full Conference of the 28th ITTC the procedure was updated with a statement that the procedure is applicable mainly for large ships and that additional work is required for smaller ships, and state the limit between large and smaller ships. Besides this substantial improvements to the terminology and symbols were made to improve readability for more general audience and to be consistent with existing EEDI guidelines. References to recent and relevant benchmark data were added.

In the second round of improvements, as part of the regular round of revisions a few minor additional revisions were made. These were aimed at improvement of consistency between this procedure and the related procedures 7.5-02-07-02.1 and 7.5-02-07-02.2 as noted in the above, mainly in the symbols for spectral wave period symbols. A discussion on the uncertainty of various prediction methods was included as a discussion in Section 3.1 of this Final Report, as agreed upon with the Advisory Council and the Executive Committee.

5.8 ITTC Procedures on Tests with High Speed Marine Vehicles

Similar to the 28th ITTC, the Seakeeping Committee was requested to review the procedures on High Speed Marine Vehicles (HSMV). These include Procedure 7.5-02-05-04 HSMV Seakeeping Tests, procedure 7.5-02-05-07 HSMV Structural Loads, and procedure 7.5-02-05-07 HSMV Dynamic Instability Tests. A specific request was made to add guidelines on motion control for high speed craft.

The procedure on HSMV Seakeeping Tests was found to be the most mature of the three procedures. Besides minor editorial changes, more substantial revisions include a modernisation of the section on model construction, materials used and manufacturing tolerances, removal of outdated or incorrect sections on run duration (based on linear statistics) and side-by-side comparison testing and a removal of superfluous discussion of very specific details of wave and motion measurement systems. As the derivation of linear Response Amplitude Operators (RAOs) is generally not advised for nonlinear motions such as those of high speed marine vehicles recommendations on the use of RAOs are removed.

In addition to reviewing the procedure on HSMV Seakeeping Tests the Seakeeping Committee was requested to develop a new procedure for motion control of HSMV during seakeeping tests. Due to the high workload of the committee, the Seakeeping Committee proposed in consultation with the Advisory Council and the Executive Committee to defer this activity to a future committee, possibly a specialist committee of HSMV. In preparation for this new procedure, the 29th Seakeeping Committee prepared a comprehensive discussion on HSMV control during seakeeping tests in Section 3.2 of this Final Report.

Procedure 7.5-02-05-07 on HSMV Structural Loads was found to be at a significant lower level of maturity. The description of the purpose of the procedure was considerably updated to provide more context to this procedure and to explain the link to related procedures, most notably the general seakeeping procedure on global loads, 7.5-02-07-02.6. The unrealistically high recommended sampling rate of 100kHz for impacts was reduced to 10-20kHz and the section on the parameters to be taken into account was expanded. Finally, the language was improved and references were updated.

Lastly, procedure 7.5-02-05-07 on HSMV Dynamic Instability Tests was reviewed and found to be inadequate. The introduction and stated purpose were found to be not appropriate, dynamic instability behaviour types should be more adequately defined and consistently treated. In its current state the procedure is not clear on whether it treats with instability in calm water or in waves, or both. The descriptions on the experiments to be performed were found to be inconsistent and to only cover planing mono hulls. Due to the workload the Seakeeping Committee has requested to defer the activity of the complete revision of this procedure to a future specialist committee on high speed marine vehicles and in the meantime strongly recommends to withdraw this procedure from the ITTC Recommended Procedures.

6. CONCLUSIONS

6.1 General Technical Conclusions

6.1.1 New Experimental Facilities

Only a limited number of new experimental facilities have opened since 2017 or are about to become operational. These include two large offshore basins, a facility for studying the influence of waves, winds and currents on coastal defences and blue energy applications, and a towing tank with wave making capabilities.

6.1.2 Experimental Techniques

The accurate experimental determination of “added resistance in waves” continues to be a challenging topic. Added resistance is obtained by measuring the small difference between two large quantities (calm water resistance and mean resistance in waves). This makes determining added resistance in short waves particularly difficult and places high demands on the quality of such experiments. There remains a need to gain a better understanding of the uncertainties associated with seakeeping tests in general and added resistance experiments in particular. Although some pioneering work has been done in this area, including uncertainty analysis in added resistance evaluations is still rare. Only a handful of papers deal with the different sources of uncertainty and their relative importance in seakeeping.

An emerging trend is the prediction of the seakeeping performance of sail assisted vessels, where various approaches to include the effect of sail aerodynamics on the seakeeping performance are proposed. There seems to be a clear need to develop guidance on how to perform such model tests.

6.1.3 Numerical Methods

Despite the significant developments within Navier-Stokes solvers (CFD), potential theory-based boundary element methods are still the workhorses in practical seakeeping analyses.

Whereas efficient strip theory methods are still widely used, most recent developments focus on 3D methods. For ships at forward speed, multi-domain (hybrid) methods seem to gain more popularity, since they utilize the relative merits of the Rankine panel method and the Green function method in an inner and outer domain, respectively. The two methods are matched at their common boundary, and there have been some recent developments in matching techniques. There are also activities aiming at making the boundary element methods more computationally efficient.

Regarding forward speed effects, comparisons with experiments indicate that the simple Neumann-Kelvin approximation for the steady flow may sometimes give acceptable accuracy, compared to the more complex methods based on the double-body potential or the complete solution of the steady flow.

In time-domain simulations, it is common to include nonlinear Froude-Krylov and hydrostatic forces, by considering the instantaneous position of the hull beneath the incident wave profile. The so-called fully nonlinear methods, where the nonlinear boundary value problem is solved at every time-step, seem to receive less attention. The reason could be that the Navier-Stokes solvers are gradually filling this niche of high-fidelity hydrodynamic simulations. Instead, research on time-domain methods based on potential theory seem to be more focused on practical ways of addressing the combined seakeeping and manoeuvring problem.

6.1.4 Rarely Occurring Events

In many experimental studies considering impact and slamming there is an increased focus on oblique wave impact, with multiple sources reporting larger impact loads than in head seas in particular cases. This highlights the need for carefully considering the influence of wave heading on slamming both in model tests and in numerical calculations.

Most computational approaches for rarely occurring events related to slamming, green water, and impact, employ multiple fidelity levels, with more standard and efficient 2D or 3D potential flow methods to compute the overall motions and occurrence rates and higher fidelity dedicated methods for individual impacts and green water events. For the later, a shift is taking place away from analytical or empirical Von Karman or Wagner based approaches towards advanced CFD methods and meshless methods such as Smoothed Particle Hydrodynamics (SPH), often including the effects of compressibility and air-pockets on the impact load. In many cases hydrodynamic impact loading is combined with the partly or fully hydro-elastic coupled structural assessment.

Due to the usage of complex CFD there is an increased focus on validation. A comparative study of a water-entry problem was conducted by the International Hydrodynamic Committee. Thirteen institutions participated, and twenty different numerical results from a variety of computational approaches were investigated and compared with one another and with model test data. CFD results were found to be very promising for symmetric impact of simple section shapes, but there remained quite some uncertainty for the asymmetric impact case, possibly related to the formation of air-pockets.

Research on emergence of propellers and other appendages is more focused on the effects of ventilation on the performance of propellers and lifting surfaces. Detailed experiments and CFD computations are conducted to predict the steady and dynamic propeller/foil performance in different flow regimes. Similar to a hydrofoil or strut, ventilation of a propeller can lead to significant reduction in thrust and torque. This in turn can lead to rapid propeller rpm variations to maintain thrust or involuntary loss of speed and heading, with significant consequences for vessel control in a seaway and hydro-elastic propeller loading and deformation.

6.1.5 Sloshing

Assessment of sloshing loads for LNG tanks has been an important issue in the design of LNG carriers or LNG FPSOs (FLNG). For practical purposes, the experimental approach based on sloshing model tests has been the most frequently used. Many studies were focused on the evaluation of the impact load for the sloshing problem. Sophisticated phenomena that have been considered in model tests include the effects of gas-liquid density ratio and bubbles on the sloshing impact.

A large number of numerical investigations have been carried out to study the fluid-structure interaction inside the sloshing tank and the coupling effects of sloshing and ship motions. In an attempt to capture the highly nonlinear and complex nature of the sloshing problem, new techniques based on a machine learning scheme have been introduced to predict the sloshing load severity.

6.1.6 Hydroelasticity

Several advances have been made in the last decade with respect to (full-scale and model-scale) experimental, numerical and analytical modelling of the hydroelastic response of ship structures in waves. Experimental and numerical results both point to the importance of accounting for flow-induced vibrations on the dynamic loads and stresses. In particular, significant dynamic load amplification can occur near resonant conditions, which can drastically increase the vibrations and accelerate fatigue. The added mass, modal frequencies and damping coefficients change with operating conditions (confined water, speed, wave heading, submergence/draft, etc), which must be considered to avoid dynamic load amplification.

In some cases, the operational dependence of modal characteristics can lead to mode switching and modal coalescence, which can drastically increase the vibrations and dynamic load fluctuations. Such mode changes would also challenge the validity of modelling methods based on superposition of modal responses, which typically assume the mode shapes and mode order to be the same in dry and wet conditions. Recent studies of a large database of 17 post-Panamax container ship models by Lauzon et al. (2020) showed that 2-way coupled fluid-structure interaction models are needed to correctly capture the slamming loads and motions.

Even with recent advances in computing, performing fully coupled CFD-FEM calculations of a vessel oscillating and vibrating in waves is still not yet practical. However, such simulations are needed to advance our understanding of hydroelastic effects, as model-scale experiments are challenged by scaling effects, and full-scale measurements are challenged by the ability to control the loads and motions. Since much more work is still needed to improve the accuracy and efficiency of numerical fluid-structure interaction models, more experiments are also needed to validate the numerical solutions.

6.1.7 Added Resistance in Waves and Power Requirements

Predictions of ship motions and added resistance in head waves by CFD have become reliable, whereas potential flow codes often provide underestimation in the short wavelength region and overestimation at the resonance point with encounter waves. It has also been confirmed by CFD that the quadratic linear assumption for the wave height of added resistance in head waves is not satisfied in the higher wave steepness region in for short waves. This is caused by viscosity and the non-linear interaction between the fluid and the hull shape. CFD is not suitable for a practical calculation at present because of its high calculation cost, but visualization of these phenomena can deepen the understanding of hydrodynamic phenomena.

By mathematically modelling these phenomena and combining with potential flow codes, a more practical and highly accurate calculation method can be created. On the other hand, there are a number of proposals for estimating added resistance by semi-empirical formulae that do not require high-performance computation were also made. Compared to the past, the range of ship types and wave lengths that can be modelled by these methods has become much wider. This makes these semi-approaches useful for considering a wide range of design variations that meet EEDI requirements in the preliminary design phase.

There were many numerical studies and experiments that systematically investigated variations and trends of self-propulsion factors and added power in waves. In particular, experimental data obtained from various basins and numerical results from various CFD codes have been accumulated in benchmark studies, which is expected to form a good basis for further validation studies in the future.

The focus has conventionally been on ship motions and added resistance in head waves and so far there have been few theoretical studies and experimental examples for oblique waves. This is partly caused to the limited number of seakeeping basins where experiments can be conducted in oblique waves with sufficient accuracy. However, in a few of last years, such experimental data has been accumulated. Early results hint at cases where the added resistance in waves is higher in oblique seas compared to head seas, making it important to also assess added resistance in oblique conditions. In oblique waves, the effect of viscosity of the fluid appears to be stronger, making CFD the better suited to tool to complement basin experiments. In oblique waves, improving accuracy in the short wave length region is more important than in heading waves.

6.1.8 CFD Applications

The use of CFD for seakeeping has continued increasing over the past few years. It has been applied over a large variety of topics essentially thanks to two intrinsic advantages of the method: the flexibility in imposing boundary conditions; and its natural treatment of nonlinear problems. This flexibility however comes with the computational cost, which is had not become any more efficient over the years as the software used are mostly based on the same consolidated and robust methodology (implicit or semi-implicit finite-volume solvers). To overcome this issue, progress is being made on the design methodology with CFD, by reducing the number and the physical time needed in the simulations to achieve the goals.

6.1.9 Seakeeping of High Speed Marine Vehicles

Sailing with high speed craft in calm water and in waves is associated with very dynamic behaviour related to dynamic stability and slamming impacts. High speed craft in waves are subjected to significant and frequent impacts with large effects not only on the structural integrity but also on human performance and human safety. Research has not only focused on model tests and predictions by means of computations, but also full scale recordings play an important role as well as the statistics of extremes of the vertical accelerations.

Over the past five years, the most investigated types of high speed marine vehicles are monohulls, followed by wave piercing catamarans and trimarans. There seems to be a growing interest in hydrofoiling craft and foil assisted craft, possibly related to the introduction of hydrofoils in high profile sailing matches such as the America's Cup. There is more and more interest in using ride control systems to not only improve passenger comfort, but also in actively reducing slamming itself.

The nonlinear nature of the responses of high speed vessels has resulted in the adoption of nonlinear time domain methods. Besides the more traditional nonlinear 2D+t potential flow methods, nonlinear 3D panel methods have gained significant popularity in recent years. Also CFD methods are slowly gaining ground, but still suffer from the computational burden needed to obtain sufficient time duration of simulations.

The various semi-empirical methods in use by classification societies for the assessment of vertical accelerations were scrutinized by a number of authors and important questions were raised about the actual safety levels that are achieved when applying these semi-empirical methods.

6.1.10 Uncertainty in Added Resistance

The 'weather factor' f_w for decrease of ship speed in wind and waves is one of the terms in the Energy Efficiency Design Index (IMO, 2014). A key component to determine f_w is the added resistance of a vessel in waves. At this point the relevant ITTC, ISO and IMO procedures leave open many options to determine the added resistance in waves, by model experiments or by various levels of computations.

There are various ways of conducting measurements to obtain the added resistance in waves, mainly differing in the way a model is restrained, whether the model is powered or not and whether tests are performed in regular or irregular waves. A balance is sought between realism in the representation of the vessel behaviour and its propulsor and minimization of uncertainty that is inherently caused by determining the added resistance by subtraction of the relatively large values of total resistance in calm water and that in waves. This report describes in detail the various advantages and disadvantages of the choices that can be made when performing added resistance tests. Besides the test setup, a key factor in controlling uncertainty in added resistance is the understanding and management of the variability of the incident waves in the test basin. This is related to statistical variability due to the finite time duration of wave generation and to the repeatability of waves generated in a test basin.

Various numerical methods to obtain added resistance in waves are described, including their advantages and disadvantages, ranging from empirical (correction) methods, strip theory to panel methods and CFD. At this moment, for modest sea states where nonlinear effects do not play an important role modern panel methods that account for the steady flow interactions seem to offer a reasonable balance between modelling effort and calculation time and accuracy of the results. For these cases the quadratic relation between wave height and added resistance holds. For very short and steep waves and breaking waves, model experiments and/or complex CFD computations currently still seem to be the best options to obtain accurate predictions of the added resistance. Achieving sufficiently accurate predictions of added resistance requires careful attention to the details of the computations or experiments, as well as significant computational resources for CFD.

6.1.11 Control of High Speed Marine Vehicles in Model Tests

Model tests with High Speed Marine Vehicles are a very common choice for studying their hydrodynamic performance. Phenomena of importance for their operation and safety such as large relative motions, impacts in waves and dynamic stability are highly nonlinear and still difficult to fully and accurately capture in numerical simulations.

Nevertheless, performing model tests with high speed craft comes with its own set of challenges related to scaling of time, model size and weight and model control. To evaluate the hydrodynamic performance the experimental conditions for the model tests are determined according to Froude's similarity law. For high speed craft this typically leads to very small and light models that can be very challenging to build while accurately representing the loading condition.

Especially when model control is important this typically lead to small scale fully self-propelled and self-steered free running models. This is made possible by recent advances in miniaturized computing devices and battery technology. The small scale may also result in problems in control systems, as inherent time delays in control systems that may not pose problems for model testing at larger model scales now may introduce unacceptably large time and phase shifts in controller actions.

Reynolds scale effects on lift and drag by control surfaces, again exacerbated by the typical small scale models used, need to be carefully considered and mitigated. In addition, scale effects related to surface tension, spray formation and ventilation may need to be considered. Fluid-structure interactions of lifting surface may require also dynamic similitude in the hydroelastic response.

6.2 Recommendations To The Full Conference

Adopt the updated procedure No. 7.5-02-07-02.1 Seakeeping Experiments.

Adopt the updated procedure No. 7.5-02-07-02.2 Prediction of Power Increase in Irregular Waves from Model Tests.

Adopt the updated procedure No. 7.5-02-07-02.3 Experiments on Rarely Occurring Events.

Adopt the updated procedure No. 7.5-02-07-02.5 Verification and Validation of Linear and Weakly Non-linear Seakeeping Computer Codes.

Adopt the updated procedure No. 7.5-02-07-02.6 Global Loads Seakeeping Procedure.

Adopt the updated procedure No. 7.5-02-07-02.7 Sloshing Model Tests.

Adopt the updated procedure No. 7.5-02-07-02.8 Calculation of the Weather Factor fw for Decrease of Ship Speed in Wind and Waves

Adopt the updated procedure for high speed marine vehicles No. 7.5-02-05-04 HSMV Seakeeping Tests.

Adopt the updated procedure for high speed marine vehicles No. 7.5-02-05-06 HSMV Structural Loads.

Withdraw the existing procedure for high speed vehicles No. 7.5-02-05-07 HSMV Dynamic Instability Tests; due to this procedure not being up to standard for ITTC. The extensive work needed to revise this procedure is recommended as future work for a special committee.

6.3 Proposals For Future Work

6.3.1 Verification and Validation for CFD Seakeeping Applications

The Seakeeping Committee notes that the application of CFD methods such as RANS and LES, as well as particle methods, is becoming more and more common-place to seakeeping problems. Of these methods, the Finite Volume Method with Volume of Fluid interface description is the most wide-spread at this moment for practical applications. To ensure the correct applicability of these methods, there is clear need for guidance on verification and validation of these methods. The Seakeeping Committee is of the opinion that this should lead to a new procedure, next to the already existing procedure No. 7.5-02-07-02.5 Verification and Validation of Linear and Weakly Non-linear Seakeeping Computer Codes. This work is proposed as future work for the Seakeeping Committee in close collaboration with the Specialist Committee on Combined CFD/EFD Methods.

6.3.2 Weather factor for small ships

In the current procedure No. 7.5-02-07-02.8 on the calculation of the weather factor f_w it is noted that the selected 'representative sea conditions' as specified by IMO (2012) may not be suitable for ships smaller than about 150 m in length. These wave conditions may result in 'voluntary' speed reduction by the ship's master to avoid excessive motions and loads on these small-sized vessels. Figure 61 from Gerhardt and Kjellberg (2017) for instance shows that f_w for small ships is predicted to drop significantly for small vessels. More work is needed to understand and quantify this issue further. A possible outcome of this work can be the development of alternative approaches for determining weather factors for smaller vessels, e.g. reduced wave heights/milder environmental conditions like in the IMO guideline on "minimum power requirements". More experimental studies are also needed for validation of the various prediction methods.

6.3.3 Minimum Power Requirements

The Seakeeping Committee recommends the development of an ITTC Guideline to determine the minimum power requirement as laid out in MEPC.1/Circ.850/Rev.2 based on the outcomes of the Specialist Committee on Manoeuvring in Waves. Determination of this minimum power requirement is mandatory under the current EEDI rules. Nevertheless, the Seakeeping Committee feels that the existing IMO Circular 850 is not well defined and open for interpretation, leading to uncertainty with ship operators and test facilities. To clarify this issue fits with the role of ITTC defining standards for model testing and as a technical advisor to IMO.

6.3.4 Wind Resistance

Accurate and consistent determination of both f_w and minimum power require realistic determination of the wind resistance, with an accuracy that matches the accuracy of all other resistance components. Current procedures do not seem to cover this in sufficient detail, leaving open a large room for interpretation by the evaluator of both f_w and minimum power requirements. The Seakeeping Committee sees a need for developing a better defined guideline on determining wind resistance. This need seems to be widely spread over multiple committees, not only related to EEDI issues, but also for more generic problems such as the effect of wind loads on manoeuvres and dynamic stability, calm water resistance and wind loads on offshore structures, thereby affecting almost all Technical Committees. It seems that the Specialist Committee on Modelling of Environmental Conditions as well as the Specialist Committee on Operation of Ships at Sea could have an important role in defining guidelines for wind resistance. There may be the need to setup a new Specialist Committee just for this task.

6.3.5 High-Speed Marine Vehicles

It is recommended to install a Specialist Committee on High Speed Marine Vehicles

(HSMV) for the 30th ITTC term. After reviewing the procedures for High Speed Marine Vehicles it was found that especially the HSMV procedure on Dynamic Instability lacked the desired quality to be included in the ITTC Quality Systems Manual. This Special Committee should perform a comprehensive review and revision of all related procedures for HSMV and draft a procedure for motion control of HSMV during model tests. The SC should therefore also consist of experts of all related fields, including but not limited to seakeeping, manoeuvring, dynamic stability, and powering.

6.3.6 Seakeeping Benchmark Campaign

A new benchmark experimental campaign is highly recommend with a focus on the characterization of the uncertainty in the measurement of added resistance. Candidates for this study would be the KCS or the KVLCC2. Typical models for this are available at the different institutes that could be circulated as was done in previous ITTC benchmark studies. Very careful attention should be spent on accurately defining wave and test conditions, control settings, model roughness and turbulence stimulation and the mass properties of the model. Such benchmark would be a key element in the discussion on measurement uncertainty in the determination of f_w and minimum power requirements. During next term, the test requirements should be defined first, before circulating a suitable model over the different facilities. Besides getting a better overview of the uncertainty of added resistance measurement, this campaign could also be used in the validation of computational methods.

6.3.7 Real-Time On-Board Data Processing

Identify the need for ITTC recommendations for the acquisition and analysis in real-time of data, for instance obtained on board of autonomous systems.

6.3.8 Seakeeping Assessment of Wind Assisted Ships

It is recommended to consider to develop guidelines for model tests with wind assisted ships, as this particular application has gained significant attention and there still seems a wide variety in approaches by various institutes. It would be valuable to bring together these experiences in a single comprehensive guideline.

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Appendix A. : NOTE ON BENCHMARKING

A.1. Introduction

Online definition of benchmark (Merriam-webster.com) is "a standardized problem or test that serves as a basis for evaluation or comparison". Benchmarks are key to monitor scientific progresses and evaluate uncertainty or precision of a model. Consequently they are of great interest to scientists, at least if the quality of the underlying data is sufficient for the scope of the benchmark. As numerical models and experimental techniques evolve, benchmarks can become obsolete but also they could also become relevant for a scope not previously identified.

This document lists the various benchmarks proposed successively in ITTC procedures in a more comprehensive form. Some comments are formulated on the quality or relevance of very old benchmark data, then some remarks are made about what could be done to improve ITTC benchmarks during future committees.

A.2. A Bit of Background

The ITTC seakeeping committee has been discussing benchmarks from its creation under the form of comparative tests between towing tanks. Some of those tests are reported in the seakeeping report of the 7th (1955), 11th (1966), 17th (1984) and 18th (1987) ITTC, and the word benchmark appears then in the final recommendation of the 19th ITTC (1990) "The committee should encourage well documented "benchmark" seakeeping experiments". This is also mentioned in the 21th ITTC (1996) "absolutely recommended to make available benchmarks (high precision experiments/computations) and make systematic use of them for (...) uncertainty analysis and (...) validation..".

Then in 25th ITTC (2008), the objectives about benchmarking are specified "determining the requirements for benchmark seakeeping tests in oblique waves", introducing criteria. The ITTC seakeeping committee also looked back to the previous benchmarks, suggesting that their quality and usability/availability should be reviewed. Then in the 26th ITTC (2011) the seakeeping committee specified the need of benchmarking for more specific topics like added resistance or slamming loads.

The ITTC-ISSC joint committee has also proposed benchmarks, though these are not systematically referenced in ITTC recommended procedures (Kim et al. (2016), Horel et al (2019)). Outside ITTC other benchmarks exist, particularly dedicated to CFD validation for seakeeping problems, see among others CFD workshops Larsson et al. (2010) and Larsson et al. (2018).

Generally for most ITTC committees the subject is still of great importance as testified by the ongoing development of the Benchmark repository section of the ITTC website.

A.3. Definition and Criteria

Definition and criteria for benchmark tests are retrieved from the 25th ITTC (2008) seakeeping committee report.

A.3.1. Definitions

Benchmark tests are those that generate experimental data, both model and full-scale, that are presented in a way that makes the results reproducible both numerically and experimentally, to be used for the validation of numerical methods and the verification of experimental procedures. These data should be fit for the intended purpose, should include some uncertainty analysis, and should be publicly available.

A.3.2. Criteria

Minimum information needed to be reported to accurately reproduce the experiment:

- *Ship/model condition* – Hull form (both above and underwater if necessary), model scale, appendage definitions, mass/displacement, draft/trim, hydrostatics, mass distribution, radii of gyration, centre of gravity, natural periods.

- *Sailing conditions* – Ship speed and heading.

- *Wave conditions* – Wave amplitude, frequency and wave slope; type of spectrum, significant wave height, modal period, and spreading.

- *Test Details* – Free running/towing arrangement, control laws, run duration/number of wave encounters, wave measurement (fixed or encountered), and facility parameters.

- *Presentation of Data* – Units/sign convention, reference system, definitions of presented data, tabular data preferred, and uncertainty analysis.

A.3.3. Comment

The definition and criteria proposed are still relevant. It might be important to further encourage the description of the setup keeping in mind the future use for validation of time domain CFD. CFD inherently produces much more detailed flow information than older panel and strip based seakeeping methods. More precise info of waves input could enhance the usability of the benchmarks.

A.4. List of Existing Benchmarks

The list is provided in a table form given in Appendix B. It has been built by first listing the benchmarks provided in each recommended procedure and then gathering some additional candidate to be considered in next ITTC benchmarks selection. Litterature mentioned in Appendix B is detailed in the references of Appendix A. The table proposes also a first layout to compare the benchmark. This table would need to be further completed.

- 75-02-07-021 (Seak Exp - 4.2 Benchmark tests)
- 75-02-07-022 (Power Increase in IW - No benchmarks)
- 75-02-07-023 (Rarely Occuring Events - 4.2 Benchmark tests)
- 75-02-07-025 (Verification and Validation of Linear and Weakly Nonlinear Seakeeping Computer Codes - 5 Benchmark tests session is partially same as 21 procedure but not completely)
- 75-02-07-026 (Sloshing - 4.3 Benchmark Tests empty)
- 75-02-07-028 (fw factor - 7 Benchmark tests)

Each procedure does not correspond directly to a physical quantity to be assessed. A list of quantities relevant to seakeeping are discussed in the procedures.

Identified quantities that have to be benchmarked:

- Motions
- Loads
- Added resistance/ Added thrust
- Bending moment
- Green water
- Slamming

A.5. Conclusions and Recommendations for Future work

Benchmark criteria and definition from the 25th ITTC is still relevant but improvements might be needed to take into account the needs for benchmarking CFD methods that inherently generate much more detailed flow information than older seakeeping methods.

In procedure 7.5-02-07-02.8 the benchmarks are organized as a list of dataset references for each identified hull form. This might be a more efficient classification than experiment by experiment.

The proposed path forward is:

- Review criteria
- Review quantities
- Add missing relevant benchmarks
- Fill the table (checking scope and criteria)
- Decide whether existing benchmarks are obsolete or not
- Propose new distribution of benchmarks on procedures and websites

A.6. References

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Appendix B. : TABLE OF BENCHMARKS

		Benchmark set-up and information						Quantity benchmarked							Mentioned in					Criteria				
Origin	Comments	Model	Froude conditions	Wave direction	Wave conditions	Description	Litterature	Motions	Loads	Added Res/ Added thrust	Added Mass/Damping Exc forces	Bending Moment	Green Water	Slamming	Seak Exp 021	Power Increase in IW 022	Rarely Occuring Events 023	Sloshing 026	fw factor 028	Ship/model Condition	Ship speed/heading	Waves	Arrangement	Presentation of data
		Wigley					Journée (1992)																	
75-02-07-021 (Seak Exp)	Very important step but Large disappointment in conclusion and discussions, candidate for removal	S60 Cb=0.6	Fr = 0, 0.18 ,0.21 ,0.24 ,0.27 and 0.30		Lpp/H = 36, 48, 60, 72 ; Lambda / Lpp = 0.75, 1.0, 1.25, 1.5 pp	Seagoing Quality of Ships. . A model of the Todd-Forest Series 60 with C B=0.60. Results from 7 tanks are presented.	7th ITTC, 1955, pp.247-293	x							x									
Other	Wave cuts for model in circulating channel comparison with Gerritsma	S60 (Cb=0.6 and 0.8)					Maury et al (2003)																	
75-02-07-021 (Seak Exp)		Series 60 with Cb=0.60 and Cb 0.7	Fr =0, 0.1 0.17, 0.2, 0.25	also oblique		Comparative Tests of a Ship Model in Regular Waves (several studies)	11th ITTC, 1966, pp.411-426	x		x					x									
75-02-07-021 (Seak Exp)	Not particularly interesting in 2019 perhaps, candidate for removal	Fibre-glass model of the S.S. Cairndhu			RW, IW, TW	Experiments on a ship model in waves using different test techniques. Also prediction by K. Kroukovsky's theory calculating added mass and damping coefficients by Grim.	(11th ITTC, 1966, pp.332-342)				x				x									
75-02-07-021 (Seak Exp)		Destroyer H.M. "Groningen"	Fr = 0.15, 0.25, 0.35, 0.45, 0.55		L/lambda= 0.5, 0.555,0.625, 0.714, 0.833,1,1.25, 1.67, 2 (H/L=1/40)	Full Scale Destroyer Motion Tests in Head Seas Comparison among motion response obtained from full scale tests, model experiments and computer calculations	11th ITTC, 1966, pp.342-350	x							x									
75-02-07-021 (Seak Exp)		S-175	Fr = 0.275	some oblique	RW	Analysis of the S-175 Comparative Study	17th ITTC, 1984, pp.503-511					x			x									
75-02-07-021 (Seak Exp)		S-175	Fr =0.275		RW IW	Comparison of results from tests at 12 establishments in irregular waves. Absolute and relative motions	18th ITTC, 1987, pp.415-427	x		x					x									
75-02-07-023 (Rarely Occuring Event)		S-175	Fr = 0.275		IW (ITTC Hs=7.9m, T0 = 14.8)	Rare Events	19th ITTC 1990, pp.434-442	x					x				x							
75-02-07-023 (Rarely Occuring Event)		S-175					Hamoudi et al (1998)						x				x							
75-02-07-021 (Seak Exp)		S-175				The ITTC Database of Seakeeping Experiments	20th ITTC,1993, pp.449-453								x									
75-02-07-021 (Seak Exp)		S-175				The ITTC Database of Seakeeping Experiments	21st ITTC, 1996, pp.43								x									
	Ref seems to point to S60	M.V. "S.A. van der Stel"					Gerritsma and Beukelman (1972)																	
75-02-07-021 (Seak Exp)		2D Models				The ITTC Database of Seakeeping Experiments	20th ITTC,1993, pp.449-451				x				x									
75-02-07-021 (Seak Exp)		Wigley				The ITTC Database of Seakeeping Experiments	20th ITTC,1993, pp.449-452	x	x	x	x				x									
75-02-07-021 (Seak Exp)		HSMV				The ITTC Database of Seakeeping Experiments	21st ITTC, 1996, pp.43								x									
75-02-07-021 (Seak Exp)		Fast Ship?	Until Fr 0.63	head		Investigation to Evaluate Wave-Induced Global Design Loads for Fast Ships. Two segmented models were tested. Comparison with several non-linear codes	Schellin et al (2003)	x	x						x									
75-02-07-022 (Power Increase in IW)	to evaluate	SR125 - containership					25th ITTC (2008)									x								
75-02-07-022 (Power Increase in IW)	to evaluate	SR244 - VLCC					25th ITTC (2008)									x								
75-02-07-022 (Power Increase in IW)	important	KVLCC2	Fr = 0.142			Experiments performed by Osaka U. Seoul NU, INSEAN, NTNU, KRISO	Guo and Steen (2011) , Park et al (2015), Lee et al. (2017), ws2010 case1.4c Larsson et al (2010)	x		x						x			x					
		KVLCC2	Fr = 0.142	oblique		Experiments performed SSPA	unpublished, some info in Park et al (2019)			x														
	Candidate	KVLCC2	V = 4kn (EEDI)				Gerhardt et al (2020)			x														
		KVLCC2					SHOPERA D3.2 Sprenger (2017)			x														
75-02-07-022 (Power Increase in IW)	Candidate	KCS					Joncquez (2011), Simonsen et al (2014)									x			x					
75-02-07-022 (Power Increase in IW)	Candidate	DTMB 5415														x								
75-02-07-022 (Power Increase in IW)	Candidate	Delft 372 High Speed Catamaran	Fr = 0.6 0.7	also oblique Van't veer	H/lambda= 1/100 1/80 1/60 1/45 1/36, IW	DELFT, CNR-INM (INSEAN)	Van't Veer (1998), Bouscasse et al, (2013)	x		x														
75-02-07-023 (Rarely Occuring Event)		Simple Shaped FPSO					Lee et al (2012)						x				x							
75-02-07-028 (fw factor)		DTC					SHOPERA D3.2, Sprenger (2017)												x					
Other	Candidate	ISSC-ITTC Benchmark 6750-TEU				KRISO Experiments for vertical bending moments	Kim and Kim (2016), Horel et al (2019)					x												
	Candidate	Other				Bending moments	Clauss et al (2010), Fonseca et al (2004)																	
	Candidate	FPSO					Buchner (2012)						x											