The Seakeeping Committee

Final Report and Recommendations to the 28th ITTC

1 GENERAL

1.1 Membership and Meetings

The Committee appointed by the 27th ITTC consisted of the following members:

- Yonghwan Kim (Chairman), Seoul National University, Korea
- Pepijn de Jong (Secretary), Maritime Research Institute Netherlands (MARIN), The Netherlands
- Ayhan Akinturk, National Research Council, Ottawa, Canada
- Wu Chengsheng, China Ship Scientific Research Centre, Wuxi, China
- Frederick Gerhardt, SSPA, Göteborg, Sweden
- David Hayden, Naval Surface Ship Warfare Centre Carderock Division, West Bethesda, USA
- Adolfo Marón, INTA-CEHIPAR, Madrid, Spain
- Katsuji Tanizawa, National Maritime Research Institute, Tokyo, Japan
- Florian Sprenger, SINTEF Ocean (formerly known as MARINTEK), Trondheim, Norway

Four committee meetings were held at:

- INTA-CEHIPAR, Madrid, Spain, December 2014
- Seoul National University, Seoul, Korea, November 2015
- SINTEF Ocean (formerly known as MARINTEK), Trondheim, Norway, August 2016
- Bay St. Louis (hosted by NSWCCD), USA, February 2017

In addition, a joint Manoeuvring Committee and Seakeeping Committee workshop and discussion session were held in conjunction with the SHOPERA Project meeting in London, UK in April 2016.

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 28th ITTC, the modelling and simulation of waves, wind and current was 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.

The following Terms of Reference were determined by the 27th ITTC in the document ‘Tasks and Structure of the 28th ITTC technical Committees and Groups’:

(1) Update the state-of-the-art for predicting the behaviour of ships in waves, emphasizing developments since the 2014 ITTC Conference. The committee report should include sections on:

a. the potential impact of new technological developments on the ITTC

b. new experiment techniques and extrapolation methods

c. new benchmark data

d. the practical applications of computational methods to seakeeping pre-dictions and scaling, including CFD methods

e. 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:

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

b. identify the need for new procedures and outline the purpose and contents of these.

(3) Update ITTC 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. It is recommended that the developed section/procedure is reviewed by ISSC Loads and Response Committee.

(4) Update ITTC Recommended Procedure 7.5-02-07-02.1, Seakeeping Experiments, to include tests specific to active stabilisation systems, with particular attention to the modelling of the control system and the prediction of full scale behaviour. If possible, update the corresponding procedure for high speed craft.

(5) Review ITTC Recommended Procedures 7.5-02-05-06, Structural Loads, and 7.5-02-05-07, Dynamic Instability Tests, and propose updates, if any.

(6) Develop a new procedure for the determination of speed reduction coefficient f_w in the EEDI formula. Coordinate and exchange information with the Specialist Committee on Performance of Ships in Service.

(7) Develop a new procedure for model scale sloshing experiments.

(8) Review the research considering the impact of seakeeping on propulsion and manoeuvring performance. Coordinate and exchange information with the Manoeuvring Committee.

(9) Survey and/or collect benchmark data for seakeeping problems, such as motion, loads, sloshing, slamming, added resistance, full-scale measurements.

(10) Continue the collaboration with ISSC committees, including Loads and Responses and Environment Committees.

(11) Support a joint workshop on manoeuvring in waves with the Manoeuvring and the Stability in Waves Committees and the Specialist Committee on Performance of Ships in Service, for example on the subject of minimum power requirements for safe manoeuvring in adverse sea conditions and model testing methods to investigate this.

2 REVIEW OF STATE-OF-THE-ART

2.1 New Experimental Facilities

The following are the new experimental facilities inaugurated or expected to be inaugurated in this year.

2.1.1 Naval Science and Technological Laboratory (NSTL), India

This seakeeping and manoeuvring facility was inaugurated in 2015. It is listed on the ITTC website (http://www.ittc.info/facilities/ or e-mail director@nstl.drdo.in for further information). It has a 135 m long, 37 m wide and 5 m deep basin (see Figure 2).

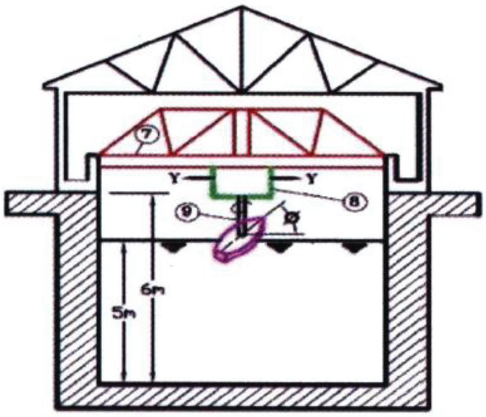


Figure 1 Cross section of the new facility at NSTL, India

The basin has a main towing carriage, which can travel in the longitudinal direction at speeds of 6 m/s forward and 4 m/s reverse directions. In addition, a sub carriage, which can move in transverse direction at speeds of up to +/-4 m/s, is attached to the main carriage. The test frame can be outfitted with a rotating table, which can simulate +/-180 degrees heading angles. Ideally 3 to 5 m long models can be tested in this facility in calm water, in up to 0.5 m regular waves or in irregular waves with up to 0.35 m maximum significant wave height. Available instrumentation and specifications are given in Table 1.

Table 1 Instrumentation list and specifications

Instrumentation	**Specifications**
Six component balance	Fx =500 N, Fy and Fz = 2500 N
Three component balance for rudders	Drag and Lift = 500 N, Moment = 4 Nm
Two propeller dynamometers	Thrust = 200 N, Torque = 6 Nm, RPM = 3000
Pressure sensors for hull slamming	0.1 to 1.0 Bar
Wave probes	Absolute and relative
Optical tracking system	For free running models

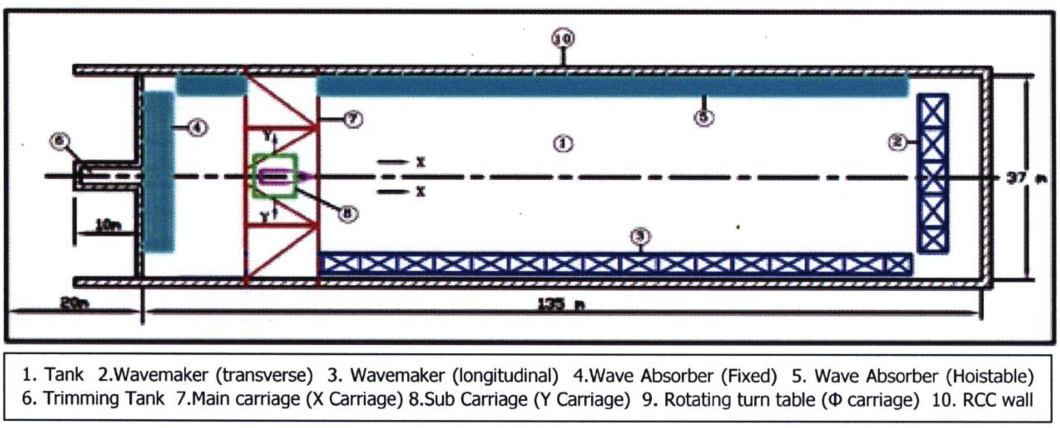


Figure 2 Plan view of the new facility at NSTL, India

2.1.2 Multifunctional Ship Model Towing Tank, Shanghai Jiao Tong University, China

The multifunctional ship model towing water tank (see http://oe.sjtu.edu.cn/eng.php / Eng/article_gallery/listPage/parentID/1619/cat_ id/1634) is located on Minhang Campus of Shanghai Jiao Tong University. The towing tank is 300m long, 16 m wide and 7.5 m deep (Figure 3), and it's equipped with a towing carriage (Figure 4) with a maximum speed of 10m/s, and a multi-unit wave generating system (Figure 5) on one side of the tank. The towing tank, when completed, can be used to carry out ship model resistance tests, propeller performance tests, wave-resistant performance tests, manoeuvring performance tests and self-propulsion and control tests of special underwater vehicles, scientific research and industrial support services.

Figure 3 Multifunctional Ship Model Towing Tank

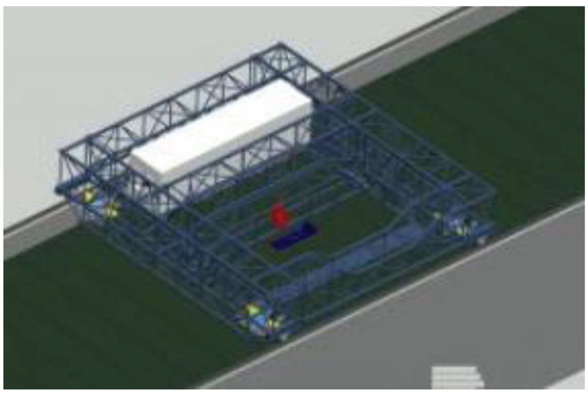


Figure 4 High speed carriage system

Figure 5 Multi-unit wave generator system

2.1.3 Multiphase Wave Lab (MWL) at MARIN, the Netherlands

This new multiphase wave lab (Figure 6) consists of a controlled environment with multiple test setups installed inside, i.e. a flume tank with a wave maker installed on one end of the flume and an instrumented, transverse wall at the other end and a large and a small flat impactor. The controlled environment consists of a 15 m long ×2.5 m diameter autoclave with observation windows; a gas and liquid supply system; and a heating/cooling system for the autoclave and test setups, facilitating testing in the vicinity of the water-vapour boundary for a large range of temperatures (5°C to 200°C) and pressures (5 mbar to 10 bar). It is expected to open late 2017.

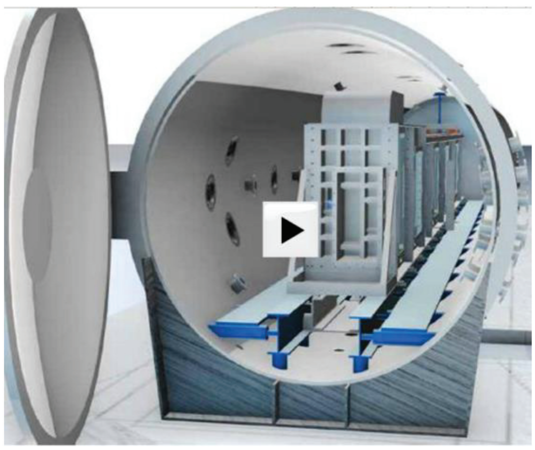


Figure 6 Multiphase test facility at MARIN, the Netherlands

2.2 Experimental Techniques

2.2.1 Hydroelastic and Segmented Models

A lot of effort had being dedicated in the last few years to the study of the effects of hydroelasticity on the global loads and fatigue of ships. Many studies are focused on Ultra Large Container Ships (ULCS) as due to their dimensions the resonant frequencies of the structure are so low as to be near the wave exciting frequencies. At least two international projects concentrated on this problem: WILS JIP and TULCS. Several papers describing their work and findings are described in the following (insofar they are related to experimental aspects). Several of them are included in the Proceedings of the 7th International Conference on Hydroelasticity in Marine Technology (2015), as well as in an special issue of the IJNAOE (2014).

A novel method for making elastic models is proposed by Bennet et al. (2015) which consist of creating the model by joining pieces produced with a 3D printer. The paper explores the mechanical characteristics of the materials used in this process and the possibilities and drawbacks but does not go so far as to build an actual model.

Once the model is fabricated, the actual vibration mode shapes have to be determined specially if results are to be used for software validation. The most common technique is the hammer test (Kim and Park, 2014). Another possibility is to apply harmonic excitations at determined frequencies with a shaker (Maron and Kapsenberg, 2014). As an alternative the results from the wave tests can be used for modal analysis and model identification in several ways (Dessi and Faiella, 2015 and Kim, Y. et al., 2016b). In order to measure the elastic deformation, a set of wireless inertial platforms is proposed by Bennet et al. (2014).

2.2.2 Uncertainty in Seakeeping Tests

There is a growing tendency to include uncertainty evaluations when presenting experimental results of seakeeping tests as recommended by the ITTC, although it is clearly a difficult task. There are some papers that deal specifically with this issue or provide so much information on the question that they are worth mentioning here. They provide values for the different uncertainties associated to seakeeping tests and identify the main sources of uncertainty and their relative importance.

Kim and Hermanski (2014) address specifically the uncertainty in general seakeeping tests with a comprehensive study of its sources. Qiu et al. (2014) perform a similar exercise but for ocean engineering tests, but obviously many problems are in common between seakeeping and ocean engineering tests. Woodward et al. (2016) present an analysis of the uncertainties in ship inclining experiments. Although it is applied to real ships, many sources of uncertainty are also applicable to models. Two good examples of how uncertainty information should be presented when reporting seakeeping tests results are Park, D.M. et al. (2015) and Jin et al. (2015).

Based on ITTC-procedure 7.5-02-01-01 Park, D.M. et al. (2015) carried out an uncertainty analysis for the measurement of ship motion responses and added resistance in waves. Heave and pitch motion as well as the added resistance of a KVLCC2 tanker were measured repeatedly in regular waves. Additionally, the same quantities were calculated using strip theory and a Rankine panel code. Seven groups of uncertainties were identified and analysed: Uncertainty of instruments, uncertainty of model mass properties, model geometry uncertainty, uncertainty of the test setup, calibration uncertainty, measurement uncertainty, and data reduction uncertainty. The analysis results in the following uncertainties (at a confidence level of 95%):

- Wave amplitude less than 3%, wave length less than 2%. The predominant source of uncertainty is a Type B uncertainty of the wave probe.
- Heave and pitch 5% and 7.5% respectively, again Type B uncertainties of the corresponding measurement devices are dominant.
- With values of up to 16% in short waves the uncertainty in the added resistance is far larger than motion uncertainty. Here the re-

sistance measurement contributes to the largest portion of uncertainty for short and long-wave regions. The uncertainty of wave measurements, on the other hand, is a large part of uncertainty in the medium wave region.

- The two numerical results (2D linear strip method and a 3D Rankine panel) method, are located within the 95% confidence band for motion and added resistance.

2.2.3 Instrumentation

The use of high speed cameras is increasing in tests related to seakeeping, especially in the fields of sloshing and slamming/water entry problems. They help to understand the physical problem and to compare the numerical results. This technique is applied for sloshing tests in Souto-Iglesias et al. (2015), Kim, S.Y. et al. (2015) and Manderbacka et al. 2014). In the last publication image detection is employed to estimate the flow of water between compartments.

Wei and Hu (2014) use high speed cameras in drop tests of cylinders. The lighting problems associated with such kind of cameras in this kind of tests are addressed and the solution found is fully documented. Also related to drop tests, Panciroli et al. (2015) describe an experimental setup to measure the flow with Particle Image Velocimetry. They tested the impact of several wedges in water fabricated with a 3D printer, again demonstrating the interest of this technology. Huera-Huarte (2014) proposes a new optical tracking system to measure 6 DOF motions based on the properties of optical lenses.

The measurement of added resistance is another hot topic in the seakeeping field. It is obtained by measuring the small difference between two large quantities (calm water resistance and mean resistance in waves) and therefore the uncertainties are large. Park et al. (2016) describe a new setup for the measurement of such quantity. Kitagawa et al. (2015) continued to develop a new methodology for free sailing tests in waves. To measure the speed loss in waves directly, they developed two devices. The first is a marine diesel engine simulator (MDES) which dynamically controls the propeller rpm during a seakeeping test based on the full-scale engine characteristics. The second device, the auxiliary thruster system (ATS), corrects for the skin friction differences compared to full scale. The authors reported on a new methodology to directly evaluate the test results in real time and simulate engine characteristics like the torque-limitation of a diesel engine. The resulting test procedure allows for direct and realistic evaluation of speed-power performance during seakeeping model tests.

Finally, Handschel and Abdel-Maksoud (2014) reconsiders the method to estimate roll damping by harmonic excitation. They use the traditional system of counter-rotating weights to excite roll motion but they proposed several new methods to carry out the tests and to analyse the results. The method should reduce the time needed for the tests and increase the amount of information that can be obtained by them.

2.3 Numerical Methods

2.3.1 Frequency Domain Methods

Improvements in computational power and time domain methods reaching a more mature state led to a further reduction of research on development of frequency-domain methods. However, the frequency domain method is still considered as a robust tool and is widely used in the early design phase of a vessel. Several relevant publications on refinement and improvement of the frequency domain approaches can be reported.

A new method to obtain passive and stable state-space models from impulse response functions for radiation force computation is presented by Hatecke (2015). It is claimed that these models can substitute the convolution integrals in the Cummins Equation and thus reduce the computational effort of radiation force calculation by about one magnitude. The application of the method has been shown on a test case of a heeled container vessel.

Söding (2014) presented a simplified method to derive second-order seakeeping analyses by means of perturbators. The application was demonstrated for the simple case of a partially immersed cylinder with horizontal axis for which wave excitation forces and moments up to second order are calculated.

Yasuda et al. (2016) proposed to modify the conventional panel shift method used in Rakine panel methods by introducing Rayleigh's artificial friction in the free-surface boundary condition. This artificial friction suppressed wave reflection from the side and/or upstream computational boundaries in the range of low frequencies.

To account for ship motions in large waves, a weakly nonlinear time-domain method using impulse response function was proposed by Wang and Kashiwagi (2016). Their frequency-domain solver was based on a Rankine panel method with a double-body basis flow. Ship motions were calculated in the time domain using the convolution integral approach. To validate their method, vertical motions of a modified Wigley hull and a bulker carrier advancing in head seas was studied. It was concluded that results of the proposed approach agree well with state-of-the-art linear methods in small waves. In large waves, a good agreement with model tests data was achieved.

2.3.2 Time Domain Methods

The majority of development in the field of numerical methods for seakeeping problems can be reported for time domain methods. Due to the nature of their formulation, they can address non-linear aspects of seakeeping. e.g. arising from the time-dependent wetted surface of the hull and enable the compilation of more holistic tools that combine e.g. forces from propulsors and control devices.

Riesner et al. (2016) developed a non-linear time-domain boundary element method for non-linear ship responses in waves. The method followed the general approach by Cummins to express the equations of motion in the time domain. Convolution of the impulse response of the ship with the motion velocity is used to define radiation forces while non-linear Froude-Krylov restoring forces are obtained from pressure integration over the instant-neous wetted surface, considering ship motions, undisturbed wave and stationary wave system. The authors provide a comparison of motions obtained from the newly developed method, model tests, RANSE-based simulations and a linear frequency domain code for three different ship types at various forward speeds, revealing differences especially for higher forward speeds.

An extension to the body-exact strip theory focusing on improved prediction of forward-speed effects was presented by Bandyk and Hazen (2015). This approach aimed to improve the treatment of forward speed terms compared to standard strip theory formulations, and a 2D+T approach was adopted, assuming that each two-dimensional frame in which a boundary value problem is solved remains fixed relative to an earth-fixed frame. Results obtained for the Wigley I hull were compared to model test data and other numerical approaches.

A fully nonlinear potential flow code that is capable to generate grids directly from industrial CAD models was proposed by Mola et al. (2014). The governing Laplace equation was complemented by unsteady fully nonlinear boundary conditions in this approach. The author claimed to bypass the known numerical instabilities in the time evolution of these boundary conditions by using a L^2 projection method to ensure accurate gradient reconstruction of the free surface nodes. A collocation boundary element method was applied for spatial discretization and the resulting differential algebraic equations were solved with an implicit backward differentiation formula (BDF) scheme. The KVLCC2 and the KCS hulls were selected as test cases for the mesh generation algorithm and the potential flow code. Comparison with experimental data was fair but only shown for wave profiles on the hulls at selected forward speeds in calm water. Computational effort seems to be rather high for the proposed method, since a parallelization and the introduction of a stationary version of the differential algebraic equations system was planned to significantly reduce computation times.

A newly developed higher-order boundary element method (HOBEM) for seakeeping problems at forward speed was proposed by He and Kashiwagi (2014b and 2014c). The linear three-dimensional approach uses Rankine panels with B-spline representation. It was based on a mixed Eulerian-Lagrangian method and directly solved the boundary integral equation for the velocity potential. A separate assessment of the radiation and diffraction problem was presented, where He and Kashiwagi (2014c) focused on radiation effects. The authors considered the comparison of obtained wave patterns, wave profiles, exciting forces, and hydrodynamic coefficients of forced oscillating motions for a prolate spheroid and two modified Wigley hulls with experimental data as encouraging to continue the development towards a fully robust seakeeping analysis tool.

Kim, H.Y. et al. (2015) developed an early design stage simulation tool to predict ship motions for single hull, multi-hull and multi-body scenarios. The proposed method was based on impulse-response functions (IRF) to evaluate the radiation and diffraction memory forces acting on the ship. The radiation IRF was split into two components: the velocity and the displacement IRF. To obtain the diffraction IRF, the response spectra for a fixed body were derived in the frequency domain by using unidirectional wave packets. Time domain forces were then obtained through inverse Fourier transformation. The Neumann-Kelvin linearized free surface condition was applied and the motions of the floating body were computed by 4th order Runge-Kutta integration. A comparison of this reduced order approach with the direct time domain solver Aegir for the Wigley hull and a multi-body scenario showed good agreement and the authors claimed that the computational effort can be significantly reduced.

A quasi three-dimensional extension of the Free-Surface Random Vortex Method (FS-RVM) developed at University of Berkeley was presented by Jiang and Yeung (2016). The new approach was called Slender Ship Free-Surface Random Vortex Method (SSFSRVM) and accounts for viscous roll damping effects for slender ships with and without forward speed in viscid fluid. The method is based on slender body theory where the ship hull was discretized longitudinally by strips. On each strip, the FS-RVM was applied, which solves the transient Navier Stokes equations. The solutions for each strip were linked. The accuracy of the approach was illustrated by comparing data from roll decay tests with the DTMB-5415 hull model equipped with bilge keels at Fn = 0 and Fn = 0.138. The agreement of numerical data obtained by SSFSRVM and model test data from INSEAN showed good agreement. Comparison with PIV data at selected locations reveals were good agreement of vortex patterns around the bilge keels as well. The authors claimed that SSFSRVM can be used for efficient numerical wave tank test. A standard desktop computer would run for approximately 6 hours to calculate 10 roll cycles.

Li et. al (2016) proposed a new method to compute the wave part of the transient free surface Green function and its spatial derivatives. The approach solved the fourth-order ordinary differential equations (ODEs) based on the semi-analytical Precise Integration Method (PIM). By comparing the proposed approach with other methods as well as analytical solutions, stability and accuracy were postulated. In addition, the radiation problem of a floating hemisphere at zero speed was solved as an example.

Zhang and Zou (2015) presented a study on radiation and diffraction of the Wigley I and S-175 hulls with forward speed conducted with a newly implemented Rakine panel method. A comparison of results with experimental data was included.

Somavajula and Falzarano (2014) approached problem of parametric roll as a nonlinear dynamics problem considering nonlinear time varying hydrostatics as well as nonlinear damping. In the presented study with the APL China hull, various realizations of the roll motion were simulated and analyzed.

Lee, J.H. et al. (2015) proposed a semi-analytical approach to capture the non-linear changes in transverse stability leading to parametric roll effects for container ships in head seas. Through a reduction of the equation of motion for roll to 1.5 degrees of freedom (negligence of coupling with vertical motions) the authors claimed that the computational cost of this method significantly reduced compared to other established approaches. Approximation methods for the influence of waves on the metacentric height and the restoring lever were introduced in the equations of motion, being solved by the 4^{th} order Runge-Kutta time integration. A comparison of the proposed method with a established impulse-response function approach revealed some deviations in regular waves that the authors claimed to arise for the different formulations used to calculate hydrodynamic forces and estimation errors for the restoring lever. Based on a comparison of results in irregular waves, the authors indicated that the semi-analytical approach was less sensitive to the phases of the wave components and uncertainty increases with increasing impulsive roll angle and hence increased non-linearities.

2.3.3 Comparative Studies

A comparative study on different numerical methods to predict added resistance of ships in waves was presented by Kim Y. et al. (2014), refer to Figure 7. The cases considered are the S175 hull and the KVLCC2 hull, both in head seas. The considered methods are:

- Strip theory according to Salvesen-Tuck-Faltinsen is combined with:
  (a) Faltinsen's near-field formulation (pressure integration);
  (b) Maruo's far-field formulation (mom-entum conservation);
  (c) Salvesen's energy radiation formulation.
- 3D time-domain Rankine panel code with:
  (a) near-field formulation (pressure integration);
  (b) far-field forumaltion (momentum conservation).
- A cartesian grid-based Euler CFD solver;
- In the short wave regimes, approaches by Faltinsen, Fujii and Takahashi as well as Kuroda were applied.

A comparison of these approaches with experimental data reveals a typical problem: differences of results are apparent not only between the different numerical methods and the experiments but also the experimental and numerical data itself is scattered. The authors concluded that the agreement of results is depending on the relative wave length and the ship speed. While the 3D panel method and the CFD method capture the overall shape (including peak location) of the non-dimensional added resistance transfer function better than the strip theory, added resistance in short waves appears to be generally under-predicted by the numerical methods.

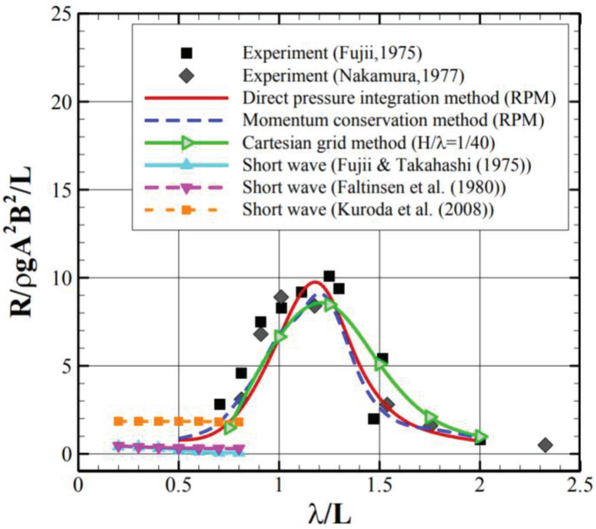


Figure 7 Comparative study on added resistance (Kim Y. et al., 2014)

A comparison of results for added resistance in head seas obtained from different methods for three different hull types—the Wigley III, KLVV2 and the WILS container ship—was presented by Söding et. al (2014). The authors showed the data obtained from the Rankine panel method GL Rankine, an extended RANS method and model tests, concluding that while the agreement between Rankine and RANSE results was satisfactory, but less favorable with model test data. These discrepancies are attributed to difficulties associated with the procedures to obtain accurate measurements of the added resistance at model scale.

A review of the developments in time-domain panel methods solving the linearized seakeeping problem with the transient free-surface Green function has been published by Bingham (2016). In this publication, the three existing methods to integrate the fourth order ordinary differential equations discovered by Clement in 1997 were compared with respect to computational efficiency. From his study, the author concluded that the Taylor expansion method developed by Chuang et al. is slightly more efficient than the original four-step fourth-order Runge-Kutta scheme (RK44) proposed by Clement. The precise integration method developed by Li et al. (2016) was found to be at least one order of magnitude less efficient than the other methods. Apart from higher computational effort compared to the standard methods of for example Newman, a finite water depth extension of ODE methods has not been developed so far.

A standard matrix-based stability analysis that has already been applied on zero-forward speed formulations and forward speed methods with Rankine-type boundary elements has been applied by Bingham et al. (2014) for a seakeeping problem at forward speed. The method used for the analysis is based on potential flow theory with Neumann-Kelvin linearized free surface conditions and uses high-order finite difference discretization schemes. It was shown that the stability of numerical solutions strongly depends on the treatment of the convective terms in the free surface boundary condition. This analysis focused on three types of horizontal grid spacing: a) a uniformly spaced grid, for which a centered treatment of these terms was shown to be stable, b) a non-uniformly spaced grid, where it was shown that an upwinded bias is required to achieve stability and c) a very strongly stretched grid that revealed instabilities in combination with the applied higher-order scheme.

2.3.4 Combined Seakeeping/Manoeuvring

Hydrodynamic aspects of a modern fishing vessel during manoeuvring in waves were studied theoretically and experimentally by Thys and Faltinsen (2014), focusing on small encounter frequencies in following and stern quartering seas, where the risk for capsizing was quantified. The presented newly developed simulation model was based on the approach by De Kat and Paulling and combines a 6 DOF seakeeping model with a 4 DOF non-linear manoeuvring model. Calm water resistance, rudder forces, propulsion forces and non-linear viscous forces, were considered by empirical approaches. It was concluded that wave-induced surge forces in following seas are over-predicted by the simulation model, leading to surf-riding and broaching events that were not observed in the experiments.

Gu et. al (2015) presented a manoeuvring simulation for the S-175 hull in regular waves using a simplified simulation model combining the traditional MMG (mathematical manoeuvring group, treating hydrodynamic force components from hull, propeller and rudder separately) model with a seakeeping model calculating first and second order wave forces. The model was validated by free running model tests in regular waves.

2.4 Rarely Occurring Events

2.4.1 Slamming

Chen, C.C. et al. (2014) investigated the local loads for an oil tanker under extreme motion conditions, defined in the CSR-H, by using computational fluid dynamics (CFD) software, STAR-CCM+. They calculated bow flare slamming pressures and bottom slamming pressures at the bottom of the bow or stern bottom. The extreme motion itself was obtained using the potential code HydroSTAR. They conducted resistance and seakeeping model tests on the oil tanker to benchmark the numerical results. They showed that the slamming pressures defined by the CSR-H are safe and conservative with regards to the structural design.

Tahara et al. (2015) developed an estimation method of slamming pressures for ship structure analysis in combination of CFD with a heuristic method. They combined three calculation methods, nonlinear time-domain strip method for the ship motions, CIP-CUP method for the impact pressure, and MSC Nastran for stress distribution of ship hull. This enabled accounting for three-dimensional effects in slamming of the ship with forward speed in irregular design waves.

Hong et al. (2015) experimentally investigated bow-flare slamming loads on an ultra-large containership. They conducted a model tests for the measurement of slamming impact loads and structural responses in the ocean basin of KRISO. A model of a 10,000TEU containership with 6 segments connected by a steel backbone was used. The bow flare and stern slamming loads were measured by distributing a number of load cells over the model. Tests were performed in regular and irregular wave conditions for various ship speeds and wave heading angles. The effects of wave heading angle and ship speed on the bow flare slamming loads were discussed based on the measured data. The importance of front-edge impact in irregular wave was also discussed.

Lian and Haver (2016) presented measured slamming loads from a model test, and discussed the observed large variability. They studied the stochastic nature of slamming loads using a simplified linear relation between the sea states and the Gumbel distribution parameter surfaces. The characteristic slamming loads with a q-annual probability of exceedance were estimated by a long term analysis using the short term distribution of the slamming loads and the long term distribution of the sea states. They also studied the effect of integration over a smaller area of the scatter diagram of the sea states. The uncertainties in the response from slamming loads were compared to a more common response process, and the relation between variability and the number of realizations in each sea state was looked into.

Rajendran et al. (2016) analyzed the vertical responses of a bulk carrier, a containership, and a passenger ship by linear to fully body nonlinear numerical methods based on strip theory. The numerical ship responses in abnormal waves and extreme sea conditions were compared with the measurements in a wave tank. They found that the linear method is able to predict the vertical responses of the conventional ships with large block coefficients, like bulk carriers and tankers, even in extreme sea conditions. However, a pronounced bow flare induces strong nonlinearities in the vertical responses in rough seas and the linear or even partially body nonlinear methods are not enough for accurate calculations for those conditions.

Wang and Soares (2016a) calculated ship motions, slamming probability and slamming loads on the bow of a ship hull in irregular waves. The results were compared with the experimental data from model tests of a 170m chemical tanker at zero speed in head seas. They used a partially nonlinear time domain code based on strip theory. The slamming occurrence at the bow was studied numerically and statistically, and compared with the experimental data. The experimental data were analyzed statistically, to determine the relationships between the measured pressure and the entry velocity and with wave parameters. They also simulated two estimated significant slamming events by using the Arbitrary-Lagrangian Eulerian (ALE) algorithm, based on the calculated relative entry velocities in the numerical procedure.

Wang and Soares (2016b) also studied stern slamming of a chemical tanker using an ALE algorithm implemented in LS-DYNA and a Modified Longvinovich Model (MLM) which was derived from the potential velocity theory and Wagner's condition. Ship motions in irregular sea states were calculated numerically by a fully nonlinear time domain method based on strip theory, and then the calculated relative vertical velocity between the ship section on the stern and wave surface was applied in the Arbitrary Lagrangian Eulerian algorithm for slamming load calculation. The problem was solved by simulating the water entry of 2D ship sections of the ship at constant speed. The numerical slamming loads were compared with the measured ones and the analytical calculations from the MLM.

Wang et al. (2016) studied the relative motions and frequency of slamming occurrence for a chemical tanker advancing in irregular waves. Ship motions in extreme waves were estimated by a fully nonlinear time domain seakeeping program, while the wave surface modelling was achieved applying a nonlinear Schrödinger equation. The probability of slamming on the bottom of a chemical tanker was predicted statistically based on the relative motions between the cross section of the ship and the wave surface. The numerical results were compared with the experimental data from model tests of a chemical tanker. The effects of the forward speed on the slamming were studied as well.

2.4.2 Whipping

Kim, J.H. et al. (2014) presented a numerical method to predict slamming loads and whipping responses. They used a Generalized Wagner Model to calculate impact loads on the two-dimensional section of the ship hull. The computational result of whipping was compared to experimental results in terms of measured vertical bending moments and pressures. They investigated the characteristics of whipping in a regular wave by the decomposition of high frequency oscillation and the comparison of slamming modal forces.

Drummen and Holtmann (2014) reported the result of benchmark study by ISSC 2012 Dynamic Response Committee on slamming and whipping. The goal of this benchmark was twofold: on the one hand, the degree of variation in estimates produced by different methods and organizations was revealed; on the other hand, the deviations of the analyses were investigated by comparison with responses measured during model tests. From the results presented, it may be concluded that the shapes and frequencies of the two and three nodes, dry and wet and horizontal and vertical flexural vibration modes determined by the participants, were well in line with experimental results for four of the six participants. Computations considering an impulse induced by a regular head wave showed significant differences the results of various tools and users. It is suggested that more complex methods are not necessarily leading to better results due to the more elaborated modeling leading to increased uncertainties in the predictions. Often results depend on the experience and skill of the user.

2.4.3 Water Entry

Iafrati et al. (2014) conducted an experimental study on the water entry of a flat plate with a high horizontal speed aiming at deeper comprehension of the physical phenomena involved in the aircraft ditching problem. They constructed a new experimental facility at INSEAN-CNR for this experiment. Measurements were conducted in terms of velocity, acceleration, pressures, strains and total forces acting on the plate. In order to avoid any misleading effect due to the scaling, experiments were carried out at quasi-full scale velocity. In this work, an analysis of the data of two different values of the pitch angle of the plate was conducted along with an estimate of the test-to-test dispersion.

Yousefnezhad and Zeraatgar (2014) studied water entry of a twin wedge penetrating the water surface at a constant vertical water speed. They solved the problem in the framework of potential theory using a boundary element method where the gravity effect on the flow is neglected. Free surface elevation and pressure distribution on the body were evaluated for different deadrise angles. A parametric study was performed to investigate effects of deadrise angle, distance between demi-hulls and the free surface elevation on maximum pressure coefficient. They proposed a regression formula for the maximum pressure coefficient. Results of the parametric study revealed that as time advances the interaction between two demi-hull gets more severe, and the interaction effect on the pressure coefficient is nonlinear.

Mohtat et al. (2015) used a finite element based arbitrary Lagrangian-Eulerian (ALE) formulation to simulate the 2D wedge entry problem. The air and water compressibility was controlled through the bulk modulus and was varied indirectly as a function of the sound speed. Numerical simulation results indicate the small influence of air compressibility for a wide range of parameters, but still contributions from air compressibility can be observed for small deadrise angles. This effect was most significant when the impact velocities and deadrise angles were small at the same time, hence the air pockets and viscous effects became more significant.

Chatjigeorgiou et al. (2015) investigated the violent hydrodynamic slamming induced by the impact of a steep wave, moving with steady incident velocity onto a vertical circular cylinder with permeable skin. The problem was set in 2D whilst for calculating the water penetration, von Karman's approach was used. The employment of this assumption was justified by the existence of large open areas of the perforations. The problem was treated analytically by expressing the solution via the integral equations approach. The numerical results indicated increasing hydrodynamic loadings for decreasing open area coefficients.

Lauzon et al. (2015) presented a new approach to improve the Generalized Wagner Model, using Kelvin's Green function to solve for the hydrodynamic velocity potential, and splitting up the flow around the impacting two-dimensional shape into a regular and a singular part, thus allowing treating the singular part with greater care through semi-analytical developments. This improved Generalized Wagner Model makes it possible to deal with any kind of impact velocity profiles and arbitrary section shapes.

Xu and Wu (2015) simulated oblique water entry of a wedge with vortex wake. To simulate water entry of a wedge with transverse flow at its tip, they imposed the Kutta condition at the wedge apex and removed the local pressure jump. Flow separation due to vortex shedding was treated properly in their method. Results for the free surface profile and pressure distribution were provided.

Helmers et al. (2015) developed an efficient two-dimensional Generalized Wagner model applicable for beam sea calculations. In order to study important differences compared to the classical vertical drop tests, pure sway velocity in calm water was considered. By superposition of harmonic solutions, this method can be combined with the theory of vertical impact models in order to handle general impact velocities.

Piro et al. (2015) extended the Generalized Wagner Method for a high-order boundary element method using the acceleration potential to obtain accurate forces, which requires a special treatment of the waterline expansion rate.

Panciroli et al. (2015) experimentally studied water entry of a rigid wedge with a fixed mean deadrise angle and varying radius of curvature. Drop tests were conducted in free-fall, and the drop height was parametrically varied to investigate the effect of the entry velocity on the pile-up evolution, the impact dynamics, and the energy transferred to the fluid. High speed imaging was used to simultaneously measure the penetration depth of the wedge and its wetted surface. PIV was also used to investigate the flow generated by the water entry. They showed that between 60% and 80% of the impact energy is consistently transferred to the risen water, which accounts for the formation of the pile-up and the spray jets.

Khabakhpasheva et al. (2016) conducted a comparative study of the two-dimensional symmetric wedge entering water and exiting from it. They calculated the pressure distribution along the wetted part of the wedge and the total hydrodynamic force acting on the wedge by three simplified models: the Original Wagner Model (OWM) of water entry and the Linearized Model of water exit (LME), the Modified Logvinovich Model (MLM) of entry and exit, and the Generalized Wagner Model (GWM) of entry and exit. CFD simulations were also used to generate reference results for the development and elaboration of the water exit models with large displacements, and to match these models with the GWM of water entry.

Semenov and Wu (2016) studied water-entry of a two-dimensional expanding circular section. The integral hodograph method was used to derive analytical expressions for the complex potential and for the complex velocity, both defined in a parametric plane, for which the first quadrant was chosen. This enabled the original partial differential equation with non-linear boundary conditions on the unknown free surface to be reduced to a system of integro-differential equations along straight lines in the parametric plane. They presented free surface shapes and streamlines corresponding to different expansion speeds.

Korkmaza and Güzel (2017) experimentally investigated water entry of spherical and cylindrical shaped objects with hydrophobic surfaces. Different fluid dynamics phenomena like jet formation, cavity formation, water splashing and flow separation on solid surfaces were investigated and compared. From images taken by a high speed camera, pileup coefficients and splash velocities were measured. It was observed that flow separation occurs earlier with hydrophobic surfaces causing no pressure pulse occurrence on the solid surface at larger penetration depths. Hydrophobicity also causes larger pileups with faster jet flows indicating more kinetic energy transference to the fluid. Along with high speed imaging, the impact loads were calculated and compared with and without hydrophobicity via strain gauge measurements. It was found that the peak strain values during slamming were smaller with hydrophobic surfaces promoting a reduction in the impact forces while distributing the pressure pulses on a larger wetted area.

2.4.4 Shipping Water

Parsoya et al. (2014) studied the effect of forecastle and sheer on the probability of green water on deck based on a linear direct calculation with forward speed effects. They calculated the relative wave elevation (RWE) from a linear 3D diffraction analysis and added non-linear corrections by way of non-linear response spectra of the RWE. The probabilities of green sea occurrence were calculated for variable heights of forecastle/sheer, vessel draft, vessel speed and sea depth for relative heading and mean zero up-crossing wave period for sea states on typical tanker routes. This comparison was done for a typical sized Aframax and a Suezmax hull.

Kawamura et al. (2016) numerically studied water shipping events on fishing vessels in severe sea states. They conducted SPH simulations of 6DOF ship motions in severe water-shipping conditions. GPUs were used to accelerate the simulations. The accuracy of the SPH method was systematically investigated through comparisons with dedicated captive and free motion tests.

2.4.5 Slamming on High-Speed Craft

Jacobi et al. (2014) investigated the slamming behaviour of a large high-speed catamaran through the analysis of full-scale trials data. The US Navy conducted the trials in the North Sea and North Atlantic region on a 98m wave piercer catamaran, HSV-2 Swift. For varying wave headings, vessel speeds and sea states the data records were interrogated to identify slam events. An automatic slam identification algorithm was developed, considering the measured rate of change of stress in the ship's structure coupled with the vessel's pitch motion. This allowed the slam occurrence rates to be found for a range of conditions and the influence of vessel speed, wave environment and heading to be determined. The slam events were characterized further by assessing the relative vertical velocity at impact between the vessel and the wave. Since the ship was equipped with a ride control system, its influence on the slam occurrence rates was also assessed.

Ikeda and Judge (2014) conducted a model experiment of a planning craft in calm water, regular waves and irregular waves to capture a sequence of individual impact events. They measured pressure on the bottom of the hull using both point sensors and a pressure mapping system. They reported individual slam event time histories to investigate the slamming on high speed planning craft hull.

French and Thomas (2014), (2015) reported the slam characteristics of a 112m INCAT wave piercing catamaran. They conducted tank experiment using a 2.5 m hydro-elastic segmented model and identified a total of 2,098 slam events over 22 different conditions, each containing about 80 to 100 slam events.

Judge et al. (2015) conducted tank experiment using a 2.4m prismatic planing hull model and measured the ship motions and hull bottom pressures. They compared the results with Rosen's method for reconstructing the momentary pressure distribution during a hull-water impact and Morabito's empirical method for calculating the pressure distribution on the bottom of prismatic planing hulls.

McVicar et al. (2015) investigated the slam process on INCAT Tasmania wave piercing catamarans by conducting RANSE based numerical simulation to estimate the transient forcing terms and the effects of the varying scales on the structural response through a uniform beam model. The simulated motion and slamming forces were compared to benchmark

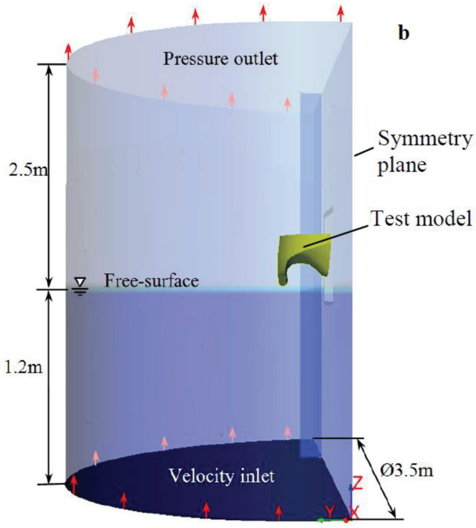


Figure 8 CFD applied to wet deck slamming of a wave piercing catamaran (Swidan et al., 2015)

experimental data. They reported that the wet deck arch slam magnitude was significantly under-predicted. This is a likely result of over-prediction of the centre bow entry force which has a significantly longer duration. This suggests that even a modest increase in the centre bow entry force can lead to a significant reduction in the peak bending moment.

Swidan et al. (2015) applied CFD techniques to calculate wet deck slamming loads and validated through a series of controlled-speed drop tests on a three-dimensional catamaran hull-form model (Figure 8). They found simulation of water entry at constant speed by applying a fixed grid method is more computationally efficient than by applying an overset grid. However, the overset grid method for implementing the exact transient velocity profile resulted in better prediction of slam force magnitude. In addition, the splitting force concurrent with wet-deck slam event was quantified to be 21% of the vertical slamming force.

Swidan et al. (2016) performed a series of drop-test experiments to investigate the hydrodynamic loads experienced by a generic wave-piercer catamaran hull form during water impacts. The experiments, that focused on the characterization of unsteady slam loads on an arched wet deck, were conducted using a Servo-hydraulic Slam Testing System (SSTS) that allowed the model to enter the water at a range of constant speeds up to 10m/s. The systematic and random uncertainties associated with the drop test results were quantified in detail. The relationships between water-entry velocity and both slam force and pressure distributions were presented and discussed with a strong relationship between the slam force peak magnitudes and impact velocity being observed. In addition, the three dimensionality of the water flow in these slam impact events was characterized.

2.4.6 Seakeeping in Extreme Wave Conditions

Hu et al. (2014) studied the response of a beam being hit by a 2D freak wave. The freak wave was generated in a numerical wave tank that solved the 2D incompressible Navier-Stokes equations. A wave absorbing method satisfying the mass conservation was applied in the numerical wave tank. They considered the influence of the beam's motion on the freak wave field and found the natural frequency had a great impact on the response of the beam.

Lu et al. (2014) numerically studied rogue waves based on fourth order nonlinear Schrödinger equation. They modeled the rogue wave event by solving the mNLS equation and compared with Peregrine breather-type rogue wave solution of NLS equation. They found the computational results in the framework of mNLS equation demonstrated a stronger asymmetry between crest and trough.

Guo and Bitner-Gregersen (2014) studied responses of an LNG tanker with and without forward speed with both model tests and numerical simulations. The model tests were carried out in the seakeeping tank of the Technical University of Berlin, and numerical simulations were performed using a 3D Panel code. They showed that increasing the forward speed increases the ship motions and hogging moment. The change of sagging moment due to the forward speed was very small at slow speed. After the ship forward speed was increased beyond a certain threshold, the sagging moment increased significantly with ship speed.

Liu, W. et al. (2015) developed a computational method that combined the strip theory method and nonlinear dynamic FEM analysis for use in nonlinear dynamic structural strength analysis of container ships subjected to large freak waves. With their method, both structural material nonlinearity and geometric nonlinearity can be considered. They showed how the strength of a ship can be evaluated in terms of its nonlinear vertical bending moment (VBM). They calculated the linear and nonlinear dynamic VBM of a ship and compared these to assess how they differ. The influence of freak wave height and wave speed on the VBMs and deformation was reported.

Fujimoto and Waseda (2015) studied the effect of 4th order nonlinearity and higher wave number components on freak waves with an Higher Order Spectral Method. They found a crescent shape and longitudinal asymmetry in the freak wave shape. They also found that higher wave number components increased the maximum horizontal velocity of freak waves significantly. They concluded that the 4th order nonlinearity and higher wave number components are important for local freak wave kinematics, as well as for determining structural impacts, the motion of floating objects and wave breaking.

Houtani et al. (2015) developed a method to generate freak waves from an arbitrary spectrum in a fully directional wave basin. Since the control signals of each segment of wave makers were calculated from numerical simulation of freak waves by the higher-order spectral method (HOSM), this method was named HOSM-WG. They used the following three methods to improve the HOSM-WG: separation of free waves from bound waves; using Biesel's transfer function in wavenumber space; and using Schaffer's 2nd-order wave maker control method. They compared gene-rated freak waves in the wave basin to HOSM simulations and found a good agreement. They showed that the difference between HOSM-WG and HOSM simulations became larger as wave steepness, frequency bandwidth of the spectrum or directional spreading became larger.

Alberello et al. (2016) conducted an experiment to measure the velocity field underneath a breaking rogue wave. The rogue wave was replicated in the laboratory by means of dispersive focusing methods such as the New Wave Theory and nonlinear focusing techniques based on the Nonlinear Schrödinger equation. While the former is basically a linear method, the nonlinear focusing fully accounts for the dynamical evolution of the wave field. Experiments were carried out in the Extreme Air-Sea Interaction flume of the University of Melbourne employing a Particle Image Velocimetry (PIV) system to measure the velocity field below the water surface. Measurements showed that the mechanism of generation affected the shape of the breaking waves as well as the kinematic field and associated hydrodynamic forces. Particularly, the New Wave Theory led to higher velocities and a more energetic breaker than the nonlinear focusing.

Fujimoto and Waseda (2016) studied how Class I & II instabilities affect the geometry of freak waves, using Higher Order Spectrum Method (HOSM), a fast simulation technique for water waves. They investigated the relationship between Class I & II instabilities and the nonlinear order of HOSM to separate the effects of the different order nonlinear instabilities on freak waves. This investigation and freak wave simulations by HOSM clarified that the four-wave Class I instability with finite width wave spectra affected both the crescent deformation and the asymmetry. The results showed that Class II instability effects to the freak wave shapes were not significant.

Guo and Alam (2016) invoked a statistical approach to find the typical shape of giant waves. They considered different sea states and unidirectional versus crossing seas and studied how each environment affects the morphology of oceanic rogue waves.

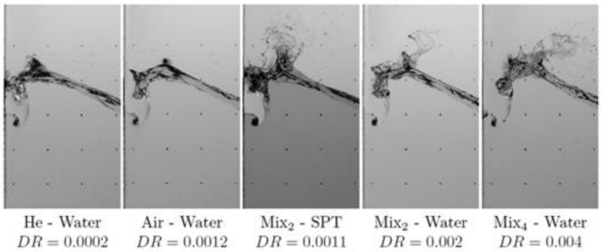


Figure 9 Free surface of the breaking wave before impact with repeated motions and different gas-liquid density ratios (Karimi and Brosset, 2014)

2.5 Sloshing

Karimi and Brosset (2014) carried out an experimental study on the kinematic and dynamic features of sloshing waves. The study investigated the effects of gas-liquid density ratio (DR) on sloshing wave shapes. It appears that, repeating the same irregular motions, the global flow keeps the same phase regardless of the tested DRs. This enables recognizing an accurate impact-by-impact relation between model tests at similar and different scales and adds a deterministic side to post-processing model test results. However, the local effects of DR clearly modify the impact geometry before gas compressibility interferences, with signify-cant consequences on induced pressures (Figure 9).

There was an effort to accurately simulate a free surface of sloshing flow using numerical methods. Scolan et al. (2016) tried to solve fully nonlinear free surface problems of a tank in forced motion. The paper proposed some new insights into the problem formulated in potential theory and extremely accelerated localized free surface motions.

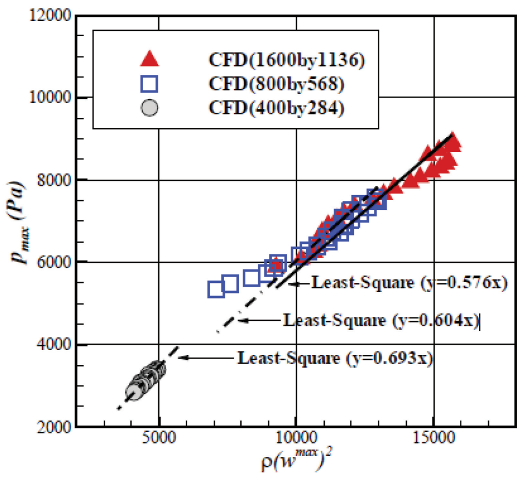


Figure 10 Relationship between peak pressure and square of local maximum vertical velocity (Yang et al., 2016b)

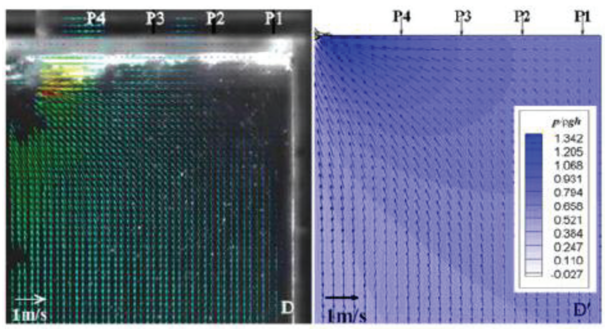
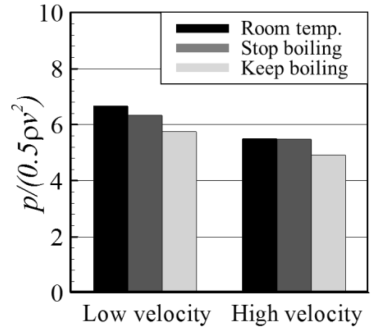


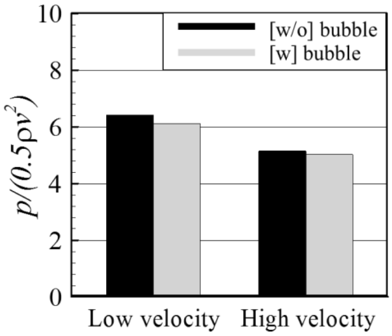
Figure 11 Experimental and numerical velocity field (Yang et al., 2016b)

Yang et al. (2016b) carried out both a numerical and an experimental study into local sloshing impact. Sloshing model tests employing Particle Image Velocimetry (PIV) and the corresponding numerical computations solving incompressible flow are considered to compare the impact characteristics around the tank top corner. The study introduced the impact pressure coefficient based on the maximum of local vertical velocity with the corresponding maximum pressure (Figure 10 and Figure 11).

More profound issues in violent sloshing flows are the effects of phase transition and



(a) Impact on boiling water



(b) Impact on water with bubbles

Figure 12 Comparison of peak pressures with water boiling or bubble generation (Kim, Y. et al., 2016a)

bubbles during impact occurrence. So far, the knowledge for these effects is very limited. Kim, Y. et al. (2016a) carried out a small scale drop test to observe such effects using boiling water including bubble generation inside the fluid. They compared the impact pressure with the case of impact on normal and calm water. Through this experiment, it was found that the magnitude of pressure peak can be smaller due to the effects of phase transition and bubbles, as shown in Figure 12.

Sloshing is a phenomenon occurring inside a tank, so that the problem of the fluid-structure interaction (FSI) is an inevitable topic for sloshing. Ringsberg et al. (2016) studied the structural response due to sloshing impact loads in LNG carriers with membrane type cargo tanks (Figure 13). The objective was to quantify the Dynamic Amplification Factor (DAF) for the structural response with respect to sloshing impact pressures. The influence of variations in the load characteristics such as load duration, extent of the loaded area, load location, as well as the influence of the insulation system was evaluated. The study showed that the response in the studied region of the hull structure experiences significant levels of dynamic amplification (the dynamic response shows DAF values of up to 2.) during impact loads with specific durations (0.7 to 10 ms).

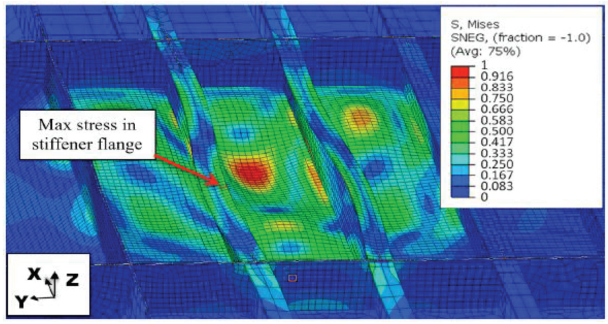


Figure 13 Von Mises stress profile for the stiffener flange corresponding to LC Plate 400 with a load rise time of 3 ms. Scale of deformation: ×20 (Ringsberg et al., 2016)

In a larger domain, Malenica et al. (2015) presented a method to account for the influence of sloshing on the global structural dynamics of the floating body. Jiang et al. (2015) carried out physical model tests to study the hydrodynamic and structural characteristics of violent sloshing in elastic tanks. The sloshing pressures and structural strains were measured at the elastic tank wall. The study described wave shapes in elastic tanks, analysed the resonant charac-teristics and the variation of the elevations, pressures, and strains.

Sloshing is important not only because it can cause damage to the tank structure but also because it affects the ship motions. There have been various researches on coupled ship motions and tank sloshing of liquid carriers applying numerical approaches. (Wang and Arai, 2014, Cercos-Pita et al., 2016, Servan-Camas et al., 2016).

Zhao and Chen (2014) carried out a series of two-dimensional model tests to study the coupling between global roll motions of a floating liquefied natural gas (FLNG) vessel and internal sloshing. The model of the FLNG was allowed to move freely in roll under the excitations of an initial heel angle, band-limited waves, and regular waves (Figure 14). The study found that the coupling phenomenon is sensitive to the period and height of excitation waves. The natural period of the roll motion shifted towards higher periods due to the effects of the internal liquid sloshing. The internal liquid flows would serve as a damper in free decay motions of an FLNG vessel in still water. Another finding was that sloshing exhibits a more obvious influence on global motions for higher filling levels than for lower filling levels.

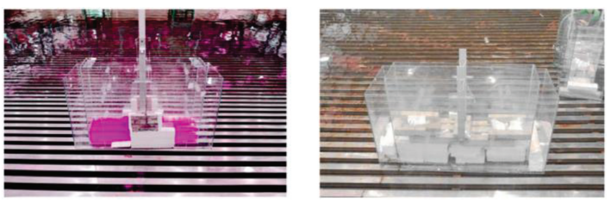


Figure 14 Snapshot of test preparation, FLNG section model (Zhao and Chen, 2014)

Also, Seo et al. (2016) investigated the influence of sloshing forces and moments on added resistance of a ship. The study found that when considering sloshing, the added resistance decreased significantly near the resonance point of the inner tank. Also, the main factor affecting the added resistance of the ship was the change of the ship motions, whereas the effect of sloshing flow itself was very small.

Sloshing impacts can cause large damage to the tank structure. Various researches have been carried out to reduce sloshing inside the tank. Many numerical studies were aimed at the installation of baffles inside side the tank vertically and horizontally (Zhang et al., 2016, Kumar and Sinhamahapatra, 2016). Also, there were some experimental studies into the influence of baffles on the sloshing flow (Jin et al., 2014, Nayak and Biswal 2015). Some studies attempted both numerical and experimental approaches (Firoozkoohi et al., 2016, Hwang, S. C. et al., 2016, Yu et al., 2017).

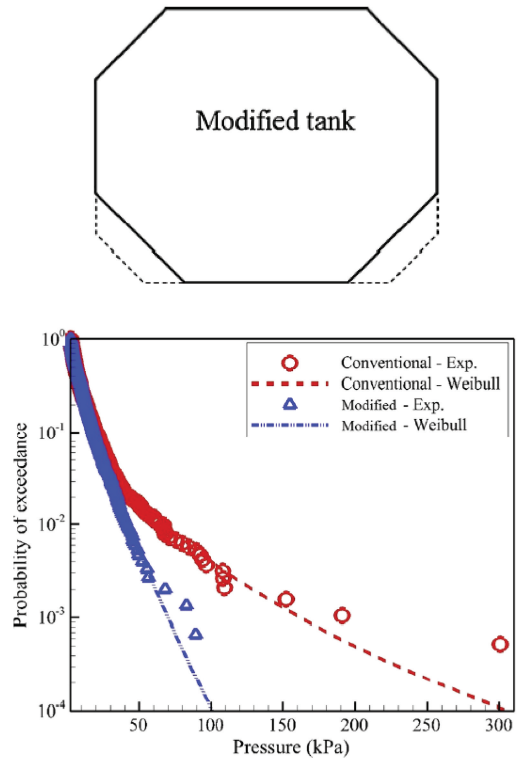


Figure 15 Comparison of sloshing-induced pressures of conventional and modified tanks (Park, J.J. et al. 2015)

Also, several researches into the relationship between tank shape and sloshing severity were carried out. Vaziri et al. (2015) investigated the effect of base aspect ratio on the sloshing resonance by applying a numerical approach. Souto-Iglesias et al. (2015) determined the influence of tank width on the sloshing impact pressure. More practically, Park, J.J. et al. (2015) carried out a numerical and experimental study to find an appropriate tank for various filling conditions to reduce sloshing. The study showed that by changing the lower chamfer height of a conventional membrane-type tank, sloshing impact can be reduced significantly compared to the original tank (Figure 15).

Until now, it has been believed by many researchers and ship classification societies that the experimental approach can provide reliable data to evaluate the sloshing load. Nevertheless, in spite of the huge effort on experimental analysis, there are many uncertainties in sloshing experiments.

Kim, S.Y. et al. (2015) carried out a comparative study on pressure sensors for the measurement of sloshing impact pressures. Various types of pressure sensors were tested in many aspects, such as noise level, thermal drift, magnitude of peak pressure, etcetera. The study showed that piezoelectric sensors, including ICP, sensors are sensitive to thermal effects. Also, two ICP sensors that are widely used by many experimental facilities, showed differences in the measured pressure, although both sensors have the same type, sensing diameter, and linearity.

Repalle et al. (2015) studied impact pressures due to droplet collision on a rigid wall, both numerically and experimentally. The study found that the impact pressure can be scaled proportional to the stagnation pressure, i.e. the pressure variation is quadratic with the droplet impact velocity. Kim, S.Y. et al. (2014) studied a statistical post-processing method for pressure data acquired from sloshing model tests. The paper presented a sensitivity study of peak sampling method and peak modelling method and proposed a new modelling parameter: impulse area. The study concluded that a model test duration corresponding to 5-hour full scale is not sufficient to acquire a converged test result.

2.6 Hydroelasticity

Hydroelastic solutions for seakeeping are becoming more common place due to improved computational power and methods. There have been several efforts to create benchmark data to verify numerical development, but additionally numerical methods have greatly improved over the last decade. The WILS JIP and TULCS cooperative efforts advanced the knowledge of hydroelastic solutions by improving and developing experimental techniques, benchmark data, and effective numerical solutions.

2.6.1 Experimental

Hydroelastic models typically involve a segmented model with a backbone as described by Jiao et al. (2016) or Maron and Kapsenberg (2014). However a less intensive solution can be created by using segments with elastic joints at the segments as described by Zhu and Moan (2015).

The results of the WILS JIP III efforts have created multiple detailed experiments of a segmented 10,000 TEU model.Results are presented for bow slamming (Hong et al. 2015) and stern slamming (Kim, K.H. et al. 2015b). This data was further advanced by performing 2-D drop tests to better relate slamming and whipping (Kim, J.H., 2015). The correlation between slamming impact loads and whipping is described by Kim, K H. et.al. (2015a).

The ULCS model test from Maron and Kapsenberg (2014) fed into the numerical method comparisons of Rajendran et. al. (2016). Zhu and Moan (2015) also tested a ULCS but investigated loading in oblique seas.

With proper design hydroelastic experiments can be performed for smaller vessels. Wu (2015) used a 1:11 scale segmented 45m high speed patrol boat to investigate how hydroelastic effects influence fatigue. Shakraki et al. (2014) used a carefully designed segmented high speed catamaran constructed with carbon-fibre shell to mitigate slamming of wave-piercing catamarans.

Future growth areas for hydroelastic model testing will involve the use of tailored extreme waves to produce maximum loading in a repeatable fashion.

2.6.2 Numerical

The improved benchmark data, and improved numerical methods have led to the development of various advance approaches to create hydroelastic solutions for large ships in waves. All higher fidelity methods involve some level of coupling between the ship structural and hydrodynamic solutions.

Kim, Y. et al. (2015) provide an overview of solution methods. They suggest a high fidelity fully coupled model of the 3-D Rankine panel method, the 2-D generalized Wagner model, and the 1-D/3-D finite element method.

Hwang et al. (2015) conducted hydroelastic analyses for a 380 m long and 58 m wide container ship. Ship motions and wave loads were calculated using a nonlinear 3D Rankine panel method. A 2D wedge approximation was used for estimating the slamming loads. Modal superposition technique was employed for the hull girder analysis in time domain. Results were presented for regular and irregular wave conditions.

Oberhagemann et al. (2015) presented the numerical assessment of wave responses of a 18000 TEU container ship and associated hull girder assessment. In their analysis, the authors used a finite-volume solver of the Reynolds-averaged Navier-Stokes equations coupled to a finite element beam model of the hull girder. The results for different sea sates and ship speeds for vertical bending moment including slamming and whipping effects are included.

Im et al. (2015) presented results of hydroelastic vibratory responses of an ultra large container ship (19000 TEU). The authors used a 3-D FEM code for structural analysis and 3-D potential flow code for hydrodynamic modelling. Their method is based on linear hydroelastic analysis with mode superposition, in which the total displacement of the ship was modelled as a series of modal displacements. The results included mode shapes, bending and torsional moments and Von Mises stresses.

Craig et al. (2015) employ a fully-coupled hydroelastic simulation method to predict slam-induced whipping. The method couples the fluid and structure in the time domain. The ship structure was modelled on a modal basis. The hydrodynamic solution employs Aegir or CFD based upon OpenFOAM. The results for the JHSS hull form were compared to model experiment data.

Kashiwagi et al. (2015) compared the results of 3D time domain Green function method versus frequency domain Rankine method using modal methods to investigate ship hydroelasticity. Chen et al. (2015) proposed a method based on the hydroelastic approach to model the hydrodynamic damping and added mass for the vibration analysis of ultra large container ships. Results for a 18000 TEU container ship were presented.

Lee and Lee (2015) presented a Lagrangian finite element formulation for nonlinear hydrostatic analysis of deformable floating structures. Their formulation includes the effects of initial stress field, normal vector change, and buoyancy changes. The numerical method they proposed can be used to calculate the hydrostatic equilibrium state and the associated stress field.

The development of numerical solutions involves looking at simpler vessels such as barges or Wigley forms. Kara (2015) investigated barge hydroelastic behaviour with direct time approximations using Boundary-Integral Equation Method with 3-D transient free surface Green function and Neumann-Kelvin approximation formulation. Lakshmy-arayanana et al. (2015) used a strongly coupled fluid-structure interaction using RANS/CFD and Finite Element software versus just one way coupling.

Because of the size of the ULCS Bennett and Phillips (2015) suggest the use of hydro-elastic calculations to predict the survivability of a damaged ship.

2.6.3 Full Scale

Interest in providing full-scale hydroelastic data for large containerships has resulted in many useful trials. Vincent Andersen and Jensen (2015) presented extreme value responses of three container ships, 8600, 9400 and 14000 TEU, based on full scale strain measurements. The authors used peak-over-threshold method for extreme value analysis. Vincent Andersen and Jensen (2014) further investigated data for the 9400 TEU ship and determined that extreme value of hogging wave bending could exceed the rule design.

Ki et al. (2015) conducted full scale measurements of whipping and springing responses of a 14000 TEU container ship in a seaway. The responses were recorded by strain and pressure gauges, accelerometers and roll and pitch sensors.

Orlowitz and Brandt (2015) instrumented a Ro-Lo vessel and obtained results for natural frequencies, damping and mode shapes for three speeds: at anchor, 10 knots and 18 knots. This was a very thoroughly instrumented ship allowing great mode definition.

Storhaug and Kahl (2015) reported the full scale torsional vibration measurements for 8400 and 8600 TEU container ships. The monitoring system consisted of a number of strain gauges and slamming sensors or accelerometers.

2.7 Added Resistance in Waves and Power Requirements

The topics of added resistance in waves and the determination of the corresponding power increase continue to be of high interest to naval architects and shipyards alike. The latest research regarding the topic can broadly be split into the following four categories to be addressed in this section:

- Development of numerical methods to predict added resistance in waves
- Development of new bow shapes to reduce added resistance in waves
- Added resistance in waves in the context of the EEDI
- Miscellaneous topics

2.7.1 Development of Numerical Methods to Predict Added Resistance in Waves

A large number of papers on numerical prediction methods for added resistance in waves has been published during the last three years. Methods can broadly be divided into viscid and inviscid methods. Although inviscid theory is still the most common way to predict added resistance, viscous flow simulations, particularly Reynolds-Averaged Navier-Stokes Equations (RANSE) solvers become more and more common, as also becomes evident from also Sections 2.3 and 2.8 on numerical methods and CFD applications. Regardless of the choice of method, numerical determination of added resistance is usually carried out in two steps: firstly, the computation of calm water resistance, and secondly, the computation of total resistance in waves. The added resistance is then taken as the difference between the two cases.

Söding and Shigunov (2015) provide a comprehensive comparison of various -both viscid and inviscid- methods for yhe calculation of added resistance for 10 ships and conclude that, despite the large scatter of results the prediction methods appear to be useful for engineering applications. Especially for waves shorter than a half ship length, most of the investigated methods, even the Euler and RANSE simulations that were analyzed, gave inaccurate results.

Inviscid Methods. The main advantage of these methods is that they are computationally inexpensive. This makes such codes attractive for applications such as hull form optimizations were a rapid evaluation of a large number of design alternatives is more important than accuracy. For example, Vernengo et al. (2015) carried out such a parametric optimization of a semi-SWATH ferry using a simple linear 3D Rankine panel code to calculate total resistance in waves.

Park et al. (2016) studied the added resistance of a KVLCC2 tanker using both, strip theory and a Rankine panel code and compared the results for four different drafts to dedicated model tests in regular waves. Results showed that both numerical methods were able to predict heave and pitch motions at all drafts. Strip theory was able to predict added resistance at scantling draft but broke down for the other drafts. The Rankine panel code on the other hand could predict added resistance for all drafts, except for short waves. The authors therefore pointed out the need for a short wave correction for panel codes.

Yang et al. (2015) used an Euler equation solver to simulate and analyze ship motion and added resistance in waves. Water, air, and solid phases were distinguished using a volume fraction function for each phase and in each cell. The volume-of-fluid (VOF) approach that was used provides reliable results even for violent flow problems in which the topology of the free-surface boundary is largely distorted, fragmented, and merged. Results compare favourably with published data from the literature and the authors were able to give recommendations regarding mesh size, grid spacing etc. Added resistance could be calculated accurately, even for short waves.

Guha and Falzarano (2015) developed a numerical method for estimating the added resistance based on an improved pressure integration method which includes the effect of the hull flare angle at the mean water surface. The proposed approach uses the 3D wave Green function method to solve the radiation-diffraction problem within the potential flow assumptions. First-order motions and added resistance obtained with this method for different non-wall-sided hull forms are compared to model test data and various other numerical methods. Interesting general conclusions regarding applicability of different types of methods for added resistance are provided.

Viscous Methods. Compared to potential flow methods RANSE solvers are computationally very expensive, especially for short waves. Nevertheless, RANSE solvers allow studying the complete physics of added resistance in waves including large amplitude motions, nonlinear effects and, of course the, effect of viscosity.

El Moctar et al. (2017) used RANS based field methods to predict added resistance in regular head waves for a 14,000 TEU containership and a medium size cruise ship numerically. Long and short waves of different frequencies were considered. Added resistance was decomposed into diffraction and radiation parts, where diffraction forces were obtained by restraining the ship motion and radiation forces by prescribing the motions of the ship in calm water. As expected the diffraction part of total resistance was found to be dominant in short waves. Calculated added resistance coefficients compare favourably to experiments but the authors conclude that: ‘Predicting wave-induced resistance of ships in waves remains challenging’.

Ruth et al. (2015) studied the added resistance of an offshore service vessel in high waves with a RANS-code and compared the results to model tests. Results from the RANS-code are consistently about 10% lower than the measured added resistance.

Tregde and Steen (2015) used an RANSE-solver to investigate the behaviour of a lifeboat in an irregular sea state with 8m significant wave height. This corresponds to the characteristic sea state defined in terms of the 99th percentile in the long-term distribution of the significant wave height $H_{W1/3}$. Simulation results for about 3 minutes full-scale time were obtained and show that the lifeboat can maintain sufficient speed to comply with the DNV-OSE406 standard.

2.7.2 Development of New Bow Shapes to Reduce Added Resistance in Waves

Improving bow shapes of merchant vessels in order to minimize added resistance in waves is of significant current interest to the industry in general and shipyards in particular. Large numbers of both numerical as well as experi-mental investigations were carried out in this field and led to the development of a large number of special bow shapes. These include:

- the COVE-bow (Sakurada et al., 2016),
- Ax-and Leadge-bows (Kim, Y. et al., 2014),
- vertical non-bulbous bows (Valanto and Hong, 2015),
- two non-bulbous shapes of Leadge-and High-bows (Lee, S. et al., 2016),
- a modified non-bulbous ‘KWP’-bow on a KVLCC2 tanker (Kim, Y. et al., 2015),
- a small ‘nose’ or bow-appendage to reduce spray in short head waves (Mitzutani et al., 2015), and
- a vertical non-bulbous bow on a container ship (Hwang, S. et al., 2016).

All these investigations conclude that a significant reduction in added resistance can be achieved by a well-designed bow. In some cases, power savings in the order of 10% could be achieved.

The finding that added resistance mainly depends on the bow shape is confirmed by the numerical and experimental studies of Wu et al. (2015) who analyzed added resistance in short head seas for a segmented KVLCC2 model. They found that added resistance is primarily concentrated on the forward part of the ship. Contributions from the aft-segment were rather small, while the added resistance of the mid-segment could be neglected.

Böckmann and Steen (2016) studied the idea of installing wing-like underwater ‘wavefoils’ in the bow area of a tanker to convert vertical motion energy into useful forward thrust. Using a combination of numerical and experimental techniques, they found resistance reductions of around 10%. For 3m head waves heave and pitch motions were reduced in between 10% and more than 20%.

2.7.3 Added Resistance in Waves and EEDI

In 2012, the IMO's regulations regarding the Energy Efficiency Design Index (EEDI) came into force. As a result, a number of researchers looked into diverse EEDI-related topics such as determining the ‘weather factor’ f_w or the minimum power required to maintain the manoeuvrability of a ship in adverse conditions.

Operational Issues and Installed Power. Dallinga et al. (2014) studied the operational consequences of the industry trend towards installing smaller engines to meet the EEDI criteria. The resulting increase in trip duration was quantified on a typical European coastal route. Added resistance in waves was estimated with a Rankine panel code. On a similar note, Gerhardt et al. (2014) used wave statistics in combination with experimentally derived Response Amplitude Operators to tailor the sea margin of an LNG tanker to suit the operational areas of the ship. In this way, the installed power and ultimately the EEDI could be reduced by about 5% while still maintaining the target speed.

f_w-factor. Chen, J. et al. (2014) experimentally determined the ‘weather factor’ f_w of a bulk carrier by model tests in a seakeeping basin. Böckmann and Steen (2016) compaired f_w-factors obtained using the STAwave-2 method to f_w-factors from strip-theory (the extended Gerritsma-Beukelmann method as well as direct pressure integration). Their results showed that the STAwave method over-predicted the speed loss. Jung et al. (2016) used Maruo's far field theory to calculate f_w-values as part of a 'design for waves' approach.

Minimum Power. In the context of the EEDI and predicting minimum power to safely manoeuvre in waves the European Union funded SHOPERA project (Energy Efficient Safe Ship Operation, shopera.org) was set up as a collaboration between class-societies, ship-owners, universities, and other stakeholders. Although the focus of the project was mainly on manoeuvring in waves, it also involved the development of methods to predict added resistance. Liu and Papanikolaou (2016), for example, explored and compared various existing and new semi-empirical methods to predict added resistance in head waves. They found that their new method gives sufficiently accurate results for a 'Level 1' assessment of added resistance. An overview of the SHOPERA project and its various experimental and numerical parts can be found in Papanikolaou et al. (2014).

2.7.4 Rankine Panel Methods Applied to Added Resistance in Waves

The Rankine panel method has been widely applied to compute the added resistance of a ship travelling in waves due to its applicability to the ship motion problem with forward speed and the computational efficiency relative to the CFD-based solver. For the prediction of added resistance, the near-field method—which consist of the integration of the second-order pressure on the body surface—can be adopted along with the Rankine panel method.

Soding et al. (2014) employed the seakeeping code called 'GL Rankine' to predict the added resistance of various ship models in head waves. In the frequency-domain panel method, the interaction of the linear periodic wave-induced flow with the nonlinear steady flow resulting from the nonlinear free surface conditions and dynamic squat were accounted for. The added resistance in waves obtained by the pressure integration generally correlated favourably with the results of RANSE solver and experimental data.

Shigunov and Bertram (2014) combined the Rankine panel method with the prediction for the wind forces, the calm-water manoeuvring forces, and the rudder and propeller forces to compute the associated resistance and power as well as changes in ship propulsion in waves. The approach was verified for a containership by comparing the predictions with the full-scale data.

Seo et al. (2014) used the higher-order Rankine panel method to calculate the added resistance in the short wave region where the wave energy is concentrated for the moderate sea states. The computational results were compared with the results of the finite volume based Cartesian-grid method, asymptotic formulas for the short wave region, and experimental data (Figure 16 and Figure 17). According to the grid convergence test, it was shown that more panels are required for short wave conditions than for longer wave conditions due to the severe variations of physical variables. The Rankine panel method gave good results for the short-wave added resistance of a blunt body while the prediction was less accurate for a slender body because the nonlinear effects cannot be considered in the linear potential based solver.

Another numerical approach to analyse the added resistance problem is the far-field method, which is based on the momentum conservation theory. Liu and Papanikolaou (2016a) validated a hybrid time-domain Rankine source

Green function method for the prediction of the added resistance of ships in oblique seas. In the study, the far-field method using the Kochin function (according to Maruo's method) was adopted, and an attempt was made to combine the hybrid method and a new generalized semi-empirical formula (Liu, S. et al., 2015) for estimating the added resistance in short waves.

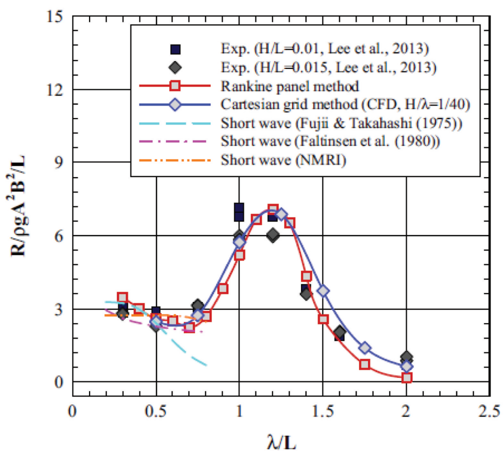


Figure 16 Added resistance: KVLCC2, Fn = 0.142, heading angle = 180 deg. (Seo et al., 2014)

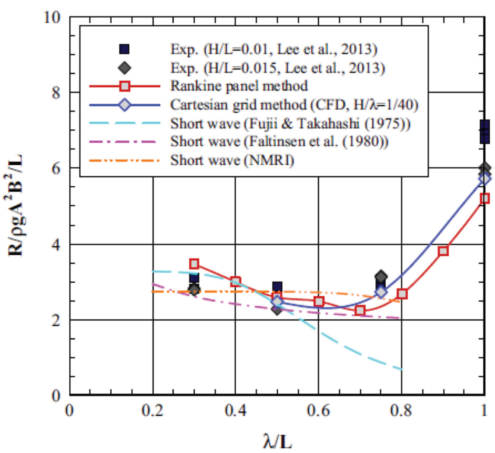


Figure 17 Added resistance: KVLCC2, Fn = 0.142, heading angle = 180 deg, zoomed on short wave lengths. (Seo et al., 2014)

Pan et al. (2016) extended a time-domain Rankine source solver to compute the wave added resistance of ships by applying the momentum conservation principle. The wave added resistance was calculated by an integration of the fluid velocities and free surface elevations over a control surface. For the selection of the location of the control surface, a convergence test was carried out. It is recommended that the control surface should be very close to the ship hull when applying the proposed momentum conservation method with double-body linearization (Figure 18 and Figure 19).

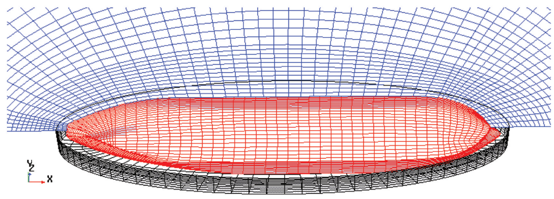
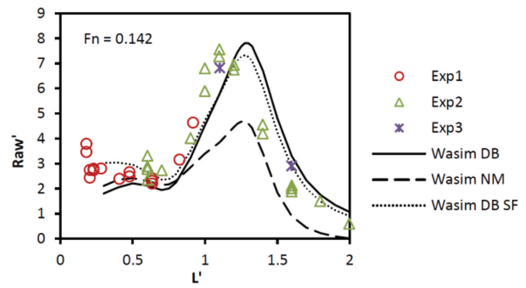


Figure 18 Discretization on free surface in the near field with wet hull and control surface (Pan et al., 2016)



DB: double-body linearization
NK: Neumann-Kelvin linearization
DB SF: double body linearization with steady flow

Figure 19 Comparison of wave added resistance: KVLCC2 (Pan et al., 2016)

Yasuda et al. (2016) investigated a new method for satisfying the radiation condition especially for low wave frequencies in the framework of Rankine panel method. The new method introduces a spatially-varying Rayleigh artificial friction in addition to the panel shift technique, which leads to the suppression of reflection waves even in low frequencies. The added resistance is computed by the unsteady wave analysis (the far-field method). Computational results for ship motions, unsteady pressure distribution and added resistance are in good agreement with the measured results both in head and following waves.

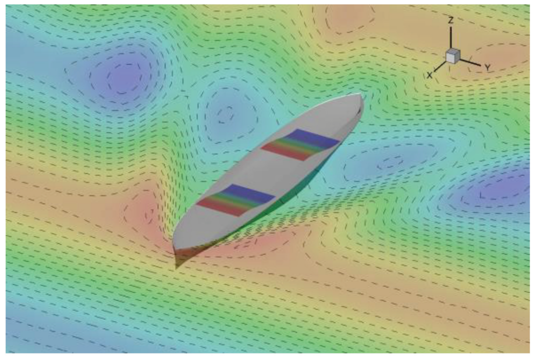
The time-domain Rankine panel method has been used to predict the added resistance of ship in combination with other external phenomena. The Rankine panel method in which the physical quantity is interpolated by a B-spline basis function was applied to compute the added resistance on a ship in regular waves coupled with sloshing-induced internal forces and moments by Seo et al. (2016). The sloshing flow of inner tanks was also simulated by applying the Rankine panel method to the linearized boundary value problem for the sloshing phenomenon (Figure 20). It was shown that the hull component of the added resistance induced by the external flow is much larger than the inner tank component attributed to the sloshing flow. Therefore, to calculate the added resistance of the liquid cargo ship accurately, the coupled motion with sloshing flow should be accurately predicted

Lee, J.H. at al. (2016b) investigated the relationship between parametric roll motion and added resistance of a container ship. A 3D weakly non-linear Rankine panel method in the time domain was used in combination with direct integration of the 2nd-order pressure to determine the added resistance. The study takes the higher-order restoring and Froude-Krylov forces acting on the wetted hull surface into account. The results show that for a parametrically rolling ship the higher-order Froude-Krylov force is the largest component of added resistance. Furthermore, the term associated with the kinetic energy of the fluid makes a major contribution to the total added resistance. In head waves, this last term is not significant if the ship does not roll parametrically.

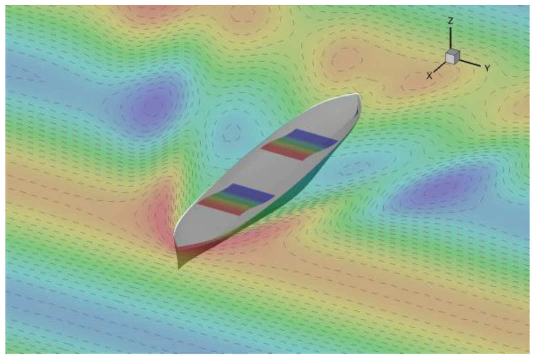
2.8 CFD Applications

Thanks to the rapid development of computer power and related technologies, Computation Fluid Dynamics (CFD) has been applied to seakeeping problems widely during the past several years and now is of high interest to scholars or even designers and engineers. This section contains the review of work concerning CFD application in the seakeeping problems analysis. After outlining the basic approaches in CFD, the next sections describe the relevant literature of CFD application to several typical seakeeping problems.

The term 'CFD method' here concerns only the field equations, i.e. the continuity equation and the Navier-Stokes equations, or the Euler equation. Current CFD methods applied to seakeeping problems can be categorised largely into two groups: grid methods and par-



(a) 50% filling ratio



(b) 70% filling ratio

Figure 20 Wave contour plot at natural frequency of inner tank: blunt modified Wigley, Fn = 0.2, heading 180 deg. (Seo et al., 2016) ticle methods. The former is an Eulerian approach, where the solution domain is discretized into structured or unstructured grids to solve the field equations on these spatial grids. In particle methods a finite number of particles are defined to represent the fluid mass and its properties to solve the field equations by using their interactions. This approach is also known as the Lagrangian approach.

2.8.1 Grid Method

Gird methods can be divided into three types, depending on the approach of discretization: Finite Difference Method (FDM), Finite Volume Method (FVM) and Finite Element Method (FEM). Each method has its own advantages and weaknesses. Presently, the FVM is the most popular method used in CFD methods applied to ships.

One of the primary features of the application of CFD to seakeeping is the treatment of the free surface. Generally, there are two types of methods to tackle free-surface flow: the interface-tracking method and the interface-capturing method. Currently, the latter dominates in the CFD application to ship hydrodynamics and will be addressed further.

The interface-capturing methods do not define the free-surface as a sharp boundary. The flow computation is performed on a fixed grid, which extends beyond the free-surface. The shape of the free-surface is determined by computing the fraction of each near-interface cell that is partially filled. Nowadays, there are two interface-capturing methods that are used widely in ship CFD: Volume of Fraction (VOF) and Level-set (LS). These two methods also have their own advantages and weaknesses. To overcome the weaknesses of the VOF method and the LS method, a coupled level-set and volume-of-fluid (CLSVOF) method has been developed. Even though, in spite of its weaknesses, VOF is now the most popular method adopted in commercial CFD software packages.

Another primary feature in seakeeping CFD application is how to deal with 6-DOF (six degrees of freedom) body motions in waves. For the grid method, there are three commonly-used method for the treatment of body motions: the non-inertial frame method, the dynamic mesh (or re-meshing) method and the overset mesh method. The method of overset mesh is becoming more and more popularly now in the community.

Figure 21 provides an overview of the grid method and the treatment methods that are employed within the grid method.

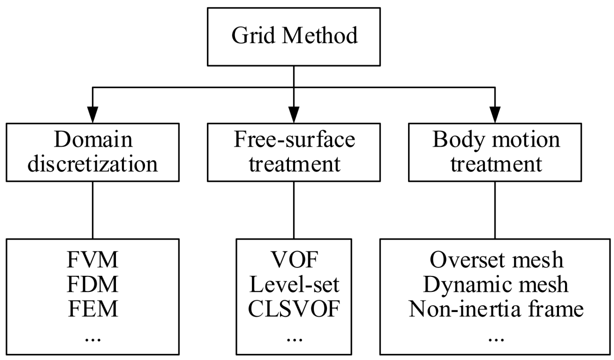


Figure 21 Grid method overview

2.8.2 Particle Method

Smoothed Particle Hydrodynamics (SPH) and Moving Particle Semi-implicit (MPS) are the most import approaches that are used to solve the fluid dynamics problems in meshfree Lagrangian framework. For both methods the fluid continuum is discretized into finite fluid particles. The weighted interpolation method is used to compute the physical quantities of each particle. Depending on whether the compressibility of the fluid particles is considered or not, the methods can be divided into two types: incompressible or (weakly) compressible.

Both SPH and MPS have several notable advantages compared to grid methods, i.e., they have a relatively easy procedure for solving the equation of motions, trace free surfaces better when handling large domain deformations and guarantee the conservation of mass. Both of them also suffer from the same disadvantages such as difficulties in handling diffusion and the high computational cost. In addition, the effects of spurious pressure fluctuations is also one of the challenging issues. To address this issue, a new particle method, named Consistent Particle Method (CPM), has recently been proposed. CPM is fundamentally different from SPH and MPS in terms of the derivative-approximation scheme. Figure 22 provides an overview of the particle method.

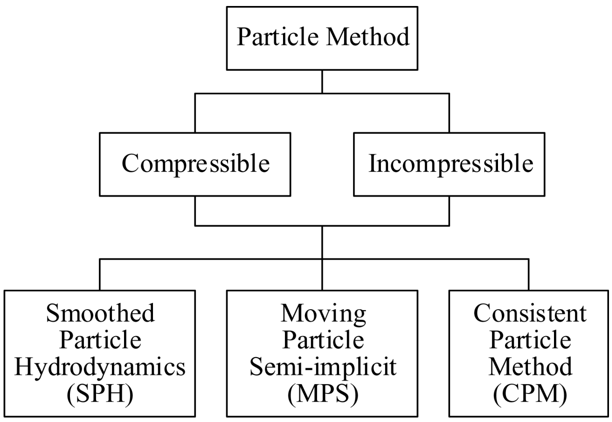


Figure 22 Particle method overview

Generally speaking, grid methods are more popular for usage in the seakeeping problem analysis, while the particle methods are likely applied to some 2D academic problems due their still high computational cost and other problems when solving 3D problems.

2.8.3 Motion Responses in Waves

The prediction of motion responses of a ship in waves is essential to evaluate the ship performance in seaway. With the development of techniques for body motion treatment in CFD, prediction of ship motion responses in waves now is becoming a routine application for CFD analysis for seakeeping problems.

Kim, J. et al. (2015) carried out URANS simulations to predict the seakeeping performance of the KCS advancing in regular head waves by using the WAVIS code. A cell-centered FVM is used for the discretization of the governing equations, the free surface is captured using a two-phase level-set method. Two degrees of freedom motions (pitch and heave) are solved in the non-inertial reference frame. The computed results of heave and pitch amplitudes generally show smaller values than experimental results, even though the agreement is fairly good.

Guo et al. (2015) use an URANS method to predict the pitch and heave motions of a wave-piercing catamaran (WPC) for various speeds and wave lengths in head seas. StarCCM+ is employed as the CFD solver, in which FVM is used for the discretization of the governing equations, the VOF method is adopted for the treatment of free surface, and an overset grid is used to deal with the ship motions. The STF method is also employed as a comparative method. Comparison of numerical and experimental results shows that for the Froude numbers of interest ($0.3 \leqslant Fr \leqslant 0.6$), acceptable agreement is achieved by using the URANS method, while only a similar trend is obtained by using the STF method for a small Froude number ($Fr=0.3$).

The seakeeping behaviour of a ship in shallow water differs significantly from its behaviour in deep water. Tezdogan et al. (2016) carried out a numerical study of ship motions in shallow water by using an URANS method (again using StarCCM+). In the study, the characteristics of shallow water waves were investigated first (Figure 23). Then, a full-scale large tanker was used as a case study to predict its heave and pitch responses in head waves at various water depths, covering a range of wave frequencies at zero speed. The motion results obtained were validated against related experimental studies and were also compared to those from 3D potential theory.

The main conclusion drawn from the com-

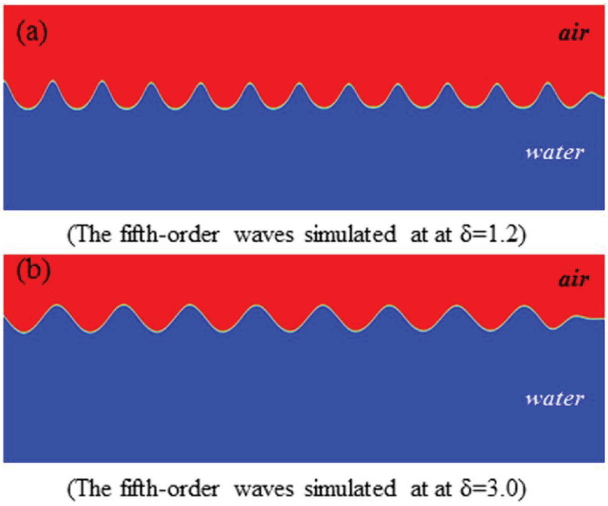


Figure 23 Shallow water waves (Tezdogan et al., 2016)

parison was that overall, the URANS method predicted the motion responses in shallow water better than the potential method used, particularly for pitch motions (Figure 24). When the water becomes shallower, heave motions decreased, whilst pitch motions increased at low frequencies and decreased slightly at high frequencies. The peak in the pitch transfer functions shifted to lower frequencies when the water depth decreased.

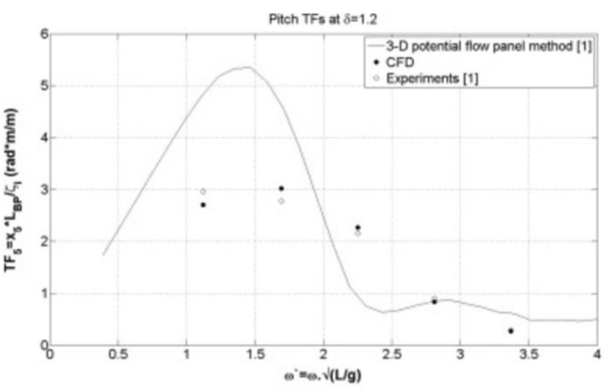


Figure 24 Pitch RAOs using different methods in shallow water (Tezdogan et al., 2016)

2.8.4 Added Resistance in Waves

Recently the discussions at the IMO have resulted in the development of the EEDI as a measure of how much greenhouse gas a ship emits, and to restrict greenhouse gas emissions from ships. For these reasons, ship designers should find optimum hull forms to minimize resistance in ocean waves, and pay great attention to the added resistance problem. The application of CFD methods to added resistance in waves is therefore of interest for the community.

As discussed in Section 2.3.3, Kim, Y. et al. (2014) carried out a systematic study on the added resistance problem by using numerical (potential flow and CFD) and experimental approaches. Regarding CFD, grid dependency tests in CFD computations showed that the grids resolution along ship length, particularly near bow region, is critical for short waves.

Wu et al. (2015) carried out CFD computations of added resistance for the KVLCC2 advancing in short regular head waves. An FVM based RANS solver with the VOF method adopted for capturing free surface was used for computation. The computed results agree quite well with the experimental data. Figure 25 shows the wave pattern for the KVLCC2 advancing in a regular short head wave (λ/L_{PP} = 0.20). As can be seen from the figure, some strong nonlinear phenomena, such as wave rolling up and wave breaking near the ship bow can be captured by CFD simulation.

Added resistance of the KCS advancing in waves was studied numerically by Sadat-Hosseini et al. (2015a). CFDShip-Iowa (FDM for discretization, Level-set for free surface, overset grid for motions) and Star-CCM+ (FVM for discretization, VOF for free surface, overset grid for motions, head waves only) were used as CFD solver. The validation studies were conducted for a range of wave lengths and wave headings. The comparison between numerical results and experimental data showed that results for added resistance obtained by CFD are promising and show better agreement than the results obtained by a potential flow

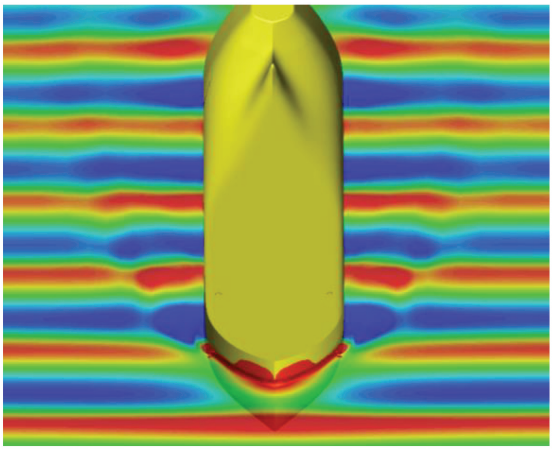


Figure 25 Wave pattern for KVLCC2 advancing in head wave-bow view (Wu et al., 2015)

method (Figure 26).

The computation of added resistance of a full scale KCS in head waves employing CFD was carried out by Tezdogan et al. (2015), obtaining reasonable results.

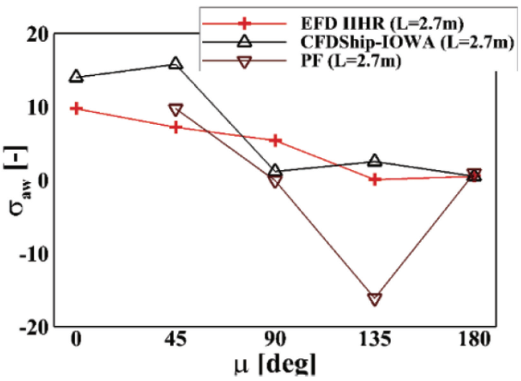


Figure 26 Comparison of CFD, PF and EFD data (Sadat-Hosseini et al., 2015a)

2.8.5 Roll Motion Damping

In most of the cases in classical seakeeping problems, the effect of viscosity is mainly of importance for roll motions. The usage of CFD to the prediction of roll motion and roll damping comes as a logical application, as the effect of viscosity, in the form of friction and eddy generation is usually included in some form or another.

Zhou et al. (2015) calculated the roll damping of ships by using a 3D CFD approach. ISIS-CFD was used as the solver in which FVM was employed as discretization method and VOF for the free surface treatment. Free decay simulations of 4 different types of ships at zero velocity were carried out. The results showed that the CFD method can simulate the free rolling of ships in the calm water at zero speed, giving a stable and well-predicted roll damping.

Jiang and Yeung (2016) developed the Slender-Ship Free-Surface Random Vortex Method (SSFSRVM) to study the roll motion of bodies in a viscous fluid. In this method, quasi-three dimensional formulation is employed that decomposes the 3D problem into a number of time-dependent 2D problems. By using this method, nonlinear time-domain solutions are obtained to accurately predict the free roll motion of a three-dimensional hull with and without forward speed. The predicted time histories of the roll motion and the vorticity distribution near the bilge keel were compared with experimental measurements with remarkably good agreement (Figure 27).

2.8.6 Slamming and Water Entry

CFD techniques are shown to be able successfully characterise slamming loads, as demonstrated by validation studies based on a series of controlled-speed drop tests.

He and Kashiwagi (2014a) validated a newly developed adaptive Cartesian-grid constraint interpolation profile (CIP) method by two 2D benchmark tests of a collapsing water column with an obstacle. They confirmed that the adaptive grid is capable of tracing regions with violent flows, automatically generating a finer grid to adapt to the violent changing of the flows.

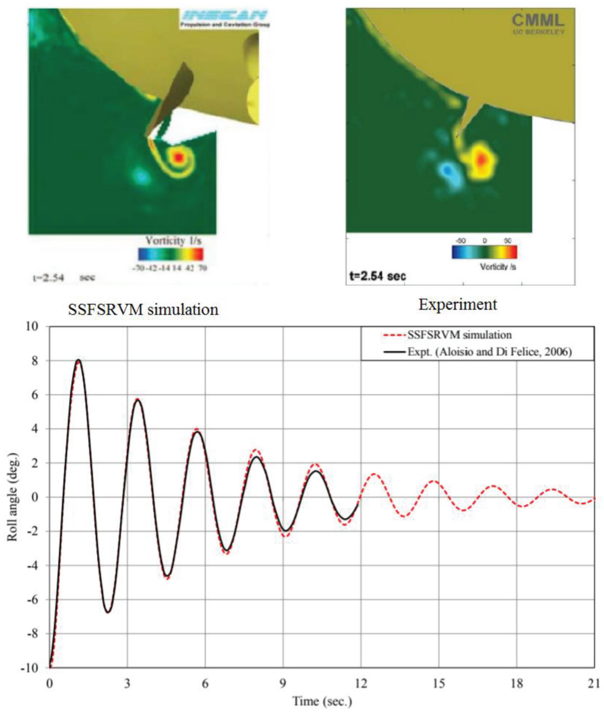


Figure 27 Comparison of CFD and EFD results (Jiang and Yeung, 2016)

Hashimoto et al. (2014) developed a coupled MPS-FEM model for strongly nonlinear fluid-structure interaction problems. In this method, semi-implicit MPS and explicit FEM are time-marching alternately to consider the coupling between fluids and structures. The developed model is validated through comparisons with a model experiment of a 2D dam-breaking test.

Numerical simulations of slamming impact loads using CFD (Star-CCM+) were carried out by Kim (2015). The simulations included a 2D ship section drop and containership bow flare slamming. CFD successfully simulated the occurrence of the air pocket above a bulbous bow and the slamming impact pressures showed good agreement with model tests. For the case of 3D ship with bow flare, the fully-nonlinear free surface flows due to bow flare slamming and green water on deck were captured reasonably well be the CFD simulation (Figure 28 and Figure 29).

Liao et al. (2014) developed a coupled

Figure 28 Bow flare slamming and green water (Kim, 2015)

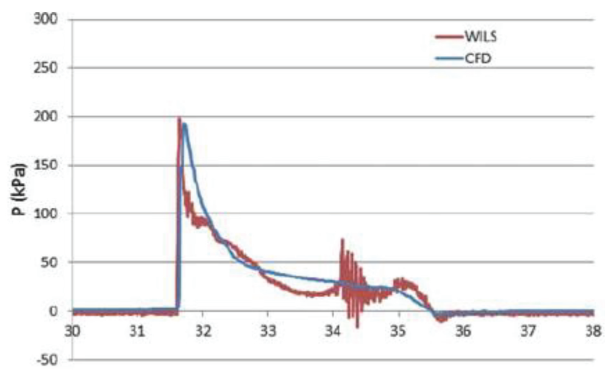


Figure 29 Bow flare slamming pressures (Kim, 2015)

FDM-FEM method for numerical analysis of strongly non-linear interaction between free surface flow and an elastic structure. They carried out a numerical simulation of an experimental case of dam-breaking with an elastic plate and showed reasonable agreement.

Li et al. (2014) applied an adaptive mesh refinement based Volume-of-Fluid (VOF) two phase method to simulate the water entry and slamming problems of solid bodies with various geometries. The computations have been performed by using the GFS (Gerris Flow Solver) libraries. They simulated the vertical water entry of a disk and showed that the adaptive VOF solver (Gerris) can be successfully applied. This solver was then used to simulate the slamming of thin plates to analyze the air cushioning effect.

Wang et al. (2014) studied the two-dimensional water entry of bow-flared section by using a Multi-Material Arbitrary Lagrangian-Eulerian formulation and penalty-coupling algorithm. The predicted results on the wetted surface of a bow-flared section were compared with published experimental values in terms of vertical slamming force, pressure distributions at different time instances and the pressure histories at different points. Comparisons between the numerical results and measured values showed a satisfactory correlation. An approximation method was adopted to estimate the sectional slamming force and its results were compared with numerical values, showing good consistency for the peak forces.

Wang and Soares (2014), investigated the hydrodynamic problem of the water impact of three-dimensional buoys by the explicit finite element method with an Arbitrary-Lagrangian Eulerian (ALE) solver. In this method the fluid is solved by an ALE solver and a penalty coupling algorithm enables the interaction between the body and the fluids. The remap step in the ALE algorithm applies a donor cell+HIS (Half-Index-Shift) advection algorithm to update fluid velocity and history variables. The interface between the solid structure and the fluids is captured by Volume of Fluid method. The numerical calculations were validated by comparing with other available results, for drop cases and cases with constant impact velocity.

Zhao and Chen (2014) developed a CIP-based (constraint interpolation profile) numerical simulation code for modelling freak waves impacting on a floating body undergoing large amplitude motions. An improved model governed by the Navier-Stokes equations with free surface boundary conditions was adopted for nonlinear wave-body interactions, in which a more accurate VOF scheme, THINC/SW, was adopted for interface capturing. The model was solved by CIP-based high order finite-difference method on a fixed Cartesian grid system. A focusing wave theory was used for freak wave generation. Experiments in a two-dimensional wave tank were performed for benchmark validation. Fairly good agreements were obtained from the qualitative and quantitative comparisons between numerical results and laboratory data with regards to distorted free surface shapes and large amplitude body motions.

Gu et al. (2014) simulated the flow problem of hydrodynamic impact during water entry of solid objects of various shapes and configurations by a two-fluid free surface code based on the solution of the Navier-Stokes equations on a fixed Cartesian grid. In the numerical model the free surface is captured by the level set function, and the partial cell method combined with a local relative velocity approach is applied to the simulation of moving bodies. After the validation by experimental data, oblique water entry of a wedge was simulated and the predicted free surface profiles during impact were compared with experimental results showing a good agreement. Formation and separation of the thin flow jets from surface of the wedge and associated ventilation phenomena for the cases of oblique water entry was also simulated for cases where the horizontal velocity was dominant.

Camilleri et al. (2015) applied the computational fluid dynamics code Star CCM+ coupled with the finite element code ABAQUS to the constant velocity impact of a flexible panel with water. They discussed issues with numerical stability, influence of different structural boundary conditions in the two-dimensional model, effects of hydroelasticity on the fluid loading by comparing the results from hydroelastic and rigid body simulations.

Varnousfaaderani and Ketabdari (2015) modified an SPH method to simulate a two-dimensional plunging solitary wave breaking process. To simulate the turbulent behaviour of the fluid flow in a wave breaking procedure, the Sub Particle Scale model was used. To correct the pressure and velocity field in the SPH method, a Riemann Solver was also implemented. This method was modified with a kernel and gradient of kernel correction to overcome the problems associated with the usage of viscous terms in Navier-Stokes equations. The modified kernel gradient was implemented to the model based on modified kernel in Element Free Galerkin Method. They simulated solitary wave impact on a seawall by the modified model and showed that the modified model has good agreement with experimental data.

Calderón-Sánchez at al. (2015) studied free fall and impact of a rectangular block of a liquid on a flat floor surrounded by a gas. This problem calls for an explicit treatment of compressibility, which is directly responsible for the pressure and density sonic waves caused by the impact. Computations have been carried out with the finite volume open-source package OpenFOAM, within a volume-of-fluid approach and a transient solver. They have developed a code extension in order to implement the Cole ("stiffened") equation of state.

2.8.7 Sloshing

The violent sloshing problem of liquids in tanks is an important topic in the design and safety of LNG related ships and offshore structures.

Yang et al. (2016a) carried out CFD computations of sloshing impact. The numerical method was based on both an in-house program and a commercial program, STAR-CCM+. In the case of the in-house program, a Cartesian-grid method where the governing equation was solved by using a finite difference method and constraint interpolation profile (CIP) method. The computational results show that in the CIP-based numerical method, the impact pressure is quite sensitive to the grid resolution (Figure 30). The impact pressure coefficient from the CIP-based method was reasonable compared with a similarity solution. However, the relation between the impact pressure and local velocity is still not sufficiently clear.

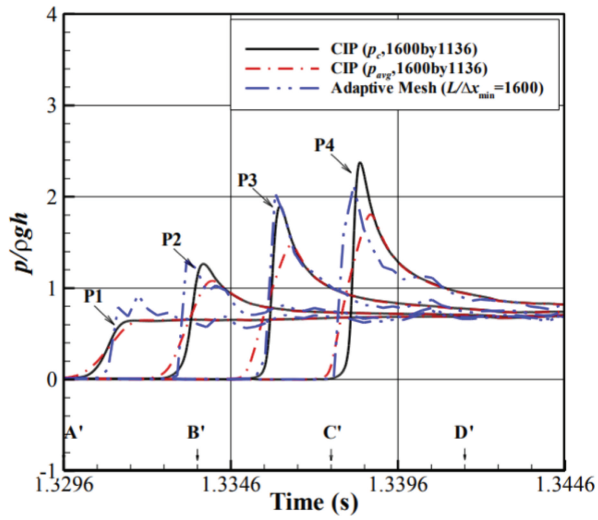


Figure 30 Comparison of pressure time histories with different grid resolution (Yang et al., 2016a)

Serván-Camas et al. (2016) carried out numerical simulations in the time domain of seakeeping problems taking into account internal flow in tanks, include sloshing. A SPH solver for simulating internal flows in tanks was coupled in the time domain to a FEM diffraction-radiation solver developed for seakeeping problems. Two examples were simulated and compared with experimental data. The first considered a barge with water in tanks, the other a modified S175 hull with an anti-roll tank (ART). Good agreement between obtained numerical results and experimental data were found.

A 3D numerical model was presented in the framework of Consistent Particle Method (CPM) by Luo et al. (2016) for the simulations of violent sloshing under regular and irregular excitations. Validated by experimental studies of sloshing, the model was shown to be robust and accurate in long time simulation of violent free surface flows (Figure 31). LNG sloshing in a real ship under sea excitations was studied. In beam seas and other general conditions such as head seas were considered. Very violent sloshing waves were found in the tank in cases where the roll motion was large. The violent sloshing not only generates large impact forces on the tank wall, but may also shift the COG of the tank sufficiently to affect the ship motions.

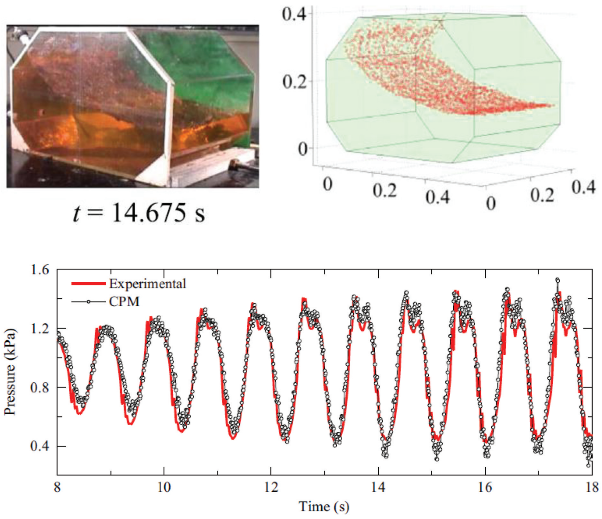


Figure 31 CPM results of sloshing wave in comparison with EFD (Luo et al., 2016)

2.8.8 Manoeuvring in Waves

The capability of CFD to deal with free running vessels in waves has been developed rapidly over the last several years. This opens up the possibility of applying CFD to the study of ship manoeuvring in waves.

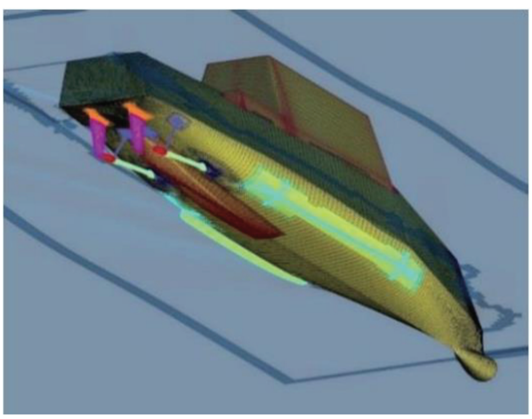


Figure 32 Pressure on CFD grid of ship hull and appendages (Sadat-Hosseini et al., 2015b)

Sadat-Hosseini et al. (2015b) carried out numerical simulations for course keeping and a turning manoeuver of the ONRT ship hull advancing at a Froude number of 0.2 in regular waves. The code CFDShip-Iowa V4.5 was used for the CFD computations (Figure 32). The results show reasonable accuracy when compared to EFD data. The studies on the propeller performance indicated that the propeller efficiency was larger in waves than in calm water. The results also showed that the low frequency results were significantly affected by turning.

Uharek and Cura-Hochbaum (2015) proposed a mathematical model for approximating mean forces and moments due to waves based on a double parametric approach based on wave encounter angle and wave length. The coefficients of the model were entirely determined by means of RANS computations. The obtained database, containing the coefficients of the model, allowed for an easy implementation of second order wave effects into existing manoeuvring simulation programs. Further work is ongoing to improve the model.

2.8.9 Miscellaneous Applications

Parametric rolling is one of the five failure modes introduced by the draft amendments to the IMO 2008 IS Code. Galbraith and Boulougouris (2015) studied the use of CFD for the detection of parametric rolling. The ONR Tumblehome model was used in the study. The simulation was setup using an overset mesh to allow motions in all 6 degrees of freedom (Figure 33). The results were validated against previously published results. The study showed that CFD can be a valuable tool for the investigation of this complex phenomenon.

Accumulated water effect due to repetitive shipping of green water can make ships with a small freeboard unstable and even capsize in severe sea conditions. Kawamura et al. (2016) carried out simulations of 6 DOF ship motions with severe shipping of water using an SPH method. The results showed that the SPH simu-

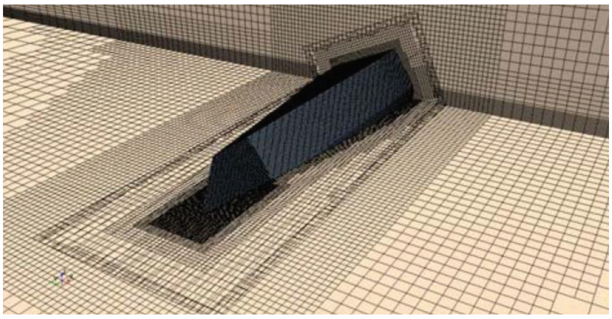


Figure 33 Rotated Overset Mesh (Galbraith and Boulougouris, 2015)

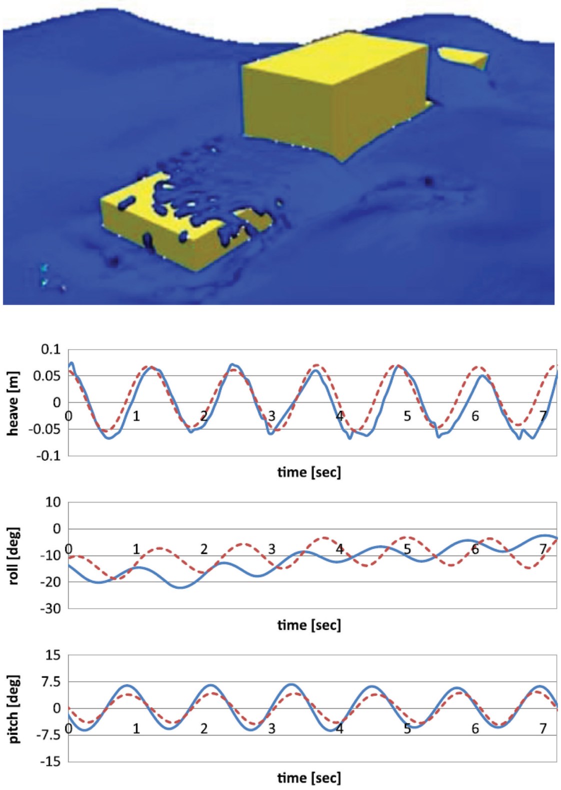


Figure 34 Shipping of green water and ship motions as computed by a SPH method (Kawamura et al., 2016)

lation can reproduce the asymmetric hydrodynamic force due to water on deck, and can reproduce the ship dynamic behaviour during severe cases of shipping of green water well (Figure 34).

Le Touzé et al. (2014) carried out systematic comparisons between MPS and SPH methods as well as a model experiment on forced roll tests of a two-dimensional damaged car deck. In order to treat trapped air in damaged compartments, different approaches were proposed for each particle method. It was demonstrated that the MPS and SPH results are in good agreement with the model experiment when the trapped air effect is relatively small. The agreement becomes worse when air is trapped. The two-phase SPH model provides quantitative accuracy even with the presence of trapped air, and the MPS model incorporating Boyle's law gives practical accuracy without increasing the computational cost (Figure 35).

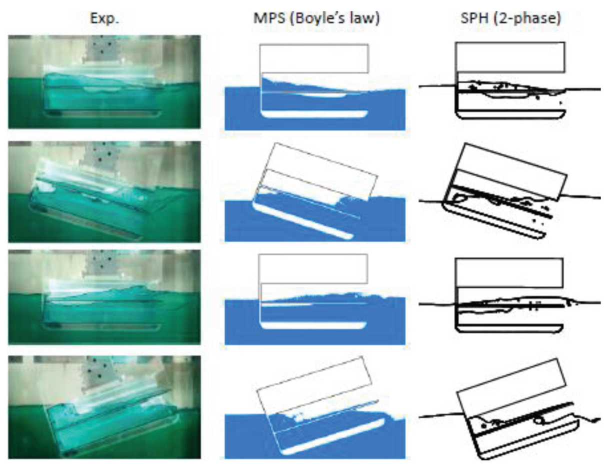


Figure 35 Simulated and experimental free surface comparison inside tank (Le Touzé et al., 2014)

3 MODEL CONTROL SYSTEMS

The following outlines recommended control system tuning approaches to be taken for seakeeping experiments, particularly with respect to autopilot and roll stabilization. The scope of this work includes the tuning of steering controllers and roll stabilizers using PD/PID-based tunings.

3.1 Assumptions and Limitations

This process assumes a standard mono hull displacement-hull vessel design with a single rudder control surface (or multiple rudder surfaces controlled together). It also assumes that care has been taken to either model the full-scale Froude scaling of lifting surfaces or to functionally map model scale deflection forces to full-scale deflection forces. The tuning method outlined here is for a defined forward speed. For each forward speed, the process must be re-iterated to capture the vessel dynamics at that speed.

3.2 Steering Theory for Heading Control

This tuning approach is based on the Nomoto first-order steering model that relates rudder as an input to yaw rate (Fossen, 1994).

3.2.1 Open-loop Manoeuvring Dynamics

The Nomoto steering model describes the open-loop steering characteristics by parameter fitting the linearised manoeuvring model (frequency domain):

$$\frac{\dot{\psi}}{\delta}(s)=\frac{K_N}{(1+T_N s)} \quad (1)$$

where $\dot{\psi}$ is the yaw rate, δ_r is the rudder angle, K_N is the static yaw rate gain, T_N is a time constant, and s is the complex variable of the Laplace transform.

To determine the model parameters, execute a standard 'zig-zag' manoeuvre (or any large rudder angle to large yaw angle manoeuvre). The resulting data set can be used to identify model parameters by either system identification methods or by graphical methods using a response plot. It should be noted that an identified Nomoto parameter pair is valid for one forward speed only. As an example, for a Mariner Class vessel K_N and T_N are given as 0.185 and 107.3 in (Fossen, 1994).

3.2.2 Closed-loop Pole Placement

The form of the first-order approximation of steering dynamics contains a single pole, defining the system steering bandwidth. There is a second pole in the system (the integrator)-so when a state feedback control is applied, the goal is to move these two poles into a complex conjugate pair to produce damped, harmonic response.

By designing a controller whose closed-loop response is within this system bandwidth, the induced response from controller influence is reduced by a separation in frequency. The controller bandwidth is chosen so that the inherent natural frequency of the vessel is not altered. This is more about not interfering with the model's natural behaviour than control system performance.

Given a state-space representation of the Nomoto steering model:

$$\begin{bmatrix}\dot{\psi}\\ \ddot{\psi}\end{bmatrix}=\overbrace{\begin{bmatrix}0 & 1\\ 0 & -1/T_N\end{bmatrix}}^{A}\begin{bmatrix}\psi\\ \dot{\psi}\end{bmatrix}+\overbrace{\begin{bmatrix}0\\ K_N/T_N\end{bmatrix}}^{B}\delta \quad (2)$$

In the above equation, all are functions of time.

The Laplace transform of the state equation with full state feedback, i.e. actually a regulator, is:

$$\begin{bmatrix}\dot{\psi}\\ \ddot{\psi}\end{bmatrix}=(A-BK)\begin{bmatrix}\psi\\ \dot{\psi}\end{bmatrix} \quad (3)$$

where K is the gain matrix containing proportional and derivative gains (Ogata, 2001).

Figure 36 shows a pole-zero map showing the placement of the open-loop pole and desired closed-loop conjugate pole pair. The closed-loop poles are located on the circle whose radius is defined by the open-loop pole frequency, and thus have equivalent natural frequency ω_0. The spacing of the conjugate pole pair from the real axis determines the damping ratio ζ and is arbitrarily chosen to be 0.707 to provide a suitably damped system time domain response.

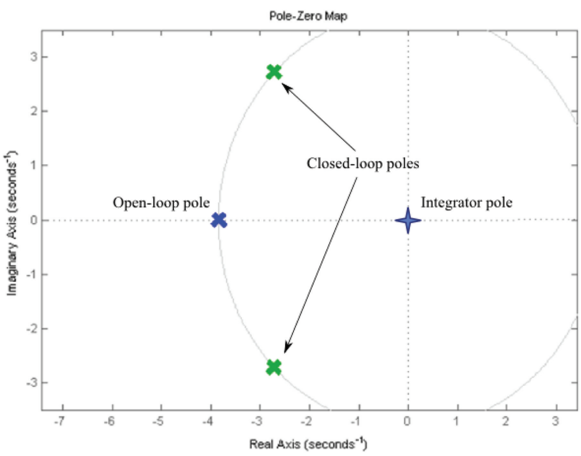


Figure 36 Pole-zero map

The damping ratio can be further tuned to provide a closed-loop response between under-damped ($0 \leqslant \zeta < 1$) and critically-damped ($\zeta = 0$). An over-damped ($\zeta > 1$) response is generally undesirable.

Pole placement involves selecting the controller feedback gain matrix **K** such that the eigenvalues of matrix **A-BK** (the poles) are located to provide the desired closed-loop response. Due to the low order of the system ($n = 2$), the gain matrix $\mathbf{K} = [k_P \quad k_D]$ $\mathbf{K} = [k_P \quad k_D]$ can be determined by direct substitution into the desired characteristic polynomial:

$$|s\mathbf{I} - \mathbf{A} + \mathbf{BK}| = (s - \mu_1)(s - \mu_2) \qquad (4)$$

where the desired poles are defined by:

$$\mu_{1,2} = -\omega_0 \zeta \pm \omega_0 \sqrt{\zeta^2 - 1} \qquad (5)$$

Solving these equations, the gains are given by:

$$k_P = \omega_0^2 T_N / K_N \qquad (6)$$

$$k_D = \frac{2\zeta\omega_0 T_N - 1}{K_N} \qquad (7)$$

3.3 Roll Motion Reduction

3.3.1 Active Fin Stabilization

Fin stabilization systems are highly effective for roll damping. Using lift generated on these surfaces at speed, fins can provide correcting moments that oppose that of the vessel's roll, thus increasing damping. Fin dynamics do not couple significantly into other axes (assuming that they are placed appropriately near midships) and should not require special control considerations to preserve vessel dynamics. Fin rates must be capable of performing a full fin angle sweep in a roll period to be effective.

The simplest control scheme for a fin stabilizer is to feed the roll rate signal (with proportional gain term) into the fin deflection controller.

3.3.2 Rudder Roll Stabilization (RRS)

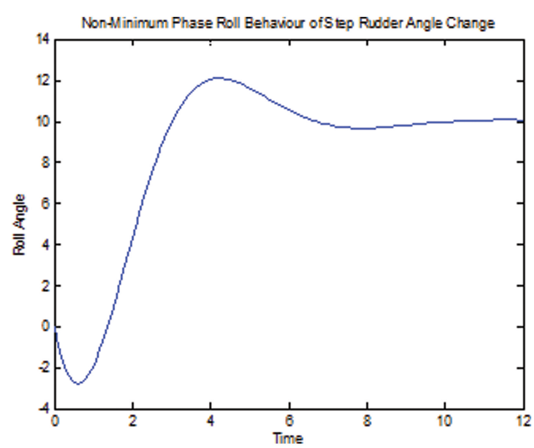


Figure 37 Non-minimum phase zero-the response of a vessel in roll to a hard-over rudder

Typically used in conjunction with an autopilot, RRS Systems use high-frequency rudder motions to stabilize a vessel in roll by adding roll damping to a ship by taking advantage of the "non-minimum phase zero" (see Figure 37) behaviour of the steering-roll subsystem.

Before modelling this type of controller, the following considerations must be made:

- A significant bandwidth separation must exist between the steering-yaw subsystem and the steering-roll subsystem, that is, the frequencies of effective roll subsystem cannot be low enough to affect the low-frequency bandwidth of the steering subsystem (as in Figure 38). This will cause degradation in the performance of both controllers.

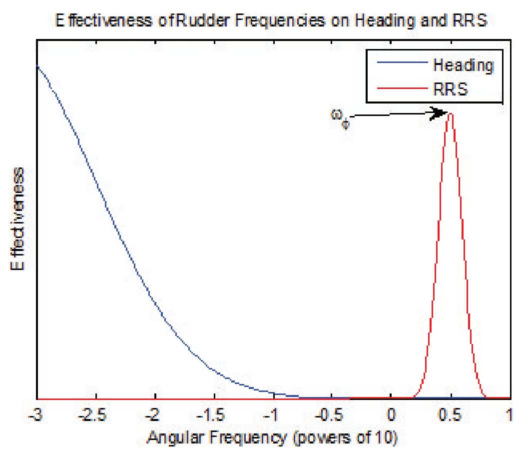


Figure 38 A significant bandwidth separation between heading and roll response (as a function of rudder input)

- The steering gear must be capable of withstanding high frequency motions (both model-scale and full-scale), in the order of the roll frequency. Steering systems are typically designed for low-frequency motions under high loads, and hydraulic pump systems typically have lower duty-cycles, unless specifically designed for RRS. In general, for a natural roll frequency of ω_ϕ:

  Assuming sinusoidal roll, rudder angle correction α must take the form:

$$\alpha(t) = \alpha_{max} \sin\omega_\varphi t \qquad (8)$$

  Taking the derivative:

$$\dot{\alpha}(t) = \omega_\varphi \alpha_{max} \cos\omega_\varphi t \qquad (9)$$

  Thus, the maximum steering gear slew rate must be:

$$\dot{\alpha}_{max} \geqslant \omega_\varphi a_{max} \qquad (10)$$

- Natural roll frequency/damping must be characterized through the speed envelope of the vessel.

Unlike the seakeeping autopilot, use of active roll stabilization systems in a test-basin setting tests the performance of the roll stabilizer controller itself, and as such, care must be taken to appropriately scale the controller properties to predict full-scale performance.

The linearised frequency and time-domain models for rudder-roll systems may be found in Perez (2005). The simplest control system implementation, provided the assumptions above hold true, is to simply add a proportional gain term to the vessel roll rate and sum it with the rudder output of the heading autopilot.

3.4 Tuning Procedure

3.4.1 Forward Speed Controller

The forward speed controller is recommended to be designed as follows:

(1) Perform initial tests to calibrate speed made-good in waves.

(2) If setting rpm manually, run forward speed tests under manual control for each de-

sired speed until calibrated.

(3) If controlling speed automatically, tune speed controller to be as responsive as possible with given slew rates and to be nearly critically damped.

3.4.2 Steering Controller

The steering controller is recommended to be designed as follows:

(1) Identify Nomoto model parameters as outlined in Section 3.2 for each forward speed.

Best-fit the parameters to the linearised Nomoto model using established procedures developed to fit these parameters from zig-zag data. If possible, system identification techniques may be used, reducing the need for 'ideal' zig-zag information.

If a prohibitive number of forward speeds are to be tested - such that determining the Nomoto for each speed is too cumbersome or time consuming - a range of parameters can be estimated including parameters for the minimum and maximum forward speeds, and two or three speeds in between.

(2) Choose, through pole placement techniques, the desired PD or PID tuning for the autopilot.

A different tuning will be utilized for each forward speed to preserve the open-loop characteristics. The following procedure is developed for first-order Nomoto approximations and a PD state feedback control system:

A damping ratio ζ is selected based on the desired response. For each calibrated forward speed KN and TN parameters will be identified, which also define the system bandwidth and natural frequency ω_0. Given these parameters, proportional gain k_P and derivative gain k_D can be calculated using the equations:

$$k_P = \omega_0^2 T_N / K_N \tag{11}$$

$$k_D = \frac{2\zeta\omega_0 T_N - 1}{K_N} \tag{12}$$

Integral gain can be conservatively added if it is deemed necessary to eliminate offset.

The gains calculated using this method provide a useful starting point for tuning steering controllers with minimum influence on seakeeping response.

3.4.3 Track Control

Simple autopilot-based track controllers typically function by providing a heading trajectory signal into the input of the autopilot heading controller. There are numerous methods available to generate a suitable path-tracking trajectory.

Track control is typically implemented in basin seakeeping experiments for the purpose of reducing sway drift-off or 'crabbing' events, i.e., to follow a straight path over ground. When used for seakeeping experiments, care must be taken to ensure that any trajectory fed into the autopilot controller does not alter the dynamics of that controller itself.

A simple straight path tracking control scheme can be seen in Figure 39. In this simple case, an outer PI control loop is used to generate the reference signal for the simple heading autopilot to hold a track (with a global Y setpoint). When tuning this controller, the overall bandwidth of the control scheme must follow the open-loop bandwidth of the vessel. Conservatively tuning the outer PI loop to control with slower dynamics than the autopilot inner-loop will suffice to ensure that the vessel can track without influencing seakeeping.

More complicated track controllers and trajectory-generating schemes are not recom-

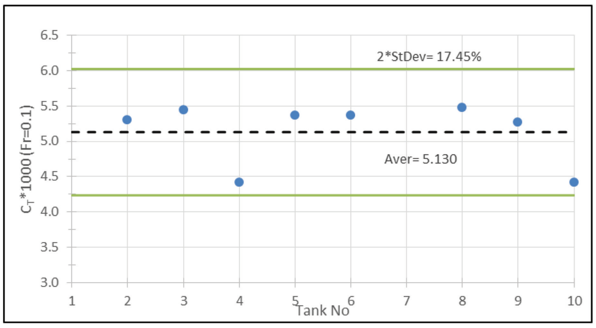


Figure 39 A simple heading autopilot (dashed box) with a simple PI "sway-keeping" outer loop

mended for seakeeping experiments, but may be implemented for other test purposes. Examples of these may be found in 'Handbook of marine craft hydrodynamics and motion control' by Fossen and other references.

3.4.4 Stabilization and Full-scale Controller Modelling

Design choices made in the scaling of lift surfaces and propellers may induce issues when attempting to model full-scale controllers in model-scale. For autopilot control and stabilization control, dynamic response is predicated mainly upon scaling the full-scale moments (and machinery slew rates) appropriately.

Modelling full-scale rudders and fins is a difficult trade-off: modelling them with the appropriate geometry scaling can result in lift curves that vary from that of the full-scale design curves. Modelling them with the correct Froude lift-scaling can result in different sizes and areas, affecting efficiency, resistance, and flow. Whichever design choices are taken to model the lift surfaces, two important aspects must be considered to achieve the appropriate model-scale response:

- Forces (and thus, moments) applied must be appropriately scaled, and,
- Time to generate these forces (generally, 'slew rates') must be scaled.

Care must be taken on the implementation of the second point: it is not sufficient to scale the machinery rates in time if the lift curves are not scaled appropriately. From a control perspective, it is not the lift surface angle that has to be achieved/limited in a span of time (i.e., a machinery slew rate), but rather the lift force (a force slew rate).

This can be achieved through a functional mapping, that is,

Full-Scale Angle → Full-Scale Force → Model-Scale Force→Model-Scale Angle

And,

Full-Scale Slew Rate → Full-Scale Force Rate→Model-Scale Force Rate→Model-Scale Slew Rate

Control gains are also scaled via Froude scaling laws.

4 COLLABORATION

4.1 Joint Workshop on Manoeuvring in Waves

A workshop on Manoeuvring in Waves, jointly organized by the ITTC Manoeuvring, Seakeeping, Stability in Waves, Performance of Ships in Service Committees and the EU SHOPERA project, was be held at Lloyd's Register in London on 14th April 2016. The Seakeeping Committee was present with five members at the workshop and gave a presentation on minimum power requirements for safe manoeuvring in waves and the necessary coupling between the fields of powering, manoeuvring and seakeeping seen from the perspective of seakeeping.

Following the workshop there was a closed debriefing session between representatives of the ITTC Committees that were present. Items discussed included the need of research into propulsion performance in waves and the effects of propeller and engine dynamics and the impact on propulsive efficiency. One of the aspects that still needs further attention is the effect of accurate treatment of the unsteady velocity (speed and power variations) in the horizontal plane, both in experiments and in numerical methods.

There was agreement that seakeeping and manoeuvring should be solved in a coupled manner for the minimum power requirements in waves. Further research should be pursued in this area, possibly leading to new formulations to solve the coupled problem while avoiding overlap between the various hydrodynamic components.

4.2 Third Joint Workshop on Seakeeping

During the previous term, two successful workshops were jointly organised by two committees from the ISSC and two ITTC committees (Seakeeping Committee and Ocean Engineering Committee). The focus of the first workshop was uncertainty modelling for ships and offshore structures. The second workshop considered a benchmark of numerical methods applied to the prediction of motions and loads on a containership that was designed and tested in Korea.

The aim of the Seakeeping Committee is to organize third workshop in Wuxi, as part of the ITTC Conference. The topic of the workshop is still under discussion at the time of writing this report. One option is to perform a numerical benchmark with model tests with an hydroelastic model, which could be a joint effort with the ISSC. Another option is to focus on added resistance and EEDI, in cooperation with other ITTC Committees. For both cases there is a good prospect of available model test data from Korea.

5 ITTC RECOMMENDED PROCEDURES

5.1 ITTC Procedure 7.5-02-07-02.1, Seakeeping Experiments

For the 28th term the Seakeeping Committee was requested to update this procedure with to include tests specific to active stabilisation systems, with particular attention to the modelling of the control system and the prediction of full scale behaviour.

Following this request the existing section on guidance systems was updated information regarding the modelling of control systems in seakeeping experiments. Two separate purposes for modelling control systems in seakeeping experiments were addressed. Firstly, the need to replace the human pilot at model scale in a reliable and repeatable manner. Secondly, the assessment of the efficacy of a full-scale design for a particular control system or set of control surfaces.

An extensive appendix on the theory behind the tuning procedures of control systems was proposed for the procedure to select appropriate parameters for active control systems at model scale. Two cases are included: steering for heading control and roll motion reduction by active fin systems or rudder-roll stabilisation. Tuning procedures examples are included for forward speed control, steering control, and track control. Finally, some background is given on representing full scale motion and stabilisation control on model scale.

Besides the above the procedure was updated with some minor editorial corrections and clarifications.

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

After the update of this procedure in the 27th term, the 28th term Seakeeping Committee found the procedure up-to-date and adequate. Minor revisions were done to the formatting and the language and a number of typographical corrections were made.

The Advisory Council and the Executive Committee recommended the Seakeeping Committee to be aware of the implications of the procedure on the determination of the EEDI it will be distributed to an audience much wider than the ITTC community. In this light, the Seakeeping Committee reviewed the document and advises a restructuring of the procedure to make it better comprehensible for a wider audience as a recommendation for the next ITTC term.

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

After reviewing this procedure it was found that several (up to six) ITTC procedures deal with rarely occurring events from different perspectives. The current procedure deals with slamming, green water, and propeller emergence. Other procedures are dealing with seakeeping experiments in general and with model tests of HSMVs also touch the occurrence and measurement or rarely occurring events. Rarely occurring events such as broaching, bow diving, and capsize are dealt with in a procedure on intact stability.

A clarification was added to the procedure on the usage of the term ‘rarely occurring events’ and a comprehensive overview of the different ITTC procedures dealing with rarely occurring events was included to provide better guidance on the applicability of these procedures to specific problems. Furthermore the document was revised with minor editorial corrections.

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

During the 28th term an extensive revision was made to this procedure. An extensive section on the verification and validation of hydroelastic seakeeping codes was added, including verification and validation of each part of the code: fluid model, structural model, and impact model and the of the coupled response.

The existing section on internal tank effects was revised to include a simple verification case of a single simple cuboid tank and the usage of fresh water for verification cases before moving to more complex cases with the real fluid (e.g. liquefied gas). Finally, a section on V&V on rarely occurring events was added, including slamming events, impact pressures, emergence events, and emergence impacts.

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

This procedure was extended with information and guidelines on using a hydro-structural model with backbone to measure the global wave loads. For such model the hull is made of a soft flexible material with low rigidity, while the backbone is used to model the model the correct flexibility. The advantage is its gapless hull and continuous elastic deformation. Details on the design and fabrication of the model and the backbone were added to the procedure. Furthermore, small editorial changes were made.

5.6 ITTC Procedure on Tests with High Speed Marine Vehicles

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.

For the procedure 7.5-02-05-04 on seakeeping tests some minor modifications were proposed and a reference for benchmark data was added (MARIN Fast Displacement Series in head waves (Kapsenberg, 2012)). It was proposed to update the title in the header of the procedure with a reference to HSMV to avoid confusion. The addition of guidelines on motion control was proposed to be relegated to the next ITTC term, after the addition of motion control to the general seakeeping experiments during the current term.

Procedure 7.5-02-05-06 on structural loads was found to be short in length and detail. As an intermediate step an update was proposed to its introduction to make it more in line with the other HSMV procedures. Also other minor editorial changes were made to clean up the document and some more details were added. In general, a more thorough revision is recommended for the next ITTC term. More details on under which conditions hydroelasticity is important should be added, as well as guidelines on the accurate measurement of the load distribution on segmented models accounting for the model inertia.

Procedure 7.5-02-05-07 on Dynamic instability tests was found to be in need of an extensive revision or even rewrite. At the moment the procedure is aimed at instabilities in calm water such as chine walking and porpoising. The introduction and purpose should included proper definitions and descriptions of dynamic (instable) behaviour of high speed vessels.

The descriptions of experiments to be performed need to be extended, making clear how their results can be used to assess undesired dynamic behaviour. More information should be provided on the test setup to be used and on the mitigation of scale effects, for instance on lifting surfaces, and the overloaded propulsor for free running experiments. Also more details should be added on which captive tests are to be performed and how the results should be combined to describe predict dynamic instabilities with sufficient accuracy.

Based on the above the Seakeeping Committee recommends the installation of a Special Committee for High Speed Marine Vehicles for the 29th ITTC term. This Committee should be tasked with a thorough review and revision of the relevant procedures as well as drafting guidelines for motion control of high speed marine vehicles.

5.7 New Procedure for Determining f_w in the EEDI Formula

Based on the Seakeeping Committee Final Report of the 27th term a new procedure was drafted for determining the speed loss factor in waves (f_w) in the EEDI formula. First, the general definition and application of f_w is discussed in the procedure. This description is fully in accordance with the current IMO Guidelines. Specific wave conditions (wave height about 3 m and wave period (about 6 seconds and ITTC spectrum shape) are taken directly from the IMO Guidelines.

Next, the determination of the added resistance due to waves is discussed. For the different components (calm water resistance, added resistance due to waves and due to wind) in the determination of the f_w factor different approaches exist with increasing complexity and fidelity. A table is included that presents an overview of the possible combinations of methods and a ranking based on fidelity of each approach versus the practicality of each approach.

The main difficulty lies in the accurate prediction of the added resistance in waves. For this four different methods are included, to be separated in experimental methods and computational methods:

- Physical model testing (with reference to the existing ITTC procedures 7.5-02-02-01 and 7.5-02-03-01.4)

- Computational methods
  a. Slender body theory
  b. Three dimensional panel methods
  c. Computational Fluid Mechanics

A second table provides an overview of the details of the different methods and formulations, with reference to the corresponding ITTC procedures.

The simplified method based on standard curves, as proposed in IMO 2012, is included as appendix.

The Specialist Committee for Performance of Ships in Service was requested to review the procedure and a request was made regarding the data collection performed by this Committee that could be used for f_w reference curves.

5.8 New Procedure for Model Scale Sloshing Experiments

A new procedure was developed for model scale sloshing experiments. Different players have been arising in the field of sloshing model experiments, with each their own preferences. Also classification societies have their own procedures, although relative brief. It was therefore a challenge to come up with a common procedure that satisfies the needs of all these actors. The new procedure suggests the overall methodology of model-scale sloshing experiments, the selection of the test conditions, the scaling procedure of the model test results, the physical test setup, data acquisition, and subsequent analysis. Finally, the prediction of design loads is discussed. The new procedure covers the sloshing guidance notes of classification societies, including ABS, BV, DNV, and LR.

5.9 Other Procedures Relevant to Seakeeping

The ITTC procedure 7.5-02-07-04.3 Predicting the Occurrence and Magnitude of Parametric Rolling was reviewed. Based on this review an update to include new mathematical formula and new numerical approaches to predict parametric roll were suggested by the Seakeeping Committee. These comments were forwarded to the Stability in Waves Committee for further consideration.

6 CONCLUSIONS

6.1 General Technical Conclusions

A few new experimental facilities are introduced or are about to be introduced in 2017, including two multi-functional seakeeping basins and a new multiphase wave lab for the simulation of impacts in an enclosed environment where fluid and gas pressure and temperature can be controlled.

There is a growing tendency to include uncertainty evaluations when presenting experimental results of seakeeping tests, as recommended by the ITTC, although the task clearly remains a difficult one. As a result a better insight is obtained into the values for the different uncertainties associated to seakeeping tests and the main sources of uncertainty and their relative importance.

Due to the advances in computational power, time domain methods clearly dominate the development of numerical methods for seakeeping problems over frequency domain methods. Time domain methods are especially relevant in extreme sea states but also in moderate operational conditions for the determination of added resistance. Especially the latter aspect gains more and more importance due to the EEDI regulations. Non-linear methods allow to consider the instantaneous wetted surface of a hull and hence more accurate added resistance predictions.

Further advances are reported regarding the geometric input to numerical models. Several methods that allow for direct CAD import and higher order geometric descriptions are introduced. As the number of available methods increases, it is important to be aware of assumptions, limitations, and applicability. Several interesting comparative studies shed some light on this topic.

For numerical prediction of impacts loads due to slamming and subsequent whipping induced fatigue loads many studies rely on the combination of various methods. The global ship motions are often predicted using potential flow methods, linear or (weakly) nonlinear and in 2D or in 3D. Complex and violent flows during impact are either solved for short time durations during impact using advanced CFD techniques or by focusing on the local impact using CFD techniques or 2D approaches based on the Wagner condition. Comparative studies of slam induced whipping still show significant differences between experimental results and the results of various tools and users. It is suggested that more complex methods are not necessarily leading to better results due to the more elaborated modeling leading to increased uncertainties in the predictions. Often results depend on the experience and skill of the user.

Sloshing has been a critical issue in the design of LNG carrier and LNG FPSO (FLNG). The research has been consistently focused at the prediction of impact pressures inside tanks. Both experimental and numerical studies have been carried out, and many studies were focused on the occurrence of local impact pressure. More sophisticated and nonlinear phenomena have been considered than past studies, including fluid-gas interaction, hydro-elasticity and bubble effects. New techniques for experimental observation using high speed cameras of local sloshing-induced impact occurrence have been introduced, and such observations can help the understanding of local physics in violent sloshing flows. For practical purposes, sloshing analysis should include the structural responses of the cargo containment system. Research into the coupling effects of sloshing and ship motions has also been continued, particularly for the design of FLNG.

A lot of effort has being dedicated to the study of the effects of hydroelasticity on the global loads and fatigue of ships, both experimentally and numerically. Many studies are focused on Ultra Large Container Ships (ULCS) as due to their dimensions the resonant frequencies of the structure are so low as to be near the wave exciting frequencies. The WILS JIP and TULCS cooperative efforts advanced the knowledge of hydroelastic solutions by improving and developing experimental techniques, benchmark data and effective numerical solutions. The improved benchmark data, improved numerical methods, and improved computational power have led to the development of various advanced approaches to create hydroelastic solutions for large ships in waves. All higher fidelity methods involve some level of coupling between the ship structural and hydrodynamic solutions. Interest in providing full-scale hydroelastic data for large containership has resulted in the availability of useful trial data.

The topic of added resistance in waves and the determination of the corresponding power increase have continued to be of high interest to naval architects and ship yards alike. In 2012 the IMO's regulations regarding the Energy Efficiency Design Index (EEDI) came into force. As a result topics such as determining the ' weather factor' f_w or the minimum power required to maintain the manoeuvrability of a ship in adverse conditions are of high interest to the community. Improving hull forms in order to minimise added resistance in waves is of significant current interest to the industry in general and ship yards in particular. A large number of both, numerical as well as experimental investigations were carried out in this field and have led to the development of special, mostly vertical stem, bow shapes and a clear trend away from the classical bulbous bow.

As computational resources continue to increase, 3D panel methods continue to slowly replace slender-body theory as the method of choice for seakeeping analysis. Although potential flow theory is still the most common way to predict added resistance, viscous flow simulations, particularly Reynolds-Averaged Navier-Stokes Equations (RANSE) solvers get more common. Compared to potential flow methods RANSE solvers are computationally very expensive, especially for short waves. They however allow studying the complete physics of added resistance in waves including large amplitude motions, non-linear effects and, of course the, effect of viscosity. Because of their computational costs the application of viscous flow methods is still mostly confined to research projects.

Besides the accurate prediction of added resistance in waves based using numerical methods, also the measurement of added resistance is remains an important topic. Added resistance is obtained by measuring the small difference between two large quantities (calm water resistance and mean resistance in waves) and therefore the uncertainties are large. Several initiatives are undertaken to improve test setups to accurately evaluate the speed-power performance during seakeeping model tests, proposing ways to deal with the scale effect in the viscous resistance and the influence of the engine characteristics on model scale.

CFD methods continue to be more widely applied in the field of seakeeping, helped by advances in computational power, becoming more and more accessible for engineering purposes. It is valuable for those problems with strong nonlinear characteristics and where viscosity plays a considerable role. CFD methods are now applied to a wide array of seakeeping problems, including added resistance, roll damping, parametric roll, and to violent and complex flows such as sloshing, water entry and slamming and green water. The capability of CFD to deal with free running vessels in waves has been developed rapidly over the last few years, opening up the possibility of applying CFD to the complex problem of a ship manoeuvring in waves. For the most part grid based methods are used for seakeeping applications, however particle method show promising results for cases were local highly nonlinear and violent flows are important, such as the severe shipping of green water.

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.

No revision/modification for the existing procedures for high-speed vehicles, Nos. 7.5-02-05-04, 7.5-02-05-06, and 7.5-02-05-07; due to the extensive work needed, this is recommended as future work for a special committee.

Adopt the new procedure for the determination of speed reduction coefficient f_w in the EEDI formula

Adopt the new procedure for model scale sloshing experiments.

6.3 Proposals For Future Work

Survey of New Test Facilities. During the next ITTC term many new experimental facilities will be opened at different institutions over the world. Therefore to provide the community with a good overview of these new facilities, a comprehensive survey should be carried out to appropriately describe and characterize these new facilities in the final report of the 29th term Seakeeping Committee.

Procedure Updates. Update the procedure No. 7.5-02-07-02.1 Seakeeping Experiments to be more specific regarding the suggested conditions to be tested. For instance the currently recommended regular wave lengths to be tested might not be relevant for all ship types and sizes. Also, regarding the issues surrounding the EEDI and the f_w-factor, more attention should be spend on the accurate measurement of added resistance in waves in this procedure.

Because of the importance of the EEDI related issues like the f_w-factor and the minimum power requirement in adverse weather conditions the related procedure No. 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.

Update/revise the procedure No. 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. The procedure should address the statistical characteristics of these maxima, estimates of the extreme values, and the associated uncertainty.

High-Speed Marine Vehicles. After re-viewing the procedures for High Speed Marine Vehicles the Seakeeping Committee feels that major revisions are necessary for the related procedures. Following feedback received from the AC/EC, the committee therefore proposes to install a Special Committee for High Speed Marine Vehicles for the 29th ITTC term. This Special Committee should perform a comprehensive review and revision of related procedures and draft a procedure for motion control of HSMV.

Collaboration for Ship Stability. Parametric roll is covered by the IMO 2nd Generation Intact Stability Criteria currently under development and has received much attention recently. Parametric roll is a complex nonlinear problem that combines aspects both from Seakeeping and from Stability. Therefore the Seakeeping Committee should cooperate with Stability in Waves Committee on this topic and the related procedures in the 29th ITTC term.

Collection of Benchmark Data. It is recommended to survey and/or collect benchmark data for seakeeping problems, particularly for ship structural hydroelasticity in waves and added resistance. To this end, it is recommended to collaborate/liaise with ISSC committees and other ITTC committees related to these topics, for instance by organizing joint activities such as benchmark workshops.

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