26th International Towing Tank Conference
Rio de Janeiro, Brazil, 28 August - 3 September, 2011


# The Seakeeping Committee

Final report and recommendations to the 26th ITTC

## 1. GENERAL

### 1.1 Membership and meetings

The Committee appointed by the 25th ITTC consisted of the following members:

- Mr. Paul Crossland (Chairman), QinetiQ Ltd, Gosport, United Kingdom
- Mr. Dariusz Fathi (Secretary), Norwegian Marine Technology Research Institute (MARINTEK), Trondheim, Norway
- Mr. Dan Hayden, Naval Surface Warfare Center, West Bethesda, USA
- Mr. Greg Hermanski, Institute for Ocean Technology, St. John's, Canada
- Prof. Yonghwan Kim, Seoul National University, Korea
- Dr. J. A. Keuning, Delft University of Technology, The Netherlands
- Dr. Rumen Kishev, Bulgarian Ship Hydrodynamics Centre, Varna, Bulgaria
- Dr. Koichiro Matsumoto, Universal Shipbuilding Corporation, Kawasaki, Japan
- Dr. Quanming Miao, China Ship Scientific Research Center, Wuxi, China

Four committee meetings were held at:

- Delft University of Technology, The Netherlands, January 2009
- China Ship Scientific Research Center, Wuxi, China, October 2009
- Institute for Ocean Technology, St. John's, Canada, May 2010
- QinetiQ Ltd, Gosport, United Kingdom, February 2011

In addition, a workshop on validation and verification of non-linear seakeeping codes was organized in Seoul, October 2010 and a joint ISSC ITTC meeting was held in Portsmouth in November 2010.

### 1.2 Recommendations of the 26th ITTC

The list of tasks recommended by the 25th ITTC was as follows:

1. Update the state-of-the-art for predicting the behaviour of ships in waves emphasising developments since the 2008 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 predictions and scaling,
   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 procedures for uncertainty analysis).

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 content of these.
c. With the support of the Specialist Committee on Uncertainty Analysis review, and if necessary amend, the uncertainty analysis included in Procedure 7.5-02-07-02.1, "Seakeeping Experiments" to bring it into line with the ISO approach adopted by the ITTC.
d. Assess whether Recommended Procedure 4.2.4-01, "Standard Format for Exchange of Seakeeping Data on Computer-Compatible Media" shall be retained.

3. Write new procedure on the prediction of global wave loads. The procedure shall describe the design of the experiment, the set-up of the model and instrumentation, the test and the analysis.

4. Review methods used to predict power increase in waves from model tests. The methods considered should include both those based on experiments in regular waves and in irregular waves. Write a section of the committee report describing the alternative methods, and identifying those that are best current practice. Write a new procedure for the prediction of power increase in waves from model tests.

5. The new procedure should include the direct irregular wave method and relevant material from procedure 7.5-02-07-02.2 "Prediction of Power Increase in Regular Waves from Experiments in Regular Waves. Procedure 7.5-02-07-02.2 will be deleted at the conclusion of this task.

6. Organize a workshop on validation and verification of non-linear seakeeping codes, and select or develop a benchmark case for this Workshop. The results of the Workshop will be used to develop the procedure on validation and verification of non-linear seakeeping computer codes.

7. Liaise with the ISSC and the Ocean Engineering Committee.

## 1.3 Cooperation with the ISSC

The importance of cooperation with the International Ship and Offshore Structure Congress organisation was acknowledged during the 25th ITTC with the Seakeeping Committee participating in a Joint meeting at the National Technical University of Athens in 2007. This meeting underlined the importance and benefits of further cooperation between the two international committees. There was a clear overlap in both committees' mandates and available expertise such that both organisations could benefit from further cooperation. One of the tasks of the 26th Seakeeping Committee was to develop further the relationship with the pertinent ISSC committees.

A Joint meeting was hosted by Lloyd's Register in Portsmouth in November 2010 to discuss potential ISSC/ITTC opportunities for further collaboration in the future. This one day meeting, held in conjunction with the RINA William Froude Conference, was attended by members of the ITTC Seakeeping and Ocean Engineering Committees and the ISSC Loads & Responses and Environment Committees.

The extent of the cooperation between the two organisations could be at various levels:

Simple exchange of reports and reference lists – This would require a low level of cooperation based mainly on the dissemination of work from the individual committees.

Scheduled joint meetings – The 25th ITTC Seakeeping Committee proposed that the second (or 3rd) ITTC meeting and the first ISSC meeting of their respective committees become permanently scheduled as a joint committee meeting; this continued during the 26th ITTC.

Review of reports and procedures – This would required a higher level of interaction possibly mandating the task of undertaking the review by the committee .

Joint workshop – Jointly organise a workshop relating to a topic of interest to both conferences would require a higher level of commitment mainly on the local organising committee.

Joint projects – The development of a suitable joint project, that has to take account of the fact that the ITTC and ISSC are out of phase with each other by about a year, would require the highest level of commitment from both organisations over and above the respective committees normal business. Specific items would need to be mandated in committees' task and planned to account for the phase shift in conference periods.

A joint project was seen as requiring a level of cooperation that would significantly increase the workload on the committees which does not represent a feasible way forward. It was decided that the most appropriate level of cooperation at this point in time would be the joint organisation/sponsorship of a workshop. Therefore it is recommended that the next ITTC Seakeeping Committee participate in a joint workshop, based on uncertainty in the measurement and prediction of wave loads and responses, to be held around September 2012.

In addition to the joint workshop, the chair of the ISSC Loads & Responses committee agreed to review the Global Loads procedure in support of a task of the Seakeeping Committee. The Chair of the ISSC Environment agreed to distribute papers relating to uncertainties & application of reliability methods in a decision support system (Bitner-Gregersen and Skjong, 2009) and one relating to uncertainty modelling for load prediction (Bitner-Gregersen *et al.*, 2002).

Finally, it is recommended that to help future collaboration prosper some form of continuity amongst the two committees should be ensured by encouraging common membership, where practicable, and having common members to improve liaison between the two organisations.

## 2. REVIEW OF STATE-OF-THE-ART

### 2.1 Developments in experimental and analytical techniques

Waves. Imperfections of waves generated in model experimental facilities are recognized as one of more significant contributor to experimental uncertainty. New developments in wave theories, calibration and generation techniques aim to mitigate facilities limitations.

Masterton and Swan (2008) describe the calibration procedure adopted for the new 3D wave basin located in the Hydrodynamics Laboratory at Imperial College London. Unlike traditional calibrations, based on observations of regular wave trains, the method used a focused wave approach. Such waves, produced by the constructive interference of freely propagating wave components, have led to a number of recent advances in theoretical wave modelling in which it was essential to know the underlying linear components. The study provided a calibration based upon a realistic JONSWAP spectrum, described the details of the methodology employed, and highlighted how the application of focused wave techniques eliminated spurious calibration effects due to unwanted reflections from the boundaries of the basin.

Spinneken and Swan (2009) provide an experimental verification of the new second-order wave maker theory for regular wave generation. This theory concerns the generation of regular waves by a flap-type wave maker using force-feedback control. When the wave maker is controlled by a first-order force command signal; comparisons between the theory and experimental observations confirm two key points: (i) the first-order behaviour is crucial for the absorption characteristics of the machine, (ii) the second-order behaviour leads to a spurious, or unwanted, freely propagating second harmonic that is substantially smaller in amplitude when compared to an identical wave paddle operating with first-order position control.

Irregular deep-water sea states generated in a tank and represented by a JONSWAP spectrum have been investigated by Petrova and Guedes Soares (2008) with respect to the statistics of the largest waves. Linear and second order statistical models were applied to fit the crests and heights of the maximum observed waves. Special attention has been given to the extreme waves. Statistically, the non-Gaussian behaviour of the considered wave fields has been demonstrated by means of the coefficients of skewness and kurtosis estimated from the time series. Moreover, analytical formulae taking into account the effects of spectral bandwidth and finite depth have been applied to improve the predictions of the normalized cumulants. The laboratory results are compared with results for full-scale data gathered during a storm at the North Alwyn platform in the North Sea.

Petrova and Guedes Soares (2009) presented a study to assess the adequacy of describing bimodal sea states of different non-linear probability distributions that have been developed for single sea states. The measurements represent three bimodal sea states with individual unidirectional wave systems propagating at 60, 90 and 120 from each other.

An approach for modelling multi-peaked directional wave spectra was proposed by Boukhanovsky and Guedes Soares (2009). For model identification, a numerical optimization technique that uses the random linear search algorithm is applied. This technique allows the fitting of spectral models to measured or hindcast data. The HIPOCAS hindcast data for North Atlantic was used in this study.

Clauss (2008) proposed a technique to generate a sequence of waves for the simulation of extreme seas. The generation procedure is based on two steps and permits the deterministic generation of design rogue wave sequences in extreme seas; it is well suited for investigating the mechanism of arbitrary wave-structure interactions, including capsizing, slamming, and green water as well as other survivability design aspects. Even worst case wave sequences, such as the Draupner New Year wave, can be modelled in the wave tank to analyze the evolution of these events and to evaluate the response of offshore structures under abnormal conditions.

One of the key parameters for ship design to ensure safe operations is the vertical wave bending moment. Previous investigations revealed that longitudinal forces significantly influence the vertical wave bending moment. As the overall effect of longitudinal forces is still not fully understood, further efforts to investigate structural loads in detail by model tests, especially in extreme seas, are required. Clauss, et al. (2009), within the framework of the project ”Handling Waves”, funded by the European Union, systematically investigate three ships in various deterministic sea states at several cruising speeds. The tests are carried out with a bulk carrier, a container vessel and a Ro/Ro vessel covering head as well as following seas. The ships are segmented and connected with strain gauges to detect the vertical wave bending moments as well as the superimposed longitudinal forces. Frequency and time domain results are discussed and compared to numerical calculations.

Development of numerical facilities and techniques aims at improving experimental and computation efficiency and confidence in results. Malekmohamadia *et al.* (2008) proposed a new procedure for coupling a numerical wave model (NWM) and artificial neural networks (ANNs) for wave prediction applied to hindcasting. The ANN model is capable of mapping wind-velocity time series to wave height and period time series with low cost and acceptable accuracy.

Mousaviraad *et al.* (2010) present a procedure for obtaining a RAO from a single calculation. The procedure is compared with regular wave and transient wave group procedures, using an unsteady RANS solver. In the procedure incoming waves are generated by linear superposition using a number of component waves. The regular wave approach requires multiple runs, whereas a single run procedure obtains the response amplitude operators (RAO) for a range of frequencies at a fixed speed, assuming linear ship response.

Model Tests. Even though potential flow and CFD based codes are becoming more reliable when predicting responses and loads on conventional hull geometries, model experiments are still indispensable for predictions involving unusual or modern forms and unconventional applications as well as validation of numerical codes.

Roused *et al.* (2010) focused on experiments performed on a rigid segmented model in irregular, unidirectional and bi-directional waves, without forward speed. The study of these different configurations was performed through the comparison of several parameters including occurrence and location of slamming events, ship motions and global loads.

Chiu *et al.* (2009) carried out a study on the nonlinear hull surface pressure of a high-speed vessel in irregular waves. The authors were particularly interested in the pressure responses of alternately wet and dry areas near the water line and near the bow zone. The vessel had high deadrise angles that may be subject to slight impact and water pile-up effects. A series of experiments in regular and irregular head waves were conducted, and the validity of applying Volterra modelling was investigated.

Experiments to evaluate the performance of a submarine operating on surface was undertaken by Hermanski and Kim (2010). The paper emphasised seakeeping responses and discussed the importance of modelling the free flow under the casing on the roll response. The authors presented a description of the model, roll, pitch and heave responses, roll decay results and uncertainty in measured data. All of the model information and results meet ITTC requirements for benchmark data.

The prospect of an increase in natural gas production and the shipping of its large quantities from environmentally sensitive areas to commercial processing centres demands high safety standards for LNG carrier design. This demand results in emergence of new experimental facilities and R&D projects investigating sloshing phenomena and its effects on ship responses and vice versa.

Understanding of local behaviour of sloshing is essential for the design of LNG containment systems. Yung *et al.* (2009) considered the fundamental aspects of sloshing from first principles to identify relevant dimensionless numbers necessary for dynamic similarity of scaled model tests involving local pressures.

The pressure statistics obtained from model experiments have to be scaled to derive full scale design loads. The approach for scaling is not obvious as multi-phase physics occur within the impacts. The study presented by Kimmoun *et al.* (2010) is an attempt to show evidence of so-called compressibility bias of modelling sloshing. In order to have a direct deterministic comparison of Froude-similar liquid impacts on a wall, the study deals with single breaking waves in a laboratory wave canal at two different scales. In conclusions the study describes how a relatively good similarity between flows at the two scales is obtained.

A series of experiments have been carried out by Panigrahy *et al.* (2009) to estimate the pressure developed on the tank walls and the free surface displacement of water from the mean static level due to liquid sloshing in a tank on a shaking table. Maillard and Brosset (2009) investigated the influence of density ratio in sloshing (water and gas), including theoretical, numerical and experimental studies. The authors advise that the sloshing model tests should be performed with water and a mixture of Sulphur hexafluoride ($SF_6$) and nitrogen (N2). Similar findings are reported by Braeunig *et al* (2009, 2010) based on parametric study using numerical simulations. The authors report that the impact pressures can be strictly derived at full scale from model scale values using Froude scaling by adopting model tests with water and a mixture of Sulfur Hexafluoride (SF6) and Nitrogen (N2) in the right proportion. To address, the complex situation of phase transitions between the liquid and its vapour in thermo-dynamical equilibrium along the phase boundary they analysed different thermal boundary conditions and different scales through a simple 1D semi-analytical model of gas pocket compression. In order to have a direct deterministic comparison of Froude-similar liquid impacts on a wall at two different scales, Jeon *et al.* (2008) used 1/25, 1/50, and 1/100 scale models of a 138K LNGC tank to study scale dependency on fluid sloshing loads.

Kim *et al.* (2009d) investigated the hydrodynamic impact on two dimensional models by experimental method with models of 1/25 scale longitudinal and transverse models 138K LNGC tank excited by longitudinal mode motion.

<u>Experiment and Simulation.</u> Combined applications of numerical and experimental tools to investigate various hydrodynamic phenomena provide a practical and economic alternative when studying new concepts, evaluating performance or developing typical designs.

Jang *et al* (2010) identified the functional form nonlinear roll damping for a particular ship from experiments. The problem of damping identification is formulated as an integral equation of the first kind. However, the solution of the problem lacks stability properties, due to the ill-posedness of the first-kind integral equation. To resolve this problem, a stabilization technique (known as a regularization method) is applied to the present problem of the identification of nonlinear damping. The identified results for nonlinear roll damping are compared with those from a conventional roll identification method.

Broglia *et al.* (2009) and Atsavapranee *et al.* (2008) report on a joint US/Italian project investigating, experimentally and numerically, the free roll decay of the Italian Patrol Boat Nave Bettica. Both sea trials and model scale tests have been undertaken; numerical analysis has been performed by means of unsteady RANS simulations. Full scale measurements including PIV were presented.

The combination of numerical and experimental methods found also application to investigate sloshing phenomena.

Huang *et al.* (2009) investigate loads induced by liquid flow in cargo tanks and their coupling with LNG Carrier (LNGC) motions. The seakeeping tests and numerical predictions confirmed that even though sloshing impact pressures are nonlinear and stochastic, global tank loads and LNGC motions are deterministic. Moirod *et al.* (2010) present experimental and numerical investigations on global forces exerted by fluid motions on LNGC prismatic tanks that lead to improving the prediction of the dynamic seakeeping/sloshing coupling. Delorme *et al.* (2009) investigated impact pressures in shallow water sloshing during forced roll motion both experimentally and numerically. Experimental results are compared with numerical data obtained using SPH. Tabri *et al.* (2009)

investigated experimentally and numerically sloshing interaction during ship collision. They found that sloshing affects the collision dynamics and reduces the amount of energy that may cause structural deformation.

Free liquid surfaces inside the cargo tanks of seagoing ships not only reduce the initial stability but also influence the seakeeping characteristics, in particular roll motions. Clauss *et al.* (2010b) analysed a 138,000-m3 LNG carrier using potential theory based software that was validated by experiments.

Ryu *et al.* (2009) presented model tests and a numerical study on the assessment of sloshing loads in floating LNG designs, LNG FPSO and LNG FSRU. The authors discuss the pros and cons of two systems regarding the structural safety of the tank subjected to sloshing loads under partially filled conditions, hull strength against topside module weight, onboard maintenance availability, accumulated experiences with proven technologies and construction costs.

<u>Full-scale</u>. Sea trials are believed to provide most reliable and realistic data with respect to ship behaviour in various environments. Even though the value of the data is unquestionable, there are some uncertainties that are relevant to data collection that need to be considered when results are examined. Lack of control over the ocean environment, for example, create uncertainty in defining the sea parameters.

Pascoal and Guedes Soares (2009) proposed a fast iterative procedure for estimating the ocean wave directional spectrum from vessel motion data. It used, as input data, the measurements from motion sensors that are commonly available on vessels with dynamic positioning or which may easily be installed on any ship. The procedure presents an ideal solution for providing offline estimation of sea conditions and sea spectral updates under quickly changing weather conditions. A Kalman filtering algorithm for iterative harmonic detection, and frequency domain vessel response data are used in the estimation procedure.

Nielsen and Iseki (2010) deal with the estimation of sea state parameters on the basis of time histories of ship responses. The outcome of this Bayesian estimation concept is controlled by a set of hyper-parameters, which theoretically must be optimised to provide the optimum solution in terms of sea state parameters.

An increasing number of ships are now equipped with monitoring systems that provide a source of information that can be used studies of ship hull responses in actual sea conditions.

Lee *et al.* (2010d) presented the results from a Hull Stress Monitoring System (HSMS) installed on a container carrier for recording hull girder loads. Vibratory responses of the hull girder were recorded during certain conditions, such as in the limited fetch storm waves in the Mediterranean Sea.

Remote and advanced measurements of wave parameters will allow for better understanding of actual ship responses and more realistic simulation-prediction of future responses and avoidance of projected extreme environments. Lyzenga and Nwogu (2010) discussed methods of estimating phase-resolved wave fields and wave spectra from shipboard radar measurements, and presented results from two field experiments.

Developments in remote offshore natural gas fields and its transportation to distribution centres causes increased interest in sloshing impact loads phenomena. Data obtained from full-scale trials are important not only to ship designers but also to code developers and experimentalists alike. Kaminski and Bogaert (2009, 2010) describe full scale experiments on a real membrane containment system subjected to action of breaking waves representative of sloshing impacts in LNG tanks. The waves were generated in a water flume using a wave focusing method. The authors discuss steps undertaken to improve the test repeatability, analysis of data to investigate scaling laws, hydro structural interaction and effects of membrane corrugations that are characteristic for the Mark III membrane systems .

Repalle *et al.* (2010) investigated the initial location of impact pressures and its topological features from full-scale trials. The paper investigates the pressure distribution on the sidewall of an oscillating tank with a low fill level, the velocity and direction of the impact along the vertical wall and how the pressure intensity varied during impact.

## 2.2 New facilities

There were several new facilities developed during the last three years. As the demand for deep sea test is getting larger, some facilities have been constructed or are under construction, particularly in China. Also a large sloshing facility has been developed in South Korea and this facility is still expanding. In this report, four new or upgraded facilities are introduced.

Deepwater Offshore Basin at Shanghai Jiao Tong University. Shanghai Jiao Tong University (SJTU) in China recently opened a large deep offshore basin in their new campus (2008). This basin is 50m long, 40m wide, with a maximum water depth of 10m. A large area of the tank floor is movable, so it allows modelling of water depths from 0-10m. This basin also has a 40m deep pit allowing the modelling of water depths up to 4000m for vertically moored structures at 1/100 scale.

A secondary movable floor in the deep pit also allows intermediate water depth to be considered. A current recirculation system around the basin can be applied to generate adjustable vertical current velocity profiles over the complete water depth of 10m. Also a 222 multi-flapped wavemaker is installed covering two sides of the basin with wave absorbing beaches on opposing sides. Multi-directional long-crested and short-crested waves with significant wave heights up to 0.3m and wave periods of 0.3~3.0s can be generated.

Wind spectrum can be generated by a system of axial fans; by adjusting the position of the system, wind in any direction can be produced.

Pistani *et al.* (2010) introduces a new laboratory at the University of Western Australia that has been equipped for sloshing experiments inside tanks. This paper reports on challenges that were faced during the set-up and operation and suitable solutions that were adopted.

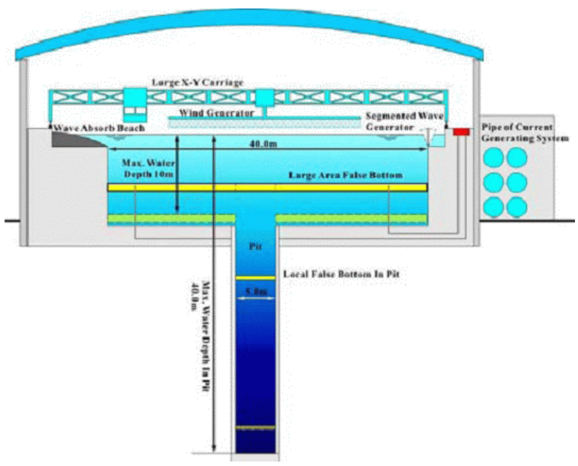



Figure 1 Sectional view of the deepwater offshore basin in SJTU.

Sloshing Test Facility at Seoul National University. A sloshing test facility has been introduced by Seoul National University (SNU) in Korea. The project for this new facility is not completed as yet, but two platforms have already been equipped and used for research. Operation of the 1.5 tonne and 5 tonne capacity excitation platforms is underway, and a very large 10 tonne platform is under construction.

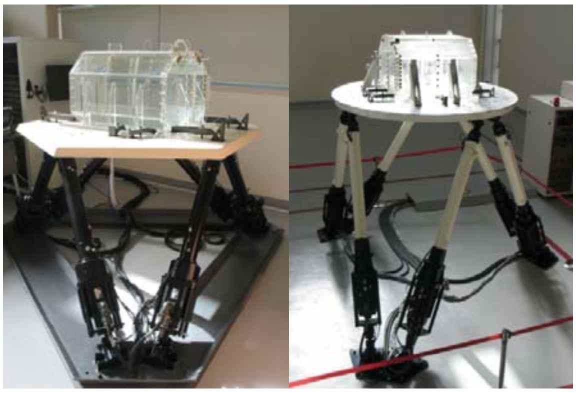


Figure 2 Two hexapod-type excitation beds at SNU (1.5tonne machine: left, 5-tonne machine: right).

Table 1 Capacity of the 6DOF motion platforms at SNU

| | 5-tonne platform | | 1.5-tonne platform | |
|---|---|---|---|---|
| | Disp. (mm, deg) | Vel. (mm/s, g/s) | Disp. (mm, deg) | Vel. (mm/s, g/s) |
| Surge | 1030 | 2000 | 340 | 1000 |
| Sway | 980 | 1900 | 320 | 900 |
| Heave | 540 | 1000 | 240 | 650 |
| Roll | 35.0 | 83.0 | 26.0 | 70.0 |
| Pitch | 35.0 | 83.0 | 25.5 | 70.0 |
| Yaw | 65.0 | 170.0 | 34.0 | 90.0 |
| Maximum load (kgf) | 5,000 | | 1,500 | |

The Upgraded Wavemaker at the Bulgarian Ship Hydrodynamics Centre. The existing wavemaker in the Seakeeping-manoeuvring tank at the Bulgarian Ship Hydrodynamics Centre (BSHC) has been modernized by equipping a new power driven system (Rakitin V. *et al.*, 2010). A wave generating system has been developed based on AC servomotors and ball-screw pairs.

The upgraded wavemaker has the following main technical characteristics:

- Overall length: 39.840 m
- Length of each plate: 9.960 m
- Height of the plate: 3.1 m
- Depth of immersion of the plate: 2.5 m
- Inclination angle from vertical position: ± 11.5°

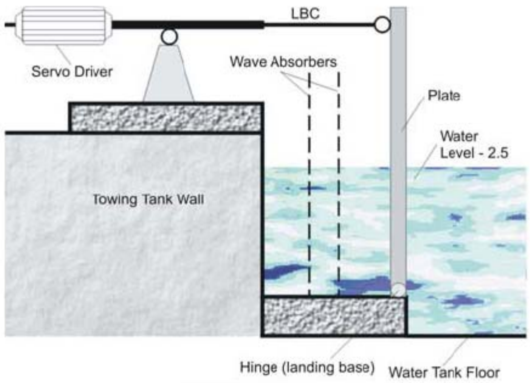



Figure 3 Mechanical system of the wave maker in BSHC.

Ocean Basin at Harbin Engineering University. Harbin Engineering University (HEU) opened their new ocean basin in 2009. The main dimension of this basin is 50m x 30m and 10m deep. This basin can generate only a local current at this moment, but HEU intend to upgrade in the future. The maximum speed of the main carriage 3 m/s (with a sub-carriage capable of 2m/s).

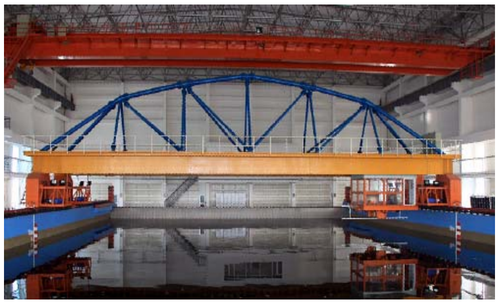


Figure 4 Deepwater tank at Harbin Engineering University.

### 2.3 Developments in theory and validation

Frequency Domain (Motions and Loads). Time domain seakeeping simulations have advanced to an extent that frequency based seakeeping and loads simulations are performed less routinely. However, frequency domain approaches still provide a quicker, but accurate solution which can be utilized in early ship design. The frequency based solution is advantageous to evaluate hydrodynamic and structural concerns involving natural frequency and modal problems. With respect to multi-body problems the frequency domain provides a much less intensive approach to assess interactions. While most sloshing problems are aided by the time domain to evaluate peak velocities and loads, the frequency domain allows a way of looking at effects on the ships frequency response as a result of sloshing interaction.

Elangovan (2009) used a Rankine panel method (RPM) to calculate seakeeping qualities including forward speed effects. Calculations of forces and motions on a Wigley hull form for Fn= 0.2 and 0.4 are compared with experiments.

Frequency domain transfer functions obtained using a strip theory method, and viscous roll damping corrections for different advance speeds are utilized in a design comparison by Ribeiro e Silva, *et al.* (2009). This was performed for six different fishing vessels operating in coastal areas. The most relevant performance criteria related to the absolute motions, relative motions, accelerations, slamming, green water on deck, etc., is introduced to evaluate the seakeeping performance and define limiting sea state operability.

Lewandowski (2008) uses frequency domain, traditional two dimensional (2D) and three-dimensional (3D) boundary element methods to study two vessels in close proximity. Added mass, damping, and the behaviour of the free surface between the vessels are examined in some detail. At ‘‘critical frequencies’’ corresponding to standing waves between the hulls, the hydrodynamic forces undergo significant changes.

Two ships operating in close proximity in shallow rough seas has been shown to be quite different in comparison to the deep-water situation. Li (2009) studied the characteristics of two-ship interactions in deep water and in shallow water in a heavy storm to demonstrate the differences. The deep water and shallow water rough seas irregularity have been considered by using the TMA spectrum which combines JONSWAP spectrum with the shallow water and deep water effect transformation factors.

A linearized radiation and diffraction problem of a floating body in two-layer fluids was calculated by the Numerical Wave Tank (NWT) technique in the frequency domain by Koo and Kim (2010). In two-layer fluids, two different wave modes exist and wave induced body motions should be computed separately for each mode. In this study, two-domain Boundary Element Method (BEM) in the potential fluid using a whole-domain matrix scheme was used to calculate floating body motions in both wave modes.

The use of frequency domain is particularly suited for understanding fluid-structure interaction issues. With respect to the representation of the hull as a beam, frequency domain analysis allows for easy correlation with vibration, springing, and modes of deflection. Coppotelli *et al.* (2008) used correlation between modal accelerations on an elastic model segmented to back estimate the model loading. These accelerations in turn can be used for full scale onboard structural monitoring and fatigue-life prediction. A procedure for the prediction of extreme wave induced hull girder loads on a containership including slamming and green water effects is outlined by Jensen *et al.* (2008). The combined wave frequency loads and high frequency transient loads are obtained from a simplified solution and are presented in a closed-format equation. The estimate of wave frequency bending moment and shear forces is obtained from frequency domain based quadratic strip theory. The lower modes of hull vibrations are obtained by modelling the hull as a single non-uniform using Timoshenko formulation.

Malenica, *et al.* (2010) performed seakeeping calculations within the potential flow assumptions, using the Boundary Integral

Equation (BIE) techniques. Within this approach, the fluid flow was represented by a distribution of singularities over the 3D wetted part of the body The hydrodynamic model includes not only the parts modelled by the panels but also some slender elements (bracings) which are usually modelled using the Morison formula. Morison formula uses the information of the undisturbed fluid flow at the position of element and applies explicit expressions which give the drag force and the added inertia forces. Chen and Malenica (2010) further advance these efforts with the implementation of the supplemented boundary integral equation method to remove irregular frequencies, and the analytical integration of the wave terms in the Green function over a flat panel to ensure the numerical precision at high wave encounter frequencies. The hydro-structural interface is realized by re-computing the hydrodynamic pressures at points of structural model and the hydrodynamic coefficients (added mass and radiation damping) and wave excitation loads are computed following each mode of structural model.

<u>Time-Domain Analysis of Motion and Loads.</u> Time-domain methods are becoming more popular for seakeeping analysis. Time-domain approaches have some advantages in the extension to the analysis of nonlinear motion and structural loads, and coupling with external or internal forces. Time-domain formulations for seakeeping problems have been introduced by some pioneering researchers such as Cummins (1962) and Liapis and Beck (1985). After the successful release of SWAN (Nakos, 1990, Kring and Sclavounos, 1995) and LAMP (Lin and Yue, 1990, Lin *et al.*, 1994), time-domain codes are fast replacing frequency-domain for many problems.

The current time-domain approaches can be divided into several categories based on their respective methodology as shown in Table 2, including the advantages and disadvantages of each method.

At this moment, two methods seem to take a lead in terms of practical applications. Those are the strip-based time-domain and Rankine panel methods. The former is relatively simple and easy to be developed by extending strip-based frequency-domain codes to the time domain; the latter is more sophisticated and needs more effort to develop the code. Furthermore, 3D geometry handling, i.e. panelization on the ship hull and free surface, is not a simple task. However, as the success of LAMP and SWAN shows, Rankine panel methods offer a practicable solution in some engineering applications.

Mikami and Kashiwagi (2009) applied a time-domain strip method for ship motions including structural flexibility, and Sun and Faltinsen (2010) used a time-domain approach based on a 2D+t theory for planing vessels, which is an extension of the sectional approach. Kim and Kim (2009) introduced the application of a Rankine panel method for the weak-scatterer hypothesis and the computational results for large amplitude ship motions; the same Rankine panel method (WISH) has been applied by Song *et al.* (2010b) for the computational of structural loads by using weakly nonlinear method. Dai and Wu (2008) applied a combined method which was based on a Rankine panel method for the near-field and transient Green function method for the far-field. Also Liu and Papanikolaou (2009) introduced a time-domain method, combined with a Rankine panel method and a wave Green function method.

In time-domain approaches that use Rankine panel methods and CFD methods, the computational efficiency is one of crucial factors in its application. Some effort to increase the efficiency of time-domain simulations has been introduced by Nwogu and Beck (2010) using an FFT accelerated panel method.

It is recognised that many of the time domain methods can be used to evaluate ship stability in waves. So, whilst a detailed state-of-the-art review of dynamic stability problems

Table 2 Computational methodology for time-domain approaches

| Numerical Method | Advantage | Disadvantage | CPU capacity and time |
|---|---|---|---|
| Impulse-Response-Function approach | Easy to implement, fast computation require small computer memory | Need pre-computed hydrodynamics coefficients Limited applicability | Minimal |
| Strip/sectional-based approach | 2D BVP Fast computation require small computer memory | Limitation as 2D sectional method Poor accuracy in low frequency | Minimal |
| Transient wave Green function approach | Radiation condition is automatically satisfied. Panel distribution on only body surface | Hard to compute Green function for non-zero speed Limited application | Moderate |
| Rankine panel method | Good practicality Easy extension to nonlinear analysis Good overall accuracy | Difficulty in 3D geometric modelling and panel generation Need a numerical method for radiation condition | Moderate |
| CFD method solving field equation(s) | Capability for violent ship motion Can include viscous effects | Huge computational time and effort Poor accuracy in memory flow | Heavy |
| Hybrid method combing two methods | Taking advantages of combined method | No benefits in many combinations Additional effort for combinations | (Varying) |

such as parametric rolling, broaching, surf-riding, and capsizing is outside the scope of this Committee, it is worth reporting some examples of using seakeeping tools for dynamic stability. For instance, Kong and Faltinsen (2008) simulated the motion of ship in a damaged condition, including the modelling of water ingress and egress. Grochowalski and Jankowski (2009) showed the validation of computational results for simulation of capsizing in extreme waves as well as ship motion responses.

Besides ship motion responses, the prediction of nonlinear ship structural loads is an important reason for undertaking time-domain analysis. The size of modern commercial ships is getting larger, and the importance of nonlinear motion and loads is increasing. Nonlinear computations are made possible by using the time-domain methods. Song *et al.* (2010b) compares the time signals of the vertical motion and hydrodynamic loads on a model of a 6,500TEU containership with experimental data from the WILS I joint industry project. The nonlinear motion and structural loads computed by using a time-domain Rankine panel method show a fair correspondence with experimental observation.

Hydroelasticity represents the most significant activity related to the development of time-domain seakeeping analysis. Like nonlinear motion and loads, very large modern ships have a big potential of springing and slamming-induced whipping.

Manoeuvring in waves is an additional issue in ship hydrodynamics. Sutulo and Guedes Soares (2008, 2009) simulated the ship motion coupled with manoeuvring and obtained the structural loads. They applied a strip theory with constant turning speed. A 3D method for coupled seakeeping and manoeuvring by using a B-spline-based Rankine panel method has been applied by Seo and Kim (2010).

Ship-ship or ship-offshore platform interaction is also another problem which is of great interest particularly for the design of offshore structures. Frequency-domain approaches have been used previously, but time-domain methods have been applied recently for the multiple body interactions, particularly when those bodies are connected in some way. In addition, when active stabilizing fins with a non-linear control system are fitted to a ship, the motion responses should be solved in time domain. For instance, Kim *et al*, (2009a) showed the time-domain computation for multiple body interaction.

The effects of finite depth have been considered using frequency domain approaches, e.g. Hauteclocque *et al.* (2008), and Ferreira and Newman (2008) by using a Green function approach. However, this can also be done by a time-domain approach; Kim and Kim (2010a) applied a Rankine panel method adopting a time-domain formation, and the motion RAOs were observed for different bottom topologies.

<u>High-Speed.</u> Planing hull form designs have been used extensively for passenger ferries, pleasure boats and in some naval applications. Assessment of the required power as well as seakeeping are fundamental steps in designing such high-speed hulls. A difficulty associated with the analysis of hydrodynamic lift does not lend itself to standard strip theory based tools; non-linear hull responses to hydrodynamic loads do not allow an RAO approach for performance evaluation; the Fridsma and Savitsky-Brown empirical formulations applicable to simplified prismatic hull form do not produce reliable results for a wide range of hull forms.

Experiments in regular oblique waves were conducted by Manderbacka *et al.* (2008) to investigate: (i) nature of the higher order wave loads and their dependence upon heading, wave height, wavelength and frame shape, (ii) a magnitude of springing-type loads acting at ship's bow in terms of pressures and total forces, and (iii) to find the effect of bow form on the higher order springing type wave loads. Model of a large cruise ship was used and tests were carried out in bow regular waves with the heading angles of 120 and 150 degrees. The authors concluded that higher order wave loads are strongly associated with a deformation and breaking of the oncoming waves. Wave steepness has a strong effect on the higher order components of loads as well.

Begovic and Bertorello (2009) undertook an experimental program focused on the behaviour of a, non-uniform deadrise, planing hull form in regular and irregular head sea was undertaken using the Towing Tank the University of Naples. A scale model was tested at Froude numbers from 0.9 to 1.4 in regular waves with $\lambda/L$ ranging from 1 to 5. Tests in standard ITTC two parameter spectra were also performed for three different speeds.

<u>Rarely Occurring Events.</u> Shipping of green water (or deck wetness) occurs when the deck of the ship is immersed in the water; the result of the bow of the ship submerging is that a large volume of water can be taken onboard which can subsequently damage exposed stuctures. Le Touzé *et al.* (2010) applied the SPH method to predict the fluid behaviour for two different flooding scenarios. The first is the interaction between a vessel and undulating travelling waves. The second is the transient flooding behaviour that occurs during and immediately after a side collision between two vessels. Water heights are measured close to the point of impact within the vessel. They believe that flows produced by such events tend to be highly dynamic, with large amounts of free surface deformation. For this reason, SPH is a valuable method for predicting the physics of such flows.

Colicchio *et al* (2010) proposed a 3D Domain-Decomposition strategy where a linear potential-flow seakeeping analysis of the vessel is coupled with a local nonlinear rotational-flow investigation for the prediction of water-on-deck phenomena. The Navier-Stokes solver is applied in the region close to the ship bow. Preliminary numerical results are discussed and compared against 3D water-on-deck experiments.

Shibata *et al.* (2009) developed a numerical analysis method based on the moving particle semi-implicit method for simulating shipping water on a moving ship. Towing tests of a very large crude carrier were numerically analyzed for three typical wavelengths. The calculated fluid behaviour and the impact pressure on the deck were compared with the experimental results.

Lee *et al* (2009) developed an efficient numerical simulation technique to predict the green water impact on the bow structure based on the comparison between various numerical methods. The marker-density method had been applied to capture the extremely complicate free-surface, including breaking, associated with the differentiated nonlinear governing equations.

Zhu *et al.* (2009) developed a numerical program to model green water occurrence on floating structures based on a commercial CFD code. A combination of numerical programmes is presented in which the motions of the FPSO are calculated by potential theory in advance and CFD tools are used to investigate the details of green water. A technique of dynamic mesh is introduced in a numerical wave tank to simulate the green water occurrence on the oscillating vessels in waves.

Lu *et al.* (2010) developed a numerical time domain simulation model to study green water phenomena and the impact loading on structures. A volume of fluid (VOF) technique was used to capture the violent free surface motion. The incompressible Euler/Navier-Stokes equations, written in an Arbitrary Lagrangian-Eulerian (ALE) frame, were solved using projection schemes and a finite element method on unstructured grids.

Lee *et al* (2010c) analyzed and compared experimental results of green water on the deck of three different FPSO bow shapes in regular head waves. They established a database for CFD code validation and proposed some design considerations as well.

Kendon *et al.* (2010) considered results from a 2D model test setup, and compared the measured vertical loading on the deck against two simple potential theory based methods and against results from a commercial CFD code. The results demonstrate that a second impact event closely following a first impact event can have a much flatter free-surface profile (and stronger water entry force) as a result of its interaction with the (deck) diffracted wave from the first impact event. They concluded that for isolated impact events the simple potential flow based models, which does not consider the influence of one impact event on another, are adequate to predict the vertical loading on the deck.

The focus of the research on slamming, whilst based in fundamental research, is tailored towards practical applications.

A typical example is the study carried out by Kapsenberg and Thornhill (2010) to develop a fast and accurate method capable of long term simulation of a ship in a seaway from which the statistical properties of impact loads can be derived. The procedure includes an approximation method based on the momentum theory (Wagner) enhanced with pile up effects due to immersing bow and the draft dependent bow wave. It is shown that the latter effects are crucial for a good prediction of the impact loads.

Hermundstad and Moan (2009a and 2009b) also presented a practical calculation method for assessing slamming pressures with emphasis on bow flare slamming. A time domain strip theory ship motion calculation procedure and a two dimensional generalized Wagner formulation for the actual slamming are used. They reported that the calculated ship motions and slamming pressures in the bow flare region of a Ro-Ro ship compared well with their experimental data.

Dessi and Ciappi (2010) related the slamming excitation and whipping response to each other by using proper estimators of both the water impact occurrences and the corresponding levels of whipping vertical bending moment. The measured data from towing tank tests with a segmented and an elastic model, one of a fast ferry sailing at 40 knots and one a cruise ship of almost double the length, are analysed. It turned out that a key point in these tests was the use of on board wire probes for measuring the (instantaneous) draft. The key points in the subsequent analysis were the slamming detection technique used and the extraction of the whipping contribution to the vertical bending moment measurement.

Pedersen and Jensen (2009) presented rational procedure for the prediction of extreme wave induced hull girder bending moment in slender monohull displacement vessels. The probabilistic procedure is fast and easy to apply and aimed at assessing the sectional forces on a ship including the effects of non linear contributions due to bow flare and hydro elastic effects associated with slamming loads. As an application example they use the container ship MSC Napoli and conclude that reasonable engineering accuracy is obtained

Sun and Faltinsen (2009) investigated the two dimensional water entry problem of a bow flare section of a ship with a constant roll angle. They used a boundary element method in which the fully non-linear free surface condition and exact body boundary conditions were satisfied. Numerical simulations were compared with experiments. They found In general that the vertical force on the section did not change much with small roll angles; the horizontal force however increased with increasing roll angle.

A different approach to solving the pressure distribution on falling wedges was used by Veen and Gourlay (2009). They used an SPH approach to the problem of slamming by focussing primarily on the impact of a number of two dimensional wedge forms on a free surface contained in a hydrostatic tank. Their results from these wedge simulations showed reasonable good agreement with experimental studies carried out earlier. The completed validation of the SPH algorithm as applied to the two dimensional dam breaking test case is also discussed.

Wet deck slamming of multi hulls was investigated by Lin *et al.* (2009). They developed a hybrid numerical method for predicting the wet deck slamming of high speed catamarans. The fluid domain is divided into an inner domain that encloses the ship and the nearby flow field and an outer domain that extends from the near to the far field flow. The flow in the inner domain is modelled with viscous flow theory while the flow in the outer domain is described with potential flow. It showed that the hybrid method captures the essential physics of the complex flow problem while making the simulation more efficient than using a viscous flow code for the entire computational domain.

Davis *et al.* (2009) investigated the slamming and whipping of a wave piercing catamaran of the INCAT type. Sea trials on various INCAT wave piercing catamarans have demonstrated the whipping and slamming behaviour of the ship structure and the influence of the centre bow on slam forces. A segmented hydro-elastic model has been developed to simulate the main whipping mode, elastic links in the model facilitating the measurement of bending moment and the determination of the slamming loads. Comparison of the measured slam loads in model and full scale compare well. Very high forces almost equal to the ship displacements have been found with durations lasting from 0.4 to 1.1 seconds.

One form of the water impact problem is the impact of a flat which appears to be a simple phenomenon; however, the physics of such a problem can be very complicated. Oh *et al.* (2009) used high speed cameras to look at the evolution of the air pocket during the impact of a flat box.

Qiu *et al.* (2010) investigated slamming force on a planing hull using 2D and 3D numerical methods, experiments and empirical formulae. Strip theory was used to compute the slamming forces on a planing hull, where the impact force on each 2D section was calculated using 2D and 3D CIP methods.

Yang and Qiu (2010) presented numerical solutions of slamming problems for 3D bodies entering calm water. This highly nonlinear water entry problem is governed by the Navier-Stokes equations and was solved by a CIP-based finite difference method on a fixed Cartesian grid. The solid body and the free surface interfaces were captured by density functions.

Ermanyuk *et al.* (2009) presented an experimental study looking at the effects of small positive and negative curvature of the bottom of a circular disk on the flow patterns and the dynamic properties of impact on shallow water. The possibility of trapping air by a convex body and the effect of trapping air on touchdown of the body onto the bottom of the test tank in shallow-water setup was investigated.

Colicchio *et al.* (2009) presented an experimental and numerical analysis to study a circular cylinder either freely falling on or exiting the water. A detailed measurement of the velocity field and of the local loads around the cylinder was undertaken.

Greco *et al.* (2009) proposed a weakly-nonlinear seakeeping model. A simplified criterion for the slamming occurrence was implemented, based on the impact angle and the pressure level associated with the phenomenon. The slamming and water-entry local loads used the Wagner approach

Yoon and Semenov (2009) investigated a limited combination of initial parameters corresponding to flow separation from the 2D wedge vertex during the initial stage of the oblique impact of a wedge.

Xu *et al.* (2009) studied twin wedges entering the water surface through during free fall using a time domain numerical method. Wu *et al* (2010) presented a comprehensive study of water entry of a wedge based on the fully nonlinear velocity potential theory. The solution procedure is based on the boundary element method for the complex velocity potential. In particular, they solved the problem in a stretched coordinate system. Xu *et al* (2010) presented a wedge entering the water through the free fall motion in three degrees of freedom based on this method.

Gong *et al.* (2010) applied a SPH model to study the hydrodynamic problem of a two-dimensional wedge entering the water. They proposed a non-reflection boundary treatment for the SPH method to reduce the size of the computational domain. Both single- and multi-phase SPH models were used to simulate the details of water entry and enclosing.

Tassin *et al.* (2010) proposed an efficient numerical method for three-dimensional water impact problems based on the Wagner approach and the Boundary Element Method (BEM). Lee *et al* (2010a) studied violent free-surface motions interacting with structures using the MPS method. A more efficient algorithm for Lagrangian moving particles is used for solving various highly nonlinear free-surface problems without using the Eulerian approach or the grid system. The convection terms and time derivatives in the Navier–Stokes equation can be calculated more directly without any numerical diffusion, instabilities, or topological failure.

<u>Sloshing</u>. Liquid sloshing is a very complex phenomenon of fluid movement, showing a strong nonlinearity and apparent randomness. The liquid in a partially filled container, subjected to external excitation, can be extreme; the liquid can then impact on the internal structure of the container impacts resulting in damage. This is why sloshing is extensively studied to support the LNG shipping industry. The overall knowledge on this subject has reached an unprecedented level. Particularly, the feed-back and lessons learned from the incidents involving LNG carriers provide data that are of great use to the scientific community, and help increase the

knowledge associated with this phenomenon. However, some particularities the sloshing phenomenon still have not been as yet explained to the satisfaction of the community. Numerical solutions and model tests have been developed extensively over the period of this committee to reliably capture aspects of sloshing behaviour such as wave profiles and impact pressures. For the purpose of this report, the wealth of information available in open literature is too extensive to describe in any detail, therefore the contributions are captured in the form of tables. However, they have been some references that have provided an overview of the subject.

Faltinsen and Timokha (2009a) gave an overview of sloshing in the tanks of ships.; details about viscous effects, in particular, associated with swash bulkheads were presented. They focused on the coupled effect of sloshing and ship motions, where it is stressed that nonlinearities are important for sloshing while the exterior flow can in most cases be handled by linear theory except for viscous roll damping. In order to improve the understanding of the sloshing phenomenon and its consequences, Gavory and de Seze (2009) reviewed the current status the methodologies used in sloshing assessment studies. Inviscid methods are still considered for solving this highly non-linear problems and to understand the limits within which these models (both linear and nonlinear) are valid, Cao *et al.* (2010) presented the range of validity of potential flow models by comparing the predictions with those by other CFD simulations and experiment measurements of the liquid motion in an oscillating tank.

Fluid-structure interaction represents a very challenging problem, however, despite the amount of experimental and numerical modelling undertaken to date, it is fair to say that no fully consistent solution exists up to now. The overall problem of sloshing impacts is extremely complex. The impact loads are highly localized both in time and in space, simplified models of hydrodynamics are often used to present such loads. A few ways of categorising sloshing pressure were introduced. For example, based on shape of the wave front just before the impact, four types of the impact have been introduced: 'Wagner-type impact', 'Steep wave impact', 'Bagnold-type impact' and 'Aerated fluid impact'. More recently, in the Sloshel project, more impact types were introduced: slosh, flip-through, aerated, air pocket. Among them, the largest impact pressure was observed during the flip-through phenomenon.

A great deal of research on sloshing has been undertaken by ExxonMobil(EM) covering many subjects. EM carried out a thorough study on seakeeping analysis, model test, statistical prediction, and dynamic structural analysis, and developed their own procedure which covered most sloshing-related subjects. For example, Kuo *et al.* (2009) presented ExxonMobil's evolution of a direct sloshing assessment methodology to resolve several challenging technical issues that are essential for evaluating integrity of LNG containment systems. They presented a probabilistic-based framework that facilitates modelling of the high variability of sloshing impact pressures due to sloshing physics and insulation materials that is inherent in products from analysis system named as EMPACT was introduced in the Sloshing Dynamics Symposium in 2009, which was held as a part of ISOPE conference.

Table 3 Numerical approaches to the sloshing problem.

| Reference | Problem addressed | 2D/3D | Numerical approach |
|---|---|---|---|
| Faltinsen and Timokha (2009, 2010) | Sloshing modes | | Linear potential flow |
| Firoozkoohi and Faltinsen (2010) | Sloshing modes | 2D | Quasi –linear modal theory |
| Rafiee *et al* (2009) | Sloshing motion | 2D | SPH |
| Rudman *et al* (2009) | Free surface characterisation | 2D | SPH |
| Luis *et al* (2009) | Free surface characterisation | 3D | SPH |
| Yang and Kim (2009) | Free surface characterisation | 2D | CCUP |
| Hu *et al* (2009) | Sloshing motion | 2D | CIP/MPS |
| Lee *et al* (2009) | Sloshing motion | 2D | CCUP |
| Hu *et al* (2010) | Impact pressure | 2D/3D | CIP |
| Gu *et al* (2010) | Sloshing motion | 2D/3D | MPS |
| Wu and Chen (2009) | Sloshing modes | 3D | Finite difference method |
| Wemmenhove *et al* (2009) | Free surface characterisation | 3D | RANS |
| Godderidge *et al* (2009) | Fluid pressure distribution | 3D | RANS |
| Chen *et al* (2009) | Free surface characterisation | 3D | RANS |
| Huang *et al* (2010) | Fluid pressure and free surface | 3D | Non-linear BEM |
| Wang *et al* (2010) | Free surface characterisation | 3D | Non-linear potential flow |
| Zhu *et al* (2008) | Free surface characterisation | 2D | Level set method |
| Ma *et al* (2009) | Impact pressure | 3D | Rankine source/SPH |
| Delorme *et al* (2009) | Impact pressure | 3D | SPH |
| Lee *et al* (2010) | Fluid structure interaction | 2D | Non-linear CFD |
| Guilcher *et al* (2010) | Two phase flow | 3D | SPH |
| Baeten (2009, 2010) | Impact pressure | 3D | |
| Khabakhpasheva and Korobkin (2009) | Impact pressure | 3D | Domain decomposition |
| Kim *et al* (2010) | Statistics of impact pressures | 3D | |
| Rognebakke *et al* (2009) | Statistics of sloshing loads | 3D | |
| Sueyoshi (2009) | Thin baffles | 3D | MPS |
| Liu and Lin (2009) | Tank baffles | 3D | RANS/LES |
| Guan *et al* (2010) | Tank baffles | 3D | ALE/BEM |
| He *et al* (2009) | Tank baffles | 2D | |
| He *et al* (2009) | Sloshing motion | 2D/3D | Non-linear BEM |
| Souto-Iglesias *et al* (2008) | Fluid structure interaction | 3D | PFEM |
| Ten and Korobkin (2009) | Fluid structure interaction | 2D | |
| Malenica *et al* (2009) | Fluid structure interaction | 3D | Semi-anaytical/FEM |
| Oger *et al* (2009) | Fluid structure interaction | 3D | SPH |
| Wemmenhove *et al* (2010) | Fluid structure interaction | 3D | ComFlow/LS-DYNA |

Table 4 Methods addressing the coupling of ship motion and sloshing.

| **Reference** | **Approach** |
|---|---|
| Lee *et al* (2008,2009) | 3D non-linear Green Functions |
| Nam *et al* (2009) | Linear IRF for ship, non-linear finite difference scheme for tanks |
| Lin *et al* (2009) | Linear potential theory for ship, non-linear CFD for tanks |
| Wang and Arai (2010) | Potential flow for ship, finite difference scheme for tanks |
| Hasimoto and Sueyoshi (2010) | Potential flow for ship, MPS scheme for tanks |
| Bunnik and Veldman (2010) | Potential flow for ship, CFD scheme for tanks |
| Clauss *et al* (2010) | Potential flow |
| Park *et al* (2010) | Potential flow |

GTT has actively carried out the research on sloshing and has introduced a lot of results. Marès *et al* (2009) described the main improvements on environmental conditions, coupling effects, off-shore projects, which integrated into GTT's methodology for sloshing assessment. Pillon *et al.* (2009) presented how GTT developed and validated its numerical models to obtain a proper representation of the complex and nonlinear behaviour of the CCS. To validate the numerical models, tests on specific subsystems are performed in order to analyze the behaviour of these components under different conditions: static, dynamic, at ambient and cryogenic temperatures. Gervaise *et al.* (2009) described today's major evolution of GTT's methodology on sloshing assessment including hardware improvements, assumptions for sea-keeping calculations, loads and strength evaluations as well as final assessment.

The procedure to predict sloshing loads and evaluate structural strength has been introduced by most classification societies. American Bureau of Shipping, Bureau Veritas, Lloyds Register and Det Norkse Veritas published their new or revised guidance for sloshing in last a few years. Based on such recent guidance they introduced application results for real ships. For instant, following ABS assessment procedures, Wang *et al.* (2009) conducted a dynamic structural analysis, considering fluid-structure interaction, to determine the design strength capacity for the No. 96 containment system using sloshing model tests in terms of selected environmental conditions, vessel configurations, and loading conditions. Spatial, temporal and statistical characteristics of the measured sloshing loads were investigated. Linear transient FE analysis of the No. 96 containment system including both the structure and the LNG was performed to obtain structural responses at predefined critical locations under short duration triangular pulse, which is referred to as triangular impulse response function (TIRF). In the FE model, orthotropic material properties for plywood and acoustic medium for LNG were considered to develop the coupled fluid structure FE model. The TIRFs were synthesized with the time history of measured sloshing loads to obtain dynamic structural response at critical locations in the box system. Statistical analysis results of peak stress values in each component of the containment system were used as the basis for determining design sloshing loads or strength assessment of the No. 96 containment system.

Eventually sloshing impact pressure is required to evaluate the structural safety of LNG CCS system. Therefore, a lot of papers have been introduced describing structural analysis and strength assessment as a part of sloshing analysis. Since the ITTC focuses primarily on hydrodynamic issues, the details of strength assessment are not described in this report. However, a recent ISSC report (2009) included some details on such issues including state of the art.

The Sloshel project is a Joint Industry Project aimed at collecting data from full-scale sloshing experiments using unidirectional focused waves impacting on fully instrumented LNG carrier No. 96 (2009~2010), Mark III(2010~2011) membrane containment panels and a concrete block within a rigid vertical wall. Brosset *et* *al.* (2009) provided an overview of the Sloshel project within the overall methodology for the sloshing assessment of partially filled LNG tanks. The experimental set-up, the parameters tested and numerical evaluation leading to new insights into the characteristics of LNG tank sloshing impacts and the influence of hydro-elasticity were described. They concluded with a summary of the numerical methods being developed and validated with this full-scale experimental data.

Through the Sloshel project, many results on the scale-law study, CFD computations for fluid flow, hydroelasticity of membrane cargo structure and structural responses have been introduced in several international conferences. For instant, Maguire *et al.* (2009) considered numerical simulations of fluid loading by computational fluid dynamics (CFD) and structural response by finite element analysis (FEA). Bogaert *et al.* (2010a) described the relation between scale and the sloshing problem based on the results from the Sloshel project. The similarity at both scales was explained and the recommendation was made for further tests. Zheng *et al.* (2010) summarized the key findings from model and full scale tests and numerical simulations. Special attention is paid to numerical simulations for sloshing waves which occur at low to medium filling levels, known as travelling waves, and their results were validate against Sloshel test data. Bogaert *et al.* (2010b) presented the behaviour of MarkIII corrugated primary membrane under breaking wave impacts based on the database of the large scale impact tests from the Sloshel project

Through the Sloshel project, some significant findings have been introduced. However, in the series of experiment, it was also found that the repeatability of generating the same impact is hard to achieve in this kind of experiment. So the measured impact loads showed large scattering. In addition, the similarity of impact due to water and LNG is another concern in this large scale experiment.

In 2009 and 2010, the 1st and 2nd Sloshing Dynamics and Design Symposiums have been held as a part of min-symposium of ISOPE conference. In these two symposiums, about 80 papers only for sloshing have been presented. Furthermore, panel sessions were organized for all day in each symposium, so many key issues were discussed by experts on sloshing. In the 1st year, a comparative study on CFD simulation was organized, and the computational results of several different numerical methods were compared with experimental data. In the 2nd symposium, a comparative study has been also performed for a free-fall water column and sequential impact on bottom, and impulsive pressure during impact has been compared between only computational results.

Hydroelasticity – Hull Girder Loads/Ship

Understanding the hydroelastic response of a ship is an important part of the overall structural response. This is true for both extreme ship structural responses and the fatigue loads of some structural details. In their research paper, Derbanne *et al* (2010) describe the hydroelastic model they had developed. In this numerical model the 3D hydrodynamics are coupled with either non-uniform or 3DFEM structural dynamics. They compared the results from this model with results obtained from several experimental campaigns.

Storhaug (2009) investigated the breaking of the MSC Napoli and whether whipping contributed to the problem or not. It had been concluded that the vessel did not have the necessary buckling strength margin and overloading could happen without whipping. He reports that experience from full scale measurements indicated that whipping can be of significant magnitude. In his report he presents the results of measurements on board a similar 4400 TEU vessel both full scale and from model tests. These tests confirm that whipping can increase the dynamic loading in similar sea states those the MSC Napoli did encounter. The measurements also illustrate that it is difficult to state exactly how much the whipping contributes in a specific sea state.

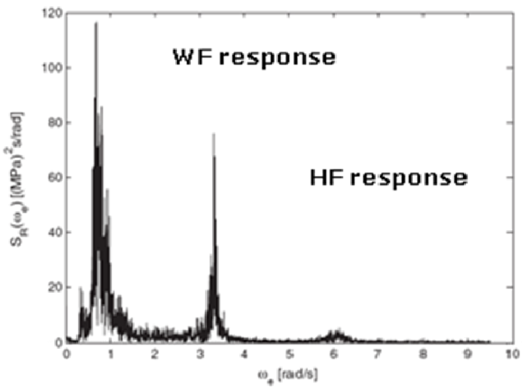



Figure 6 Stress response spectrum measured on a real ship (Vidic-Perunnovic, 2005)

The hull-girder hydroelasticity is currently one of the priority issues. There is a huge engineering demand to analyze the hydroelasticity effects of ship structures in waves. For instance, Figure 6 shows the response spectrum of stress measured on a real ship. There are two major contributions: one in the frequency range of the ocean waves, and the other in the high frequency range. The high-frequency response is due to the hydroelasticity effect of ship structure. Such high-frequency component can not be neglected when undertaking fatigue analysis of the ship.

According to recent analyses using real ship measurements, model experiments and numerical computations, the potential for structural damage due to springing and whipping is very large in large modern ships. For instance, Figure 5 shows an example of fatigue measurements from a containership operating in the North Atlantic Ocean (Ito *et al*, 2010). The high-frequency (HF) component contributes about 20~30% of the total amount. In fact, some recent studies predicted over 50% increase of fatigue damage. In any case, the contribution due to the high-frequency vibration of ship structure resulting from the hydroelastic effect can be very significant in large modern commercial ships.

Springing and whipping are two main phenomena in ship structural hydroelasticity. The key mechanisms of the two phenomena are clearly different, i.e. wave-induced quasi-steady vibration and slamming-induced transient vibration. There is a technical difficulty in distinguishing the contributions from these two phenomena in the analysis of

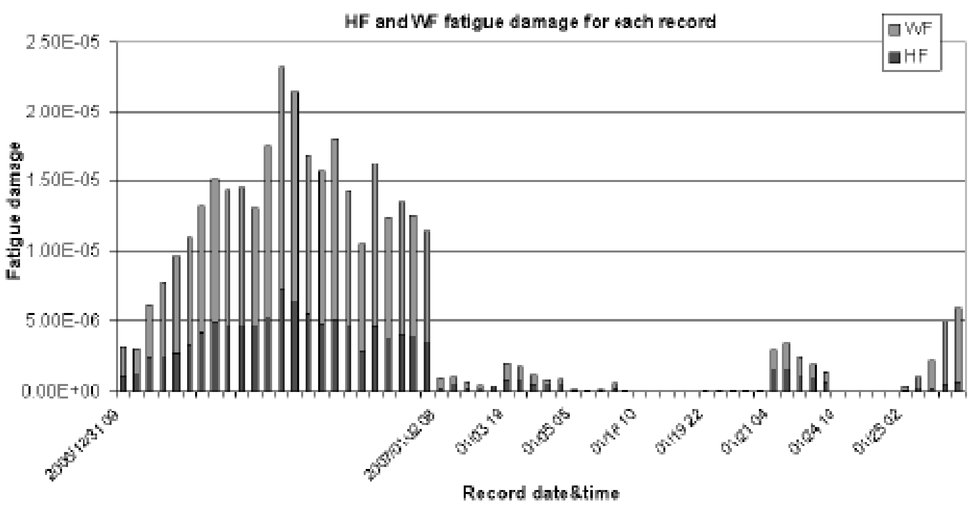



Figure 5 Estimated fatigue damages per hour for the wave frequency (WF) and the high frequency (HF) contributions: real ship measurement by Ito, Nielsen and Jensen (2010)

the stress/motion signals measured in a real ship. However, in the numerical analysis, the two problems can be solved independently and the resultant oscillatory responses can be combined.

The analyses of springing and whipping require the capability to solve the seakeeping problem and the structural problem at the same time by using a coupled scheme. In the case of springing analysis, most of the research has been based on the frequency-domain approaches, adopting strip methods for ship motion and beam-based modal superposition for the ship structure. Strip methods are still used, but 3D panel methods or CFD programs have been also introduced, and direct integration methods for the ship structure are also available.

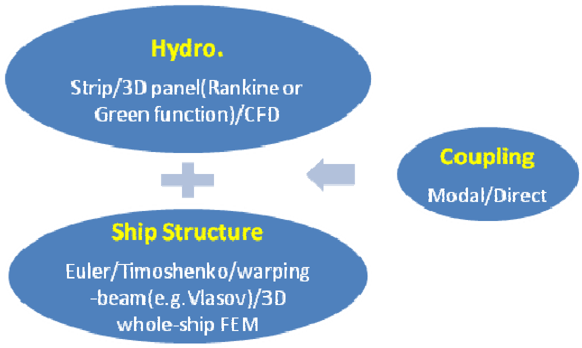



Figure 7 Typical coupled analysis methodology

Figure 7 shows a summary of typical methodology for the analysis of ship springing. Most recent computational results for ship springing belong to this category. For instance, Malenica *et al.* (2008) introduced computational results by using a coupled BEM and FEM. They solved the linear ship springing using a frequency-domain approach, particularly 3D BEM based on the Green function for the hydrodynamic problem, and 3D FEM for determining the eigenvalue of ship vibration. Then, using a modal approach, the linear springing responses were obtained. They also extended their approach to a time-domain computation adopting an impulse-response-function approach for nonlinear springing. On the other hand, Kim *et al.* (2009a, 2009b) applied a 3D Rankine panel method and a beam model based on Timoshenko and Vlasov beam theories, and the two solvers are coupled in the time domain. They also solved the linear and the nonlinear springing problem. Similar work was also introduced by Senjanovic *et al.* (2008, 2009). More studies using 3D panel methods have been introduced, for example the work of Lee *et al.* (2010d) by using NLOAD3D.

Strip methods are still widely used for springing analysis. For example, Quérard *et al.* (2008) used a strip method with the sectional hydrodynamics obtained using a RANS solver. Jensen *et al.* (2008) also applied their quadratic strip theory and Timoshenko beam model for a simple computation of bending moment. More studies based on strip methods can be found in the work of Vidic-Perunovic (2010).

CFD methods are also available nowadays. For example, Paik *et al.* (2009) applied the CFD code of Iowa University for the flow solver and beam model for structure, and they coupled the two problems for S175 model by using modal approach. There are limited number of CFD-based computations for springing and whipping, and more popular application is expected in the future.

Experimental studies have been also introduced. As the need to understand the hydroelastic response of a ship structure is growing, segmented model tests have been carried out. For instance, Miyake *et al.* (2008) introduced an experimental study for very large containership as well as numerical computation using a 3D Rankine panel method. A systematic experimental study has been carried out through WILS II joint industry project carried out at MOERI/KORDI under the support of many classification societies and shipbuilding companies. They carried out a series of springing tests for a 10,000 TEU model, and the experimental data are compared with several computational results.

The analysis of whipping requires the computation of slamming force in advance. In past studies, it is assumed that the whipping response is not much dictated by the coupling effect with hydrodynamics, i.e. ship motion. This assumption may be reasonable for practical application, but more systematic observation is needed. In recent years, the whipping coupled with the high-frequency motion of ship has been introduced in some papers, taking advantage of computer development. The analysis of whipping should be carried out in time domain, since it is transient vibratory motion.

Some experimental studies and/or real ship measurement have been introduced in last a few years, including real ship measurement. For example, Dessi and Mariani (2008) introduced the experimental study for the observation on the slamming occurrence and whipping responses of a fast mono-hull ship in head waves. Some classification societies, the shipbuilding industry, and ship owners are interested in measuring the fatigue damage in real ships. They have been measuring the loads due to springing and whipping, and some observations have been already introduced in the PRADS conference (2010) and the International Workshop on Springing and Whipping (2010).

Computational effort is also under progress. For example, Oberhagemann *et al.* (2008) applied RANS solver for the ship flow with slamming occurrence and solved a Timoshenko beam model for a 7,500 TEU containership. In their case, the hydrodynamic and structural problems were not fully coupled. However, more recently the computer programs to solve the coupled problem are available although many of them are basically the same with those for springing analysis. For instance, Derbanne *et al.* (2010) introduced the global hydroelasticity model for springing and whipping. In their whipping analysis, they applied two 2D impact theories for ship sections and observed the increase of structural loads due to whipping loads for different ship models.

## 2.4 Added resistance and power increase in waves

The prediction of power increase of ships in actual seas is very important not only for designing ships and analysing actual ship performance at sea, but also recently for estimating $CO_2$ emission from ships at sea.

In order to reduce emissions in international shipping, the estimation and measurement procedure for $CO_2$ emission is the current hot issue under discussions at the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO).

In the interim, guidelines on the method of calculating $CO_2$ emission, the Energy Efficiency Design Index (EEDI) for new ships is given by (1) (IMO/MEPC/Circ681 (2009)).

$$EEDI = \frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}\right)}{f_i \cdot Capacity \cdot V_{ref} \cdot f_w} + \frac{\left\{\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right\} - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}{f_i \cdot Capacity \cdot V_{ref} \cdot f_w} \tag{1}$$

The detailed definition of each parameter in the above formula is given in IMO/MEPC/Cir681 (2009), but its numerator describes the emission of $CO_2$ which is proportional to the fuel oil consumption, i.e. proportional to the power of main and auxiliary engines. "*Capacity*" in the denominator of the formula is the deadweight in the maximum design load condition for dry cargo carriers, tankers, etc. "$V_{ref}$" is the ship speed in calm sea condition with no wind and no waves. "$f_w$" is a non-dimensional coefficient indicating the decrease of speed in representative sea condition, e.g. Beaufort Scale 6. $f_w$ is taken as one (1.0) for the time being until its reliable simulation procedure becomes available.

According to the above definitions, the EEDI describes the $CO_2$ emission from a ship per unit of transport work, i.e. for a one tonne load transported over one nautical mile.

For determining $f_w$, an accurate prediction of involuntary ship speed loss at sea is necessary, which requires estimating the power increase of a ship in wind and waves. The prediction of ship performance at sea is to be as accurate as possible, because, based on the prediction results, $CO_2$ emission from the ship will be judged against agreed targets by third party verifiers. The required targets for $CO_2$ emissions from ships are decided by the IMO/MEPC.

Adding to the high accuracy and the reliability of the results, it is also desirable that the procedure of predicting ship performance at sea is reasonably simple and has transparency.

One step in understanding the ship performance at sea is predicting power increase in waves; currently, there are two possible procedures, one is by conducting model tests and the other one is by theoretical calculations.

<u>Model Tests.</u> For the purpose predicting the power increase in irregular waves, conducting resistance tests or self-propulsion tests in irregular waves is the most direct approach. However this is not in general a satisfactory solution, because the results are less precise than those obtained in regular waves and they are applied only to the particular wave spectra for which the experiments were carried out. In order to predict ship performance at sea, it is necessary to be able to predict ships' power performance in various irregular wave conditions. The common approach relates to the application of linear spectral analysis, for which purpose it is necessary to have basic data on the ship's response amplitude operators in regular waves. By using these data and the irregular wave spectra, power increase in various kinds of irregular waves can be predicted and evaluated.

However, several methods are in broad use at various laboratories to predict power increase in irregular waves using response amplitude operators obtained from model tests in regular waves and using basic results obtained from performance tests in still water.

The Seakeeping Committee of the 25th ITTC made a comparison of the four methods; the conclusion of that committee was that the Direct Power Method (DPM) should not be considered as a suitable approach. However, the recommendation from that Conference was for the 26th ITTC Seakeeping Committee to investigate this conclusion in more detail.

The comparison of the results by these four methods is given in Figure 8 and Figure 9 for models of a container ship and a VLCC respectively. Both data are for full load condition.

According to the comparison results given in Figure 8 and Figure 9, three methods, i.e. QNM (Torque and Revolution Method), TNM (Thrust and Revolution Method) and RTIM (Resistance and Thrust Indentify Method), give almost the same results in the case of full load condition. But, the DPM (Direct Power Method) gives slightly different results. As a result, the recommended procedures of ITTC (2011) consider only these three methods: QNM, TNM and RTIM.

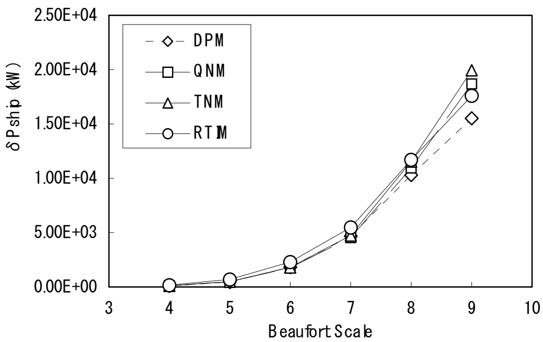



Figure 8 Power increase in irregular waves, Container ship (FULL) (ITTC25, 2008)

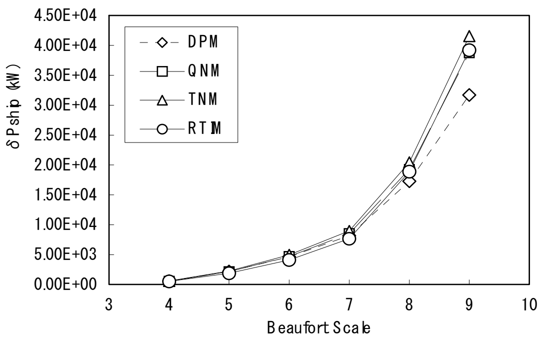



Figure 9 Power increase in irregular waves, VLCC (FULL) (ITTC25, 2008)

The predicted results by these three methods should also preferably be compared with the measured power increase in irregular waves obtained from the direct irregular wave tests, i.e. resistance tests or self-propulsion tests in irregular waves.

But the data used for comparing the above three methods do not contain the test results in irregular waves. Therefore as the secondary option, the resistance increase $\delta R$, propeller torque and revolution increase $\delta Q$ and $\delta n$ obtained from the model tests in irregular waves are compared with their predicted values from the test results in regular waves. For these comparisons, model experimental data in regular and irregular waves for different model ships from the cases are used. These data are picked up from published papers by Takahashi (1987) and Nakamura et.al. (1975) for a tanker model and a container ship model, and also data for two VLCC models that are not available in open literature.

Even with these data, there is no full set of results on resistance and self-propulsion tests in still water, in regular waves and in irregular waves. In the paper of Nakamura *et al.* (1975), a full set of experiments seems to have been performed, but the paper does not give the information on still water performance and propeller open characteristics. Therefore, for these data power prediction cannot be performed. But instead of that the three parameters $\delta R$, $\delta Q$ and $\delta n$ in irregular waves are compared.

The comparison results are given in Figure 10 to Figure 12. In these figures, the "*Predicted*" values mean those obtained from multiplication of the measured response amplitude operators in regular waves and the measured wave spectra obtained from the irregular wave tests. The "*Measured*" values are the results of irregular wave tests. The resistance increase comparison given in Figure 10 shows that the *predicted* results are scattered around the *measured* values in the range mostly of 10-20%. Therefore, the prediction method RTIM based on the resistance test in regular waves seems applicable for the prediction of power increase in irregular waves in the reasonable prediction accuracy. For torque and revolution increase shown in figures Figure 11 and Figure 12, though, *measured* values are generally larger than *predicted* values.

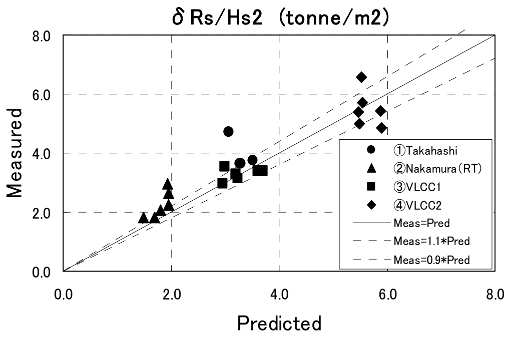



Figure 10 Resistance increase in irregular waves (ITTC26, 2011)

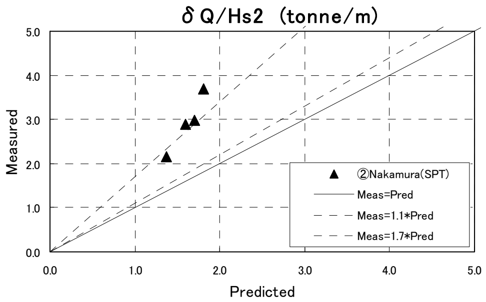



Figure 11 Torque increase in irregular waves (ITTC26, 2011)

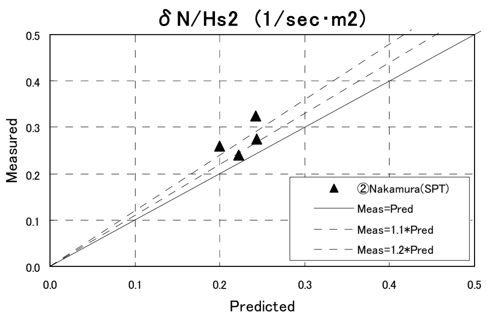



Figure 12 Revolution increase in irregular waves (ITTC26, 2011)

The above discrepancies and scattering between *predicted* and *measured* values are estimated to be due to that response amplitude operators in regular waves may not be proportional to the square of incident wave amplitude, which is the basic assumption of linear spectral analysis.

The accuracy of measurements and analysis of the values in irregular waves may be less than those in regular waves including the effect of the time duration of the measurements in irregular waves. (Naito *et al.*, 1993 and Kim and Kim, 2010b)

In the case of extreme irregular wave conditions, the propeller operates in a very hostile environment and in-and-out water effects can be severe. Then the propeller will behave differently than in calm water or mild seas. (Prpic-Orsic and Faltinsen, 2009) By using the amplitude operators obtained in milder regular waves, which is the *predicted* values in this case, can not describe such situations in severe irregular waves, especially in the case of propeller torque and revolution.

In the above analysis, the amount data for the evaluation is limited, especially for torque increase and revolution increase. For evaluating prediction methods of power increase in irregular waves from the model tests in regular waves considering the comparison with direct irregular wave test results, further investigation needs to be continued.

Even in the case of regular wave tests, the time history of ship response such as resistance in waves are fluctuating. Guo and Steen (2010) proposed to divide them into time windows and make an average of all the different time windows, which make the error smaller.

In the case of conducting model tests in irregular waves, sufficient time duration of the measurement is necessary. Kim and Kim (2010b) investigated the effect of measurement duration by simulation for the S175 container ship. In order to obtain the accurate results of added resistance in irregular waves they recommend conducting measurements or simulations for a duration of over 1.5 hours from the results given in Figure 13. It should be noted that this can be significantly longer time than what is typically required for seakeeping tests designed to measure RMS motions and similar statistics. This result is for only the

S175 hull. More systematic tests should be carried out for various models.

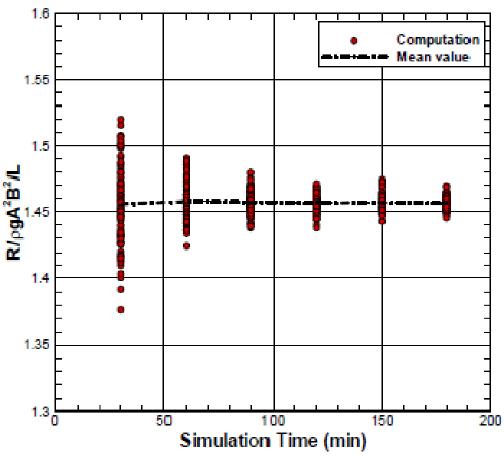
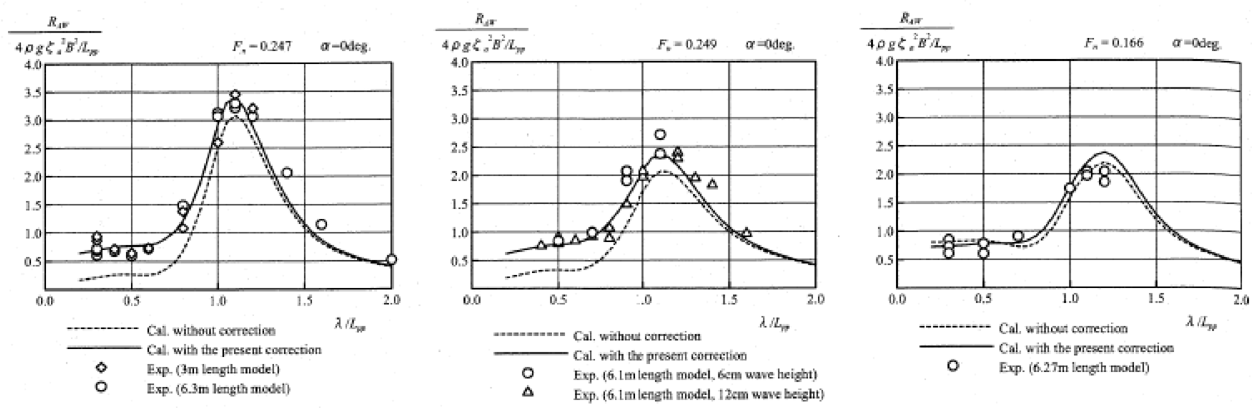



Figure 13 Added resistance vs. simulation time in irregular waves (Kim and Kim, 2010)

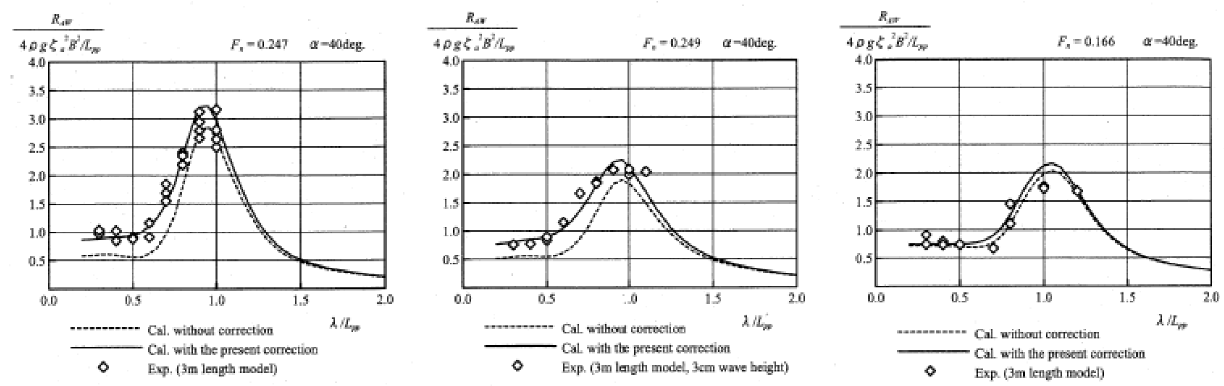
In previous years, the former approach has been widely applied due to its simplicity and efficiency, which has no need to compute hydrodynamic pressure on the complicated body surface.

Theoretical Calculations. A common procedure to predicting power increase of ships in irregular waves is using the same RTIM approach described earlier, where it is predicted by the added resistance due to waves, wind and manoeuvring, and propeller open water characteristics and self-propulsion factors in still water. Therefore, the research focus for the theoretical approach has been mainly on the prediction of added resistance in waves.

There are two theoretical approaches to predicting added resistance due to waves. One is a far-field method on the momentum-conservation theory proposed by Maruo (1960). The other approach is a near-field method by integrating the hydrodynamic pressures on body surface.




(a) CON; Fn=0.247,α=0deg (b) PCC; Fn=0.249,α=0deg (c) PXBC; Fn=0.166,α=0deg




(d) CON; Fn=0.247,α=40deg (e) PCC; Fn=0.249,α=40deg (f) PXBC; Fn=0.166,α=40deg

Figure 14 Added Resistance, Tsujimoto *et al* (2009)

This far-field method can calculate the added resistance due to the wave radiation by the ship in waves. This can be applied in the case of long waves relative to ship length and the effect of ship motion is predominant. But in the case of a large ship in short waves and especially for full ships with blunt bow, the effect of wave reflection on the hull forms a larger portion of the added resistance. The 2D strip theory based on Maruo's theorem can not describe this effect of wave reflection to added resistance. In order to describe the effect of wave reflection to added resistance, semi-empirical formulae were proposed by Fujii and Takahashi (1975), Faltinsen *et al.* (1980), and others.

Kuroda *et al.* (2008), Tsujimoto *et al.* (2008) and Tsujimoto *et al.* (2009) proposed a modification to this approach by using encountered wave number instead of actual wave number in the formulation and to modify the effects of speed as follows;

$$1 + \alpha_U = 1 + C_U F_n , \tag{2}$$

where $C_U$ is obtained from resistance tests in a short regular wave with several different ship speeds, and described by a function of bluntness factor $B_f$ as shown in Figure 15.

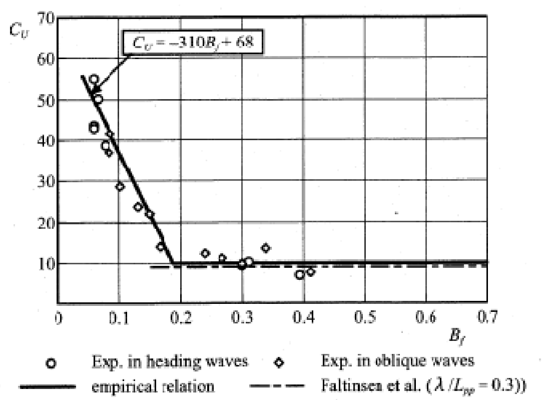



Figure 15 Relation between the advance speed $C_U$ and the bluntness coefficient $B_f$ ($\lambda$/Lpp=0.3). Tsujimoto *et al.* (2009)

The predicted results according to the above procedure proposed by Kuroda and Tsujimoto *et al.* (2008 and 2009) give better agreement with model test results of added resistance in regular waves for practical ships with various kinds of fullness, i.e. a container ship (CON), a PCC and a P'max BC (PXBC), than the conventional prediction results obtained from equation (5) and (6), as shown in Figure 14. Conventional prediction procedure shown by the dotted line in these figures has given a good agreement to model test results for a full ship (PXBC), but has not for rather fine ships such as a container ship or a PCC.

In order to obtain accurate prediction results of added resistance by the above procedure, conduct of resistance tests only with some kinds of ship speed in a short regular wave is necessary.

Investigation on the applicability and reliability of this procedure for more various kinds of ship and wave directions seems necessary and worth doing.

Guo and Steen (2010) also tried to improve the calculation accuracy of added resistance in short waves. Their equation of added resistance in regular waves is as follows;

$$R_{AW} = (1 - \alpha_d) R_{AWm} + R_{AWr} \tag{3}$$

where $\alpha_d$ is given by equation (2).

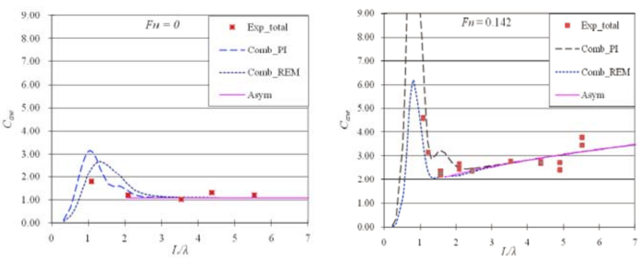



Figure 16 Added resistance coefficient at Fn=0 and Fn=0.142 (Model A) (Guo and Steen, 2010)

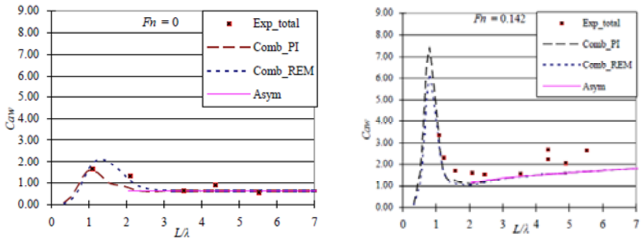


Figure 17 Added resistance coefficient at Fn=0 and Fn=0.142 (Model C) (Guo and Steen, 2010)

Examples of the comparison of predicted added resistance in head waves for MOERI KVLCC2 ship (Model A) and its modified slenderer bow ship (Model C) with their model test data are shown in Figure 16 and Figure 17.

The combined calculation of added resistance due to ship motion and wave reflection given by equation (3) gives good agreement with model test results for both cases of no forward ship speed and with ship speed.

Kashiwagi et.al. (2009) applied the Enhanced Unified Theory (EUT) to predict added resistance in regular head waves with various forward speed. EUT takes account of the effect of wave radiation by ship motion and also the effect of wave reflection at the bow through the body boundary condition in the diffraction problem in the framework of linearized slender-ship theories. In addition, 3D and forward speed effect are incorporated in the EUT through matching between the inner and outer solutions. EUT, therefore, is expected to be applied to the cases with the wide range of wave length and ship speed.

According to their investigation results on the applicability of EUT to added resistance prediction in waves for a modified Wigley model, which is not a practical hull shape though, it can predict with good accuracy the added resistance at zero forward speed, which is the drift force as shown in Figure 18. But, with forward speed, it under-predicted the added resistance in the shorter wave region as shown in Figure 19 by the dotted line (EUT Original). The amount of discrepancy between the calculation and model tests increases and approaches a constant value with increasing the forward speed.

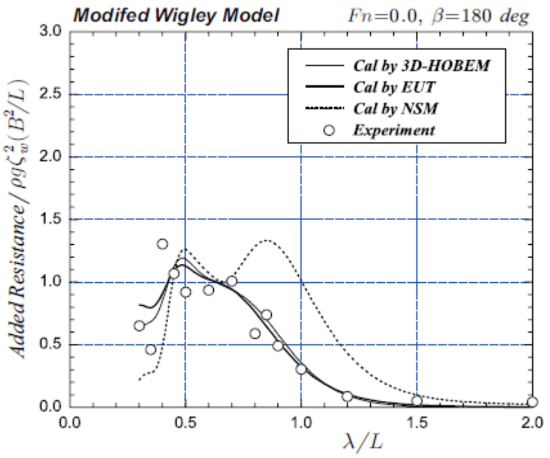



Figure 18 Wave drift force on a modified Wigley model in head waves at zero forward speed (Kashiwagi *et al.*, 2009)

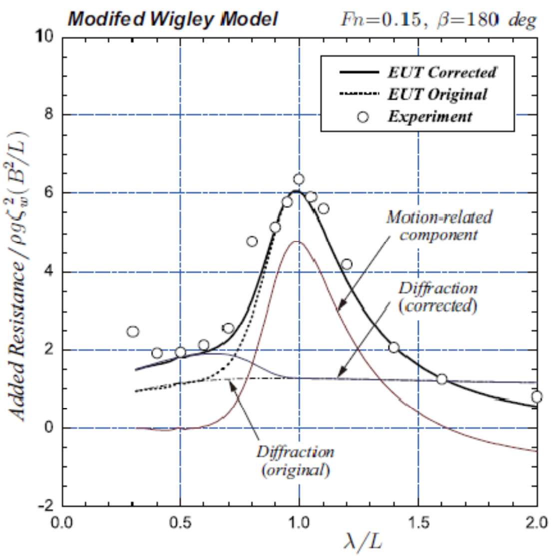



Figure 19 Added resistance on modified Wigley model in head waves at Fn=0.15 (Kashiwagi et al., 2009)

They assume that this discrepancy is due to hydrodynamic nonlinear effects in the wave reflection at the bow. Then they propose to introduce the correction factor *f* in the wave reflection component obtained by EUT as follows.

$$R_{AW} = R_{AWm} + (1 + f) R_{AWr} \qquad (4)$$

The factor $f$ is given by the following equation, which is determined by trial and error such that the results of equation (4) match the measured results.

$$f = 4 \tanh(Fn) \exp\left\{ -0.02 \frac{(\lambda / L)^{10}}{Fn^3} \right\} \qquad (5)$$

Then the corrected prediction results naturally agree well with the model test results as shown by solid line (EUT Corrected) in Figure 19.

Additionally, in Kashiwagi (2010) a comparison is made for the wave profile along a longitudinal line parallel to the ship's advancing direction. Not only measured waves but also computed ones are used to validate the wave analysis method for predicting the added resistance and to study the effects of local wave and lateral distance for the wave measurement. Discussion is also made on which part of the wave is crucial and hence where attention should be paid in predicting the added resistance from the wave-pattern analysis.

The combined prediction procedure of added resistance in waves due to ship motion and wave reflection seems practically useful for the design of ships and the evaluation of their performance in waves, but its applicability and reliability related to the effect of forward speed, wave direction and bluntness of the hull shape are desired to be investigated for more various cases.

Recent growth in computer technology and power makes the near-field approach, through the integration of pressures on the hull surface more popular; an advantage this method is that it makes it easier to understand physical phenomena and is extendable to nonlinear problems.

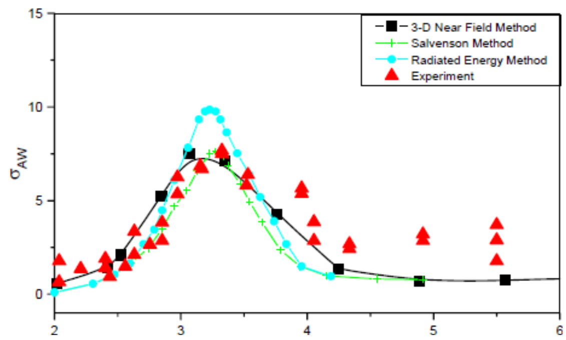



Figure 20 Added resistance of Series60 ship with CB=0.80 at Fn=0.165 in head waves (Zakaria *et al.*, 2010)

Zakaria *et.al.* (2010) used the 3D Green Function near-field approach and compared their results in regular head waves with 2D results and model tests. Predictions are for the Series 60 ship form with $C_B$ of 0.6, 0.7 and 0.8 and a fat bulk carrier ship whose $C_B$ is 0.829. Comparison results indicate that 3D method gives better agreement than 2D based

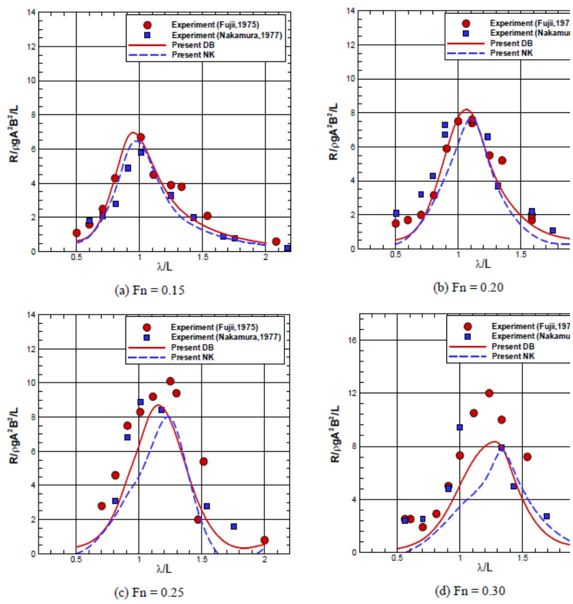



Figure 21 Added resistance of S175 container ship in head waves (Kim and Kim, 2010)

momentum conservation or radiated energy method especially around the resonance region. In the region of short waves the 3D method under-predicts the added resistance for ships with larger $C_B$ in comparison with model test results. An example of the comparison is shown in Figure 20.

Kim and Kim (2010) applied the time-domain Rankine panel method for the computation of added resistance in waves. The study included the comparison of two linearization schemes: Neumann-Kelvin (NK) and double-body (DB) linearizations. Examples of comparison between computations and model tests for S175 container ship are given in Figure 21.

According to these results, the double-body (DB) linearization generally gave better agreement than the Neumann-Kelvin (NK) linearization. At higher Froude number, the discrepancies between the theory and experiments became larger. in short wave region the theory under-predicted in general.

It is difficult to apply these methods to ship performance in severe sea conditions, where strongly nonlinear behaviour, e.g. slamming, green water, violent sloshing with impact load, are taking place; CFD codes have been recently developed that can deal with this strongly nonlinear behaviour. Even in rather mild sea condition, the added resistance in waves is also influenced by the hull shape above the still water line, which in general can not be treated by conventional calculation methods, but logically can be by CFD.

Baso *et.al.* (2010) have developed a coupled Eulerian scheme with Lagrangian particles, i.e. SPH and free surface particle on an Eulerian grid. The added of two tanker ships with slightly different hull shapes (Type A and Type B) is simulated. The predicted added resistance is compared with model test results, where the ratio of wave height to ship length Hw/Lpp is 1/50. Comparison result of added resistance is shown by Figure 22. CFD gives good agreement with experiments and better than the conventional strip theory.

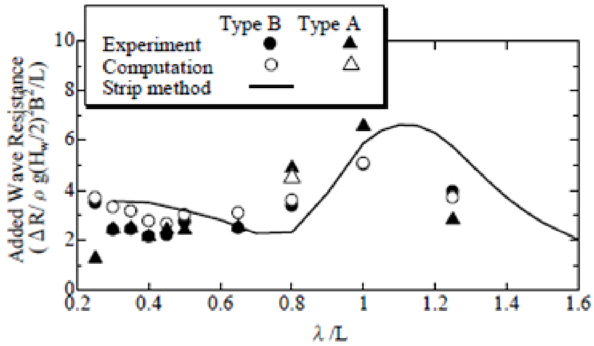



Figure 22 Added resistance of tankers at Fn=0.1385 (Baso *et al.*, 2010)

For the evaluation CFD in predicting the pressure distribution on the hull especially above the still water line and integrated to obtain added resistance Orihara (2010) applied the CFD code WISDAM-X. In this code the Reynolds-Averaged Navier-Stokes (RANS) equation and the continuity equation are solved on the overlapping grid system using finite-volume discretization. Free-surface treatment is based on the density-function method (DFM). The comparison results of added resistance on a VLCC at her ballast condition show good agreement with model test results, as given in Figure 23. The ratio of wave height to ship length Hw/Lpp of this case is 1/50.

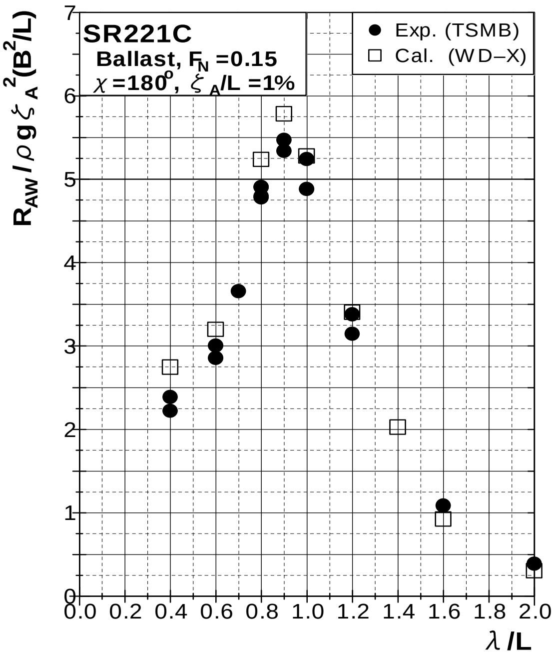



Figure 23 Added resistance of VLCC at Fn=0.15 (Orihara, 2010)

## 2.5 CFD applications in seakeeping

CFD analysis is becoming popular in marine hydrodynamics, and so is for the seakeeping problems. The primary difficulty in the application of CFD methods to ship motion analysis is the implementation of free surface flows, particularly for large scale free surface effects around ships. For the past twenty years, CFDs methods for free surface flows have been used mostly for local flows which have relatively smaller truncation volumes, i.e. computational domains. As the computational resource becomes more powerful, the applications to the ship wave problems have been introduced in recent years, showing a big potential for future application. Furthermore, CFD analysis is being extended to the problems more complicated than the classical seakeeping problems, such as springing problems and 3D ship slamming problems.

Figure 24 shows a brief summary of current CFD schemes for free surface flows, and it is valid also for the seakeeping problems. In a large sense, CFD method represents all the computational methods for fluid flow, including boundary element method (BEM), finite element method (FEM), finite difference or volume method (FDM/FVM), spectral method, etc. However, nowadays a common sense for CFD method is to concern only the field equations, i.e. the continuity equation, and the Navier-Stokes equation or the Euler equation. The current numerical methods can be categorized largely into two groups: grid methods and gridless methods. The former is known as the Eulerian approach which discretizes a fluid volume in structured or structured grids, and solve the field equation defined on these spatial grids.

On the other hand, the gridless methods have increased in popularity very recently. These methods, e.g. SPH (smoothed particle hydrodynamics) and MPS (moving particle semi-implicit method), define a finite number of fluid mass (basically, they are volume fractions), and solve the field equations by using their interactions.

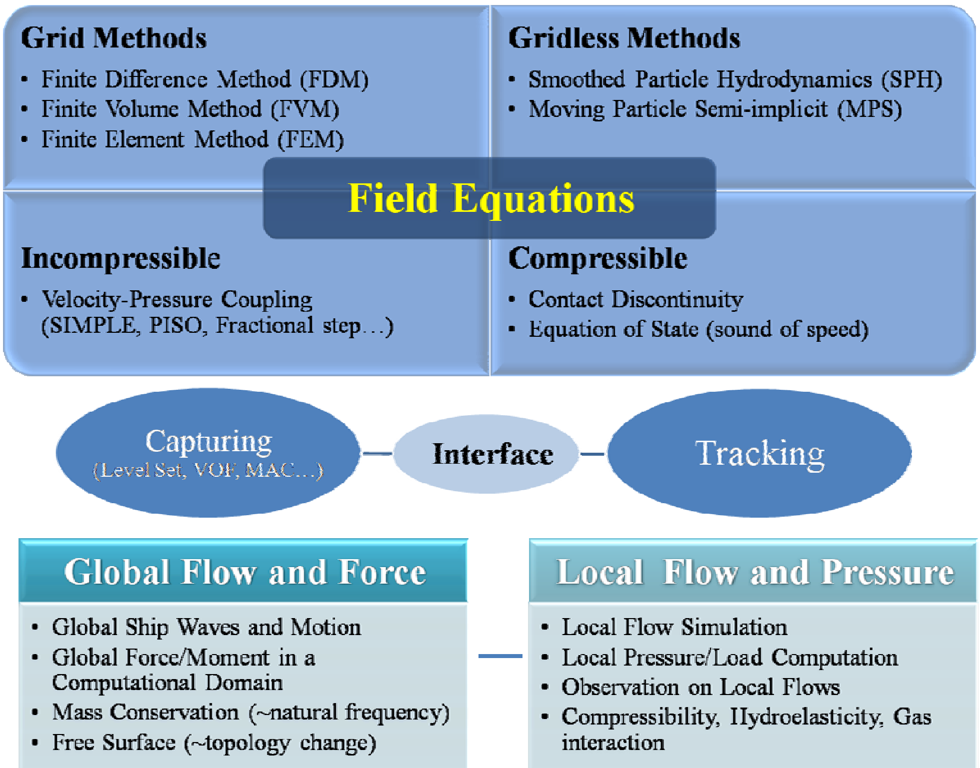



Figure 24 Overall status of the art of CFD schemes for free surface flow: Field equation solvers

In most cases, CFD methods for seakeeping problems do not have a heavy burden to take in to account the effects of viscosity. That is, most problems related to free surface flows in seakeeping problems are inertia-dominant problems, therefore the diffusion effect is relatively smaller than convection effect. In fact, this is the reason why potential theory is valid in the ship motion problem. In many cases, the more important physical phenomenon is the interaction between free surface flow and air flow. This is the case particularly when local impact hydrodynamic pressure is of primary interest.

The key technology in the application of CFD methods to seakeeping problems, including ship motion and local free-surface flows is how to obtain/trace the free-surface profile. When the grid methods are applied, there are several candidates to choose for the implementation of dynamic and kinematic free-surface boundary conditions. For the ship motion problems, VOF (Volume of Fluid) and level-set approaches are popular, but there are also recent work done using other methods. A good example is CIP (constraint interpolation profile) method. On the contrast to the grid methods, the numerical treatment of free surface in the particle methods is rather straight forward. Most of them adopt Lagrangian method, i.e. particle tacking in time-marching. Along with the simulation of particle motions inside a fluid volume, particle movement on free surface can be used to trace the profile of free surface. Nowadays, the OpenFoam program is available in public domain, and it is predicted that the application of OpenFoam to seakeeping problems will be getting popular near future.

The typical scheme of the free-surface flow solver is to solve the field equations including the dynamic condition on free surface. The dynamic condition is imposed through pressure. Then the free-surface profile can be updated from the velocity obtained from the field equations or by tacking the movement of particles on free surface. When surface tension is considered, the normal and tangential stresses obtained from the free surface profile at the previous time step or iteration can be imposed as the dynamic boundary condition. When interaction between liquid and air is considered, the air flow can be solved separately, but the same pressure on free surface should be imposed for the both domains. Figure 25 shows a typical flow chart for the SPH method.

The choice of a numerical method can be dependent on the problem to be considered. In the case of global ship motion, the grid methods are generally preferred so far, although the particle methods are catching up. However, it should be mentioned that, at this point, panel methods based on potential theory are used in the majority of cases. If the considered problem has a relatively smaller fluid volume, both the grid methods and particle methods are good candidates.

Compared with CFD methods used for ship resistance or manoeuvring problems, CFD methods for the seakeeping problem, more specifically speaking, the ship motion in waves, require the capability to simulate, precisely, the memory effects in the disturbed waves around a ship. The wave-induced ship motion is unsteady, so that the history of wave generation dictates the instantaneous force and moment on the ship. On the other hand, the resistance or manoeuvring problem have much longer time scale of the fluid flow around a ship, and the memory is relatively much less important.

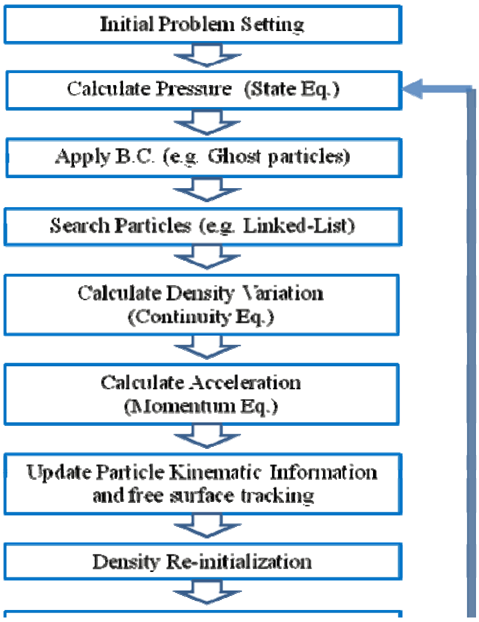



Figure 25 Typical procedure of SPH method

Over the past three years, the development and frequency of use of CFD methods for seakeeping problems have dramatically increased. There are generally two developer groups: in-house or commercial software. There are many studies using in-house codes, which are still under internal development, and a few representative groups can be introduced for seakeeping analysis. On the other hand, the application of commercial programs is also getting more popular. STAR-CCM+, Fluent, CFX are examples.

Iowa University (IIHR) has undertaken a great deal of research on resistance, and more recently manoeuvring. Their software has been extended to include the analysis of ship motions in waves. For instant, Simonsen *et al.* (2008) carried out a motion analysis for the KCS ship hull in heave and pitch motions in regular head waves using their RANS code, CFDSHIPIOWA, and compared results with the experiments. The activity of Iowa University group includes Carrica *et al.* (2008), Paik *et al.* (2008).

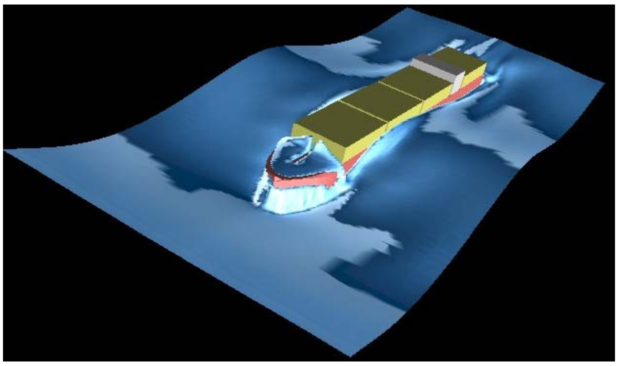


Figure 26 Example of seakeeping analysis using CIP method (Hu *et al.*, 2008, 2009)

CIP methods have been successfully applied to very violent ship motions in severe wave conditions. Hu *et al.* (2008) showed the application of their CIP method, name to RIAM-CIMEN, to a real containership under very large motion responses in waves. In 2009, Hu *et al.* replaced their scheme for free surface to THINC scheme, which approximates the free surface profile by using a tangential hyperbolic function. This scheme can consider the sharp change of free surface profile more accurately than conventional polynomial functions.

Some studies applied spectral wave explicit Navier-Stokes equation (SWENSE), Monroy *et al.* (2009, 2010) showed the simulation results of floating-body motions under wave excitation. The used the SWENSE approach combined with potential flow for incident waves.

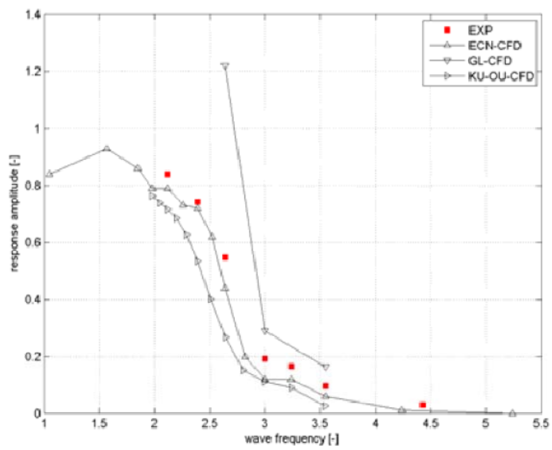
Most of field equation solvers adopts the Reynolds-averaged Navier-Stokes equation (RANS) for ship motion problems. Such example includes the result of Visonneau *et al.* (2008), Wu *et al.* (2008), Bhushan *et al.* (2009) and Deng *et al.* (2010). Many of them used the VOF scheme for the numerical treatment of free surface.

Particle methods have been also applied for ship motion problems, e.g. Baso *et al.* (2010) and some French researchers. Baso *et al.* showed the computational results of ship motion in wave, including the simulation of rather local flows such as slamming and green water. However, due to very heavy burden of CPU time, the particle methods have been applied mostly for local flows, not for global ship motion. Such cases will be introduced later. The particle methods can be a good tool to predict the motion responses of damaged ships, since typical panel methods are not effective for such problem. Most CFD methods can simulate the water-ingress into the damaged ship, and it is anticipated that t the Stability in Waves committee will cover those effectively.

It should be mentioned here about the application of CFD methods for wind-wave generation and/or large freak wave prediction, e.g. Shen *et al.* (2008). An accurate prediction of the incident waves is a crucial element in the seakeeping analysis. As the nonlinear effects of ship motion are getting more important in present engineering problems, the generation and prediction of nonlinear ocean waves should be the input of the seakeeping analysis for ships and offshore structures. Therefore, although it is not the direct ship motion simulation, such activity should be noted.

It should be mentioned that the application of CFD methods to global ship motion is not in a matured status yet. There are two primary reasons of such limitation. First of all, CFD application requires significant CPU time Although the computational power is much better than in the past, a great deal of CPU time is needed for the global ship motion calculations. Particularly, seakeeping problems require a simulation time than resistance and most manoeuvring problems. So, CFD approaches are not efficient methods for obtaining motion RAOs for a range of wave headings and frequencies. Secondly, CFD methods are still relatively poor at simulating the disturbed ship waves in the far field domain. Since the memory effect, i.e. wave propagation from a ship to far-field, is critical in the ship motion problem, the capability of simulating the disturbed waves with proper dispersion characteristics is very important. At present, CFD methods are very acceptable for the simulation of local flows; however they have limited capability for such global wave simulation. Therefore, many such studies have focused on very nonlinear problems which potential theory is not valid. To compensate such limitation of CFD approaches, potential theory is sometimes combined with CFD approaches. Despite such limited application and capability, CFD methods will be developed to overcome such limitations, and they may replace the current potential-based methodology some time later.

Efforts to compare the numerical methods, particularly potential method and CFD method including viscosity, have been of interests, but not many in publication forms. Belknap *et al.* (2010) and Grasso *et al.* (2010) compared the non-linear ship motion predictions from potential codes and a CFD code. The potential computations were based on the weakly nonlinear assumption. More systematic studies on the comparative study can be found in the recent work carried out as Cooperative Research Ships (CRS) project (Bunnik *et al.*, 2010). The CRS conducted a comparative study, like the ITTC Seakeeping workshop and the results from the different approaches have been compared. One of their important findings is that an accurate computation of restoring properties, i.e. hydrostatics, consequently ship volume, is important.




Heave

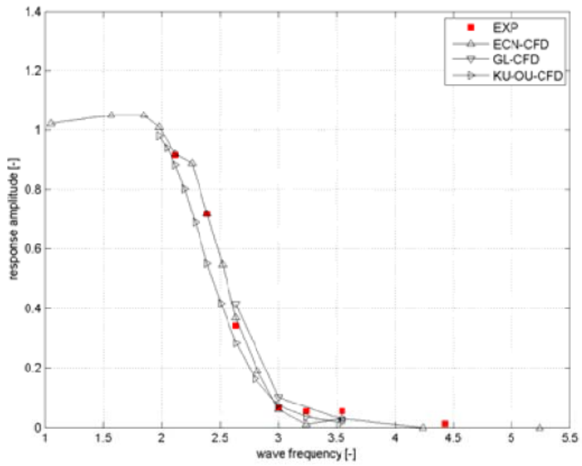



Figure 27 CFD vs experiment for the heave and pitch motion of a containership (Bunnik *et al.*, 2010)

A practical application of CFD methods is in the prediction of roll damping. The empirical roll damping coefficient derived from experiments can be replaced by the equivalent predicted using CFD. Such applications includes the works of Kim *et al.* (2008), Miller *et al.* (2008), Broglia (2009), and Greeley and Petersen (2010). In most studies, the unsteady RANS equation has been considered. Belibassakis (2010) extended such application to the roll motion of ships in vary bathymetry regions by using a hybrid BEM-vortex particle method.

Slamming is one of the problems, which many CFD applications can be found. Classically, slamming impact pressure has been predicted by analytic approaches, such as using the von Karman and Wagner theories. However, such analytic methods have clear limitations in application to arbitrary geometry, and particularly in extension to 3D bodies. To overcome the limitation of classical theories, CFD methods have been applied, and more application of CFD in future is obvious. Particle methods have been used to solve the 2D and 3D water-entry problems. Such example includes the works of Kim & Hong (2008) and Gong *et al.* (2010) for 2D wedge impact, and Maruzewski *et al.* (2009) for 3D water-entry impact.

CFD methods have been also applied to green water problems. From a consortium project organized by MARIN in 2000, a computer program called ComFlow was developed and applied to the simulation of green water on deck. CFD application has been continued in past a few years; Particularly, Colicchio *et al.* (2010) adopted a domain decomposition method which combined a BEM and NS equation solver.

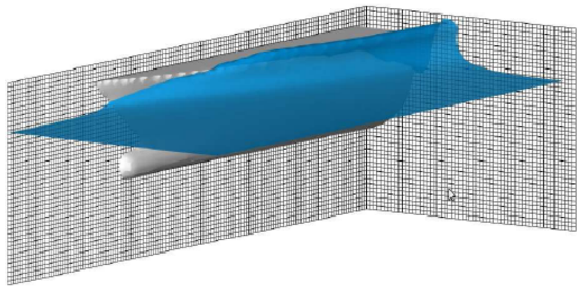


Figure 28 Green water on deck simulated by Colicchio *et al.* (2010)

CFD simulation for sloshing has been extensively carried out in a few years. Particularly, the 1st and 2nd Sloshing Dynamics and Design Symposium was held as a part of the ISOPE conference, and many papers based on CFD computation were presented. For sloshing simulations, many numerical methods have been applied, and those includes level set (e.g. Gu *et al.*, 2009), MPS (e.g. Sueyoshi, 2009), SPH (e.g. Oger, 2009), and other typical CFD methods. Some representative results are listed in the state-of-art review for sloshing described above Two extensive comparative studies have been carried out as a part of the 1st and 2nd Sloshing Dynamics and Design Symposium in 2009 and 2010. In the first year, computed and measured pressures were compared for two tanks, and the liquid drop hitting on floor has been considered in the second year.

## 3. WORKSHOP ON VALIDATION AND VERIFICATION OF NON-LINEAR SEAKEEPING CODES

With the availability of non-linear seakeeping analysis tools increasing to address these more challenging design problems, verification and validation (V&V) of these prediction tools is becoming more important. One of the tasks for the 26th ITTC Seakeeping Committee was to organize a workshop on the verification and validation of non-linear seakeeping codes in which suitable benchmark data could be identified and used in a comparative study of non-linear codes. The workshop was organized in collaboration with the Department of Naval Architecture and Ocean Engineering in Seoul National University, held in Seoul on 19th – 21st October 2010, was jointly sponsored by the Office of Naval Research, Seoul National University, Daewoo Shipbuilding and Marine Engineering Co., Samsung Heavy Industries, LRET-funded Research Centre at SNU and the Advanced Marine Engineering Centre; the full proceedings and results of the comparative study are in Kim, 2010. The aim was to use the outcomes of the workshop to further develop the procedure on V&V of non-linear seakeeping computer codes. The assumption from the Seakeeping Committee was that there would be insufficient time to include the outcomes of the workshop in an updated version of the non-linear procedure but instead would make recommendations for updating the procedure to the future committee.

It appears to be unclear over what verification is and what validation is. In terms of the development of seakeeping analysis software, there is a clear distinction between verification and the validation which is defined in Seakeeping procedure No. 7.5-02-07-02.5 Verification and Validation of Linear and Weakly Non-linear Seakeeping Computer Codes. The definitions adopted in this procedure are:

**Verification** of a computer code is the proof of its implementation. To verify a computer code one has to check that the simulation code is a correct representation of the mathematical model that forms the basis for it. One, thus, establishes that the code written echoes the intended operations and procedures necessary to fulfill or complete the required intended tasks. Its successful accomplishment means that the way the code emulates the theory in itself is correct.

**Validation** of a computer code is the proof of its applicability. To validate a computer code one has to demonstrate that the mathematical model of the verified computer code is an adequate representation of the physical reality.

The workshop provided the forum for bringing together the user and developer communities of non-linear time domain seakeeping computer programmes, to provide the means to discuss the individual approaches that are adopted in V&V activities; to help understand and gain a consensus on the most pragmatic approach to V&V. In order to facilitate this it was organised to be in two distinct formats; the first an informal conference, with proceedings, inviting technical papers on non-linear seakeeping analysis and the second presenting the results of a comparative study including a panel discussion on V&V. The informal conference consisted of sessions relating to:

- The development of non-linear theories
- Wave loads and hydroelasticity
- Verification and validation activities
- Parametric and resonant rolling
- Navier-Stokes formulations
- Applications in design

The validation activities covered in these papers are summarised in **Erro! Fonte de referência não encontrada.**.

The perception amongst those attending was that V&V activities are too expensive and in some cases developers rely on their track record as a demonstration of validation. The key to V&V is to ensure the process is streamlines and targeting key issues throughout the development process.

### 3.1 Comparative study

In preparation for the comparative study, participants were provided with a dataset of benchmark test cases from which their V&V activities of their non-linear ship motion prediction methods were compared. The ship geometry and the specific test conditions for the comparative study were made available to participants including access to sample test data. The full set of test data was made available at the workshop, including allowing the data to be downloaded for future use. The choice of hull used in the comparative study was rather limited with only data from a series of tests on the S175 identified as sufficient for this non-linear comparative study; other datasets tend to be protected and not widely releasable. The S175 provides data for linear and non-linear analysis. Figure 29 shows the body plan of the S175 with the principal dimensions of the ship in Table 5.

Table 5 Principal dimensions and mass properties of the S175 containership

| | |
|---|---|
| Length between perpendiculars (L) | 175 m |
| Breadth (B) | 25.4 m |
| Depth (D) | 15.4 m |
| Draught (T) | 9.5 m |
| Displacement | 24742 ton |
| LCG aft of midship | 2.5 m |
| Block coefficient ($C_B$) | 0.572 |
| Midship section coefficient ($C_M$) | 0.98 |
| Total mass | 23972251 kg |
| XG (from AP) | 84.97 m |
| YG (from centreline) | 0 m |
| ZG (from keel line) | 8.5 m |
| Rxx | 9.652 |
| Ryy | 42.07 |
| Rzz | 43.17 |

Two datasets were made available; one set suitable for linear analysis consisting of motions and loads RAOs at 1 speed and 4 headings: and one set suitable for non-linear analysis consisting of motions and loads varying with wave steepness and time histories of motions and loads at 3 speeds and 1 heading. Table 8 and Table 9 summarise the data that were made available for linear and non-linear analysis. There were 8 organisations participating (providing 9 contributions) from Asia, Europe and North America, **Erro! Fonte de referência não encontrada.**. The theories employed include strip theory, Rankine panel methods, Green function methods and CFD methods.

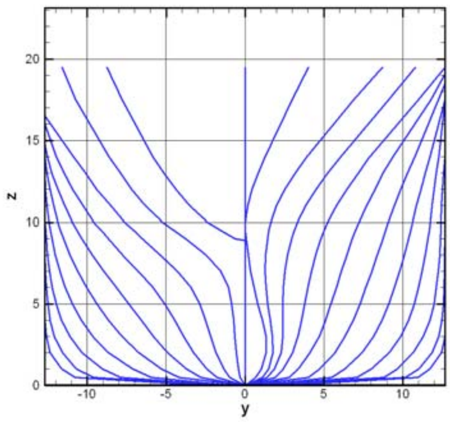



Figure 29 Body plan of the S175 containership

A complete set of the comparisons are presented by Kim (2010); here are some examples of the comparisons shown anomalously. Figure 30 shows the predictions of the 6 degrees of freedom RAOs compared with experimental data where possible. These results are from tests in waves with small amplitude so in principal are linear responses. There is quite an amount of scatter in the predictions for all degrees of freedom. In the case where there are experimental data, most methods over-predict heave around the resonant frequency. This is also the case for pitch response, but furthermore, in this case the predictions don't all tend to the same value at lower frequencies.

For the lateral plane responses, in the first instance there are not experimental data for comparison. However, considering the predictions in isolation, roll motion differs quite considerably at the lower frequencies which could be attributable cross coupling with yaw. In some cases, the participants used autopilot control as the restoring force for the lateral plane motions in some cases they used a soft spring to replicate the restoring force; thus accounting for the differences in the yaw at low frequencies.

Table 6 Validation approaches adopted by workshop authors

| Author | Method | Wave excitation RAOs | Motion responses/Hydrodynamic loading | | | | | | Exceedance probabilities | Added resistance |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Vertical plane RAOs | Lateral plane RAOs | Time histories | Harmonics | Variation with wave steepness | Spectra | | |
| Liu et al | Body non-linear | ✓ | ✓ | | | | | | | ✓ |
| Bruzzone et al | Body non-linear | | ✓✓ | | ✓ | ✓ | | | | |
| Kim et al, | Weak scatterer | | ✓✓ | ✓✓ | ✓✓ | x✓ | ✓ | | | |
| Qui et al | Body non-linear | | ✓✓ | ✓✓ | | | ✓✓ | | | |
| Miyake et al | Non-linear strip | | x✓ | | x✓ | | | | ✓ | |
| Wu et al | Body non-linear | | ✓✓ | | | | | | ✓ | |
| McTaggart | Body non-linear | | ✓ | ✓ | | | ✓ | | | |
| Walree and Carette | Body non-linear | | | | ✓ | | | | ✓ | |
| Grigoropoulos et al | Linear, body non-linear, weak scatterer | | ✓ | | x✓ | | | | | |
| Bulian et al | Mathieu equation | | | ✓ | ✓ | ✓ | ✓ | ✓ | | |
| Matusiak | Body non-linear | | | | ✓ | | | | | |
| Kim and Kim | Mathieu equation, body non-linear, weakly non-linear | | ✓ | ✓ | ✓ | ✓ | | | | |
| Kim | fully non-linear | | | | x✓ | x✓ | | | | |
| Orihara | fully non-linear | | ✓ | | ✓ | | | | | ✓ |
| Wu et al | fully non-linear | | ✓ | | | | | | | ✓ |
| Kim et al | Body non-linear | | x✓ | ✓ | | | | | | |
| Cho et al | Weak scatterer | | ✓ | ✓ | | | | | | |
| Comparative study | | | ✓✓ | ✓ | ✓✓ | | ✓ | | | |

Key: ✓- Only motions, x✓- Only loads, ✓✓- motions and loads

Table 7 Participants

| Affiliation | Methodology | Linear/Nonlinear |
|---|---|---|
| Defence Research and Development Canada-Atlantic, Canada | BEM | Linear |
| Harbin Engineering University, China | BEM | Nonlinear |
| Maritime & Ocean Engineering Research Institute, Korea | BEM, FEM | Linear, Nonlinear |
| National Maritime Research Institute, Japan | 2D-BEM | Nonlinear |
| National Technical University of Athens, Greece | BEM | Linear, Nonlinear |
| Osaka University, Japan | CIP(CFD) | Nonlinear |
| Seoul National University, Korea | BEM | Linear, Nonlinear |
| University of Southampton, England | BEM | Linear |

Table 8 Computational condition for linear analysis

| Fn | Heading angle | $\lambda/L$ | Motion | Load |
|---|---|---|---|---|
| 0.275 | 180 deg | 0.2~2.4 | Heave, pitch | VSF, VBM |
| 0.275 | 120 deg | 0.2~2.4 | Surge, sway, heave, roll, pitch, yaw | VSF, VBM, HSF, HBM |
| 0.275 | 90 deg | 0.2~2.4 | Sway, heave, roll | |
| 0.275 | 0 deg | 0.2~2.4 | Heave, pitch | VSF, VBM |

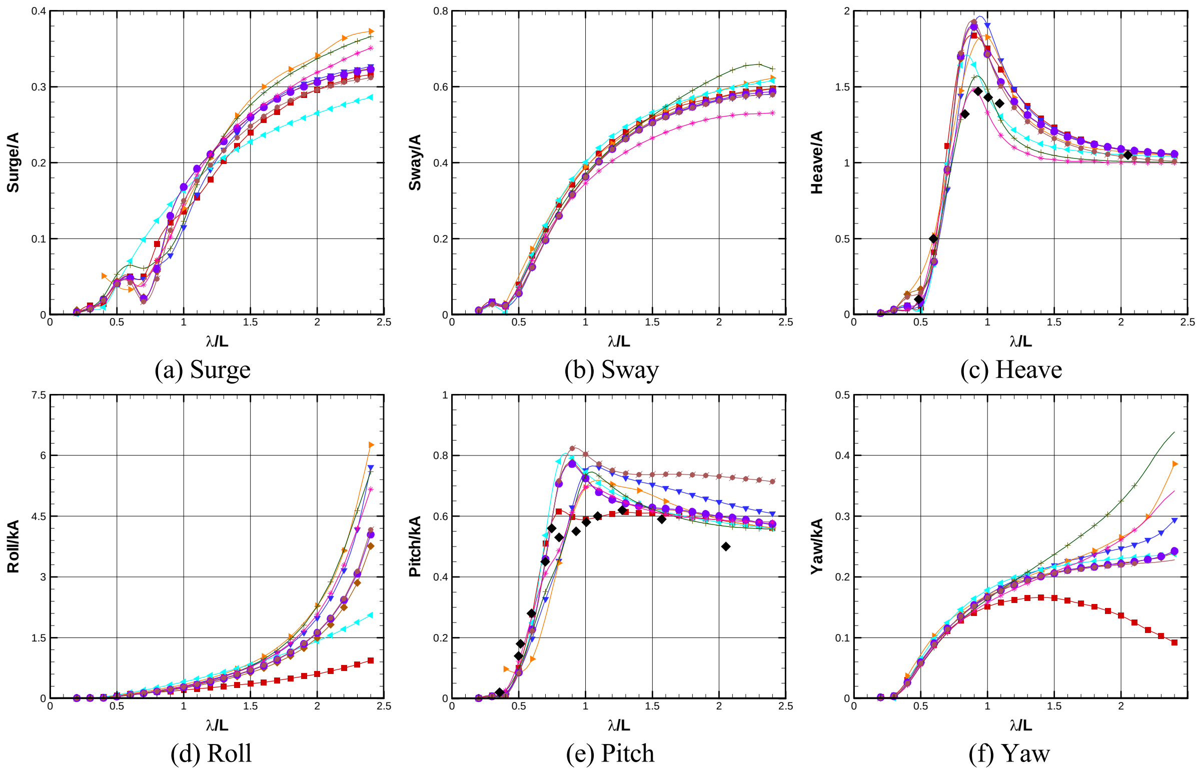
Table 9 Computational condition for nonlinear analysis

| Fn | Heading angle | λ/L | kA | Motion | Load |
|---|---|---|---|---|---|
| 0.20 | 180 deg | 1.0 | 0.01, 0.04, 0.08, 0.12 | Heave, pitch | VBM(hogging), VBM(sagging) |
| | | 1.2 | | | |
| | | 1.4 | | | |
| 0.25 | 180 deg | 1.0 | 0.01, 0.04, 0.08, 0.12 | Heave, pitch | VBM(hogging), VBM(sagging) |
| | | 1.2 | | | |
| | | 1.4 | | | |
| 0.275 | 180 deg | 1.0 | 0.01, 0.04, 0.08, 0.12 | Heave, pitch | VBM(hogging), VBM(sagging) |
| | | 1.2 | | | |
| | | 1.4 | | | |

Figure 31 shows the predictions of the structural load, as shear force and bending moment, from tests in waves with small amplitude. Here there is more scatter in the predictions of vertical and lateral shear force and bending moment compared to the motions. It is clear that experimental data for loads are lacking.

For the non-linear cases, the only available data were from vertical plane tests in increasing wave slope and time histories of some motions and loads.

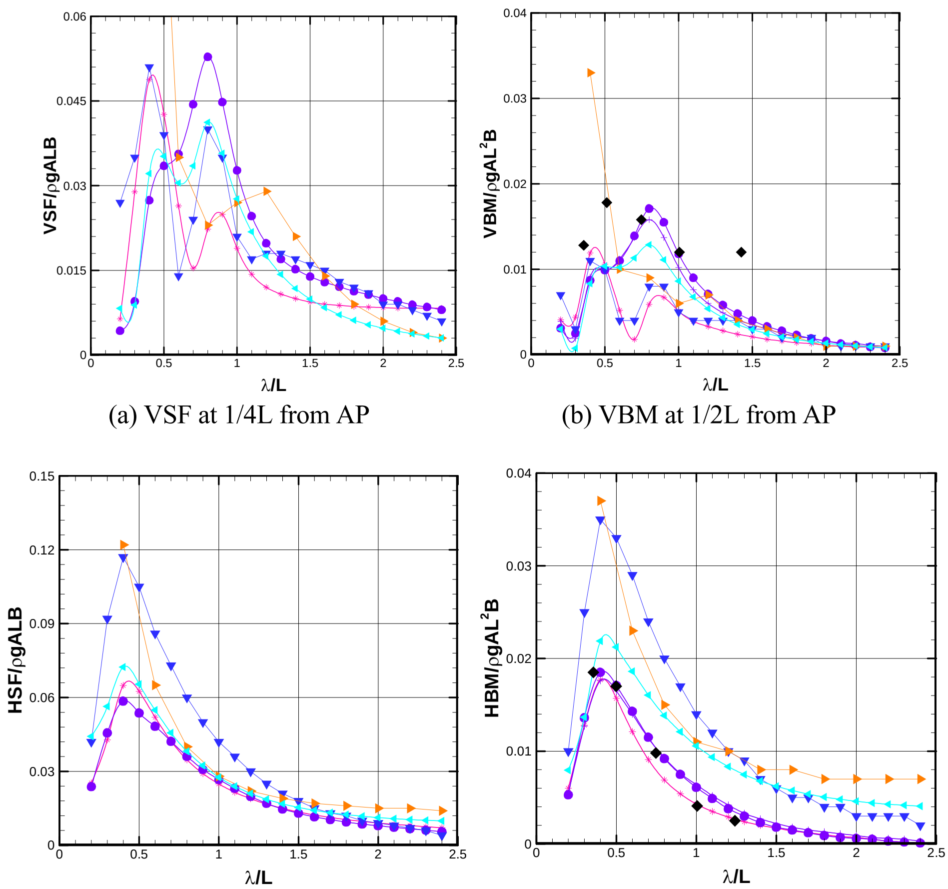
Figure 32 shows the vertical plane responses in increasing wave slope for three wave frequencies. In most cases the trends of reducing amplitude with increasing wave slope is reproduced in the predictions. The outcomes of the comparative study is the requirement for more, shared, experimental data from a range




(a) Surge (b) Sway (c) Heave

(d) Roll (e) Pitch (f) Yaw

Figure 30 Motion RAOs (120 degrees)




(a) VSF at 1/4L from AP

(b) VBM at 1/2L from AP

(c) HSF at 1/4L from AP

(d) HBM at 1/2L from AP

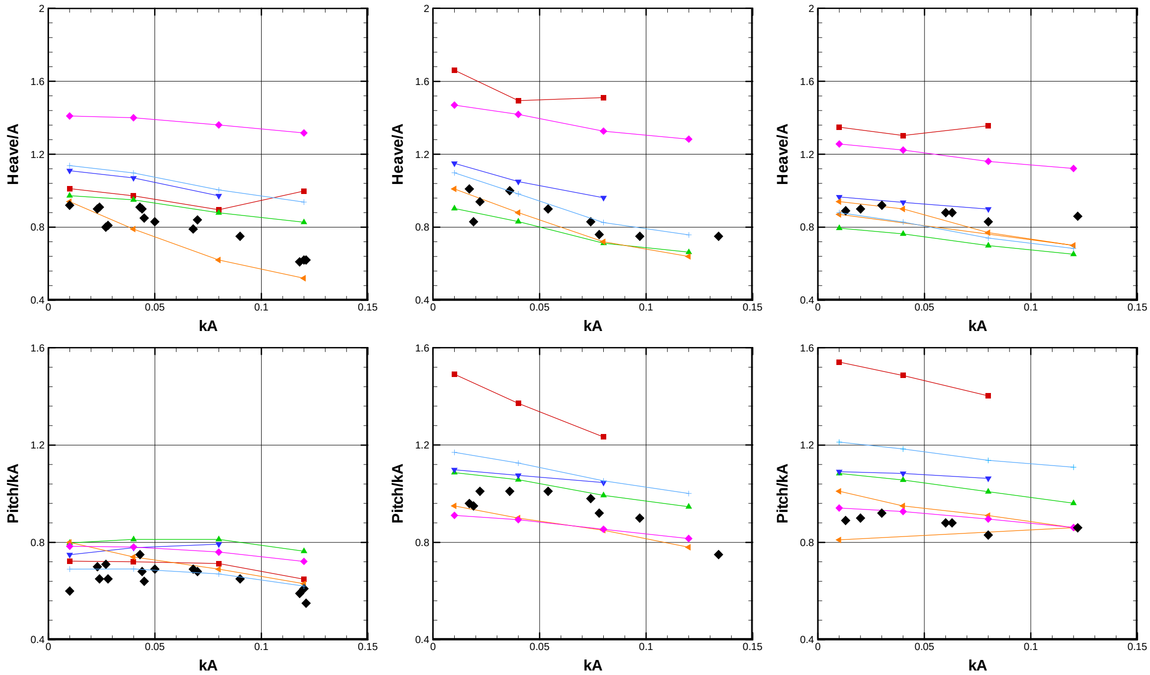
Figure 31 Structural load (120 degrees)

of ship designs that should include data from irregular waves and if possible data from hydroelastic tests.

Table 6 shows a summary of the type of validation data that the authors presented in their papers; this reflects the level of validation that authors would undertake given the choice (subject of course to availability of data) and the data set available in the comparative study.

In terms of motion responses, most of the data are from RAOs; clearly these data usually come from tests at small wave amplitude and so should only be considered as the first step in the validation of a non-linear code. There are more examples of comparisons with vertical plane RAOs rather than lateral plane (oblique waves) experiments; clearly this is a result of an oblique waves experiment being more complex and hence less popular to undertake as part of the validation process. The most popular means of assessing non-linear prediction is by comparing numerical simulations with experiments showing responses in increasing wave steepness. Inspection of time histories are also considered by can only be qualitative; in some cases these time histories are further analysed to determine the higher order harmonics in the non-linear response.

For hydrodynamic loads, again RAOs are the most popular form of validation with some inspection of time histories also included. For loads, the most popular datasets are for vertical shear force and bending moments, in the cases of lateral plane, the shear force and bending moments are also presented by there are very little data relating to torsion. In the definition of non-linear loads it is important to make clear the basis of the hydrostatic loads resulting from




(a) λ/L=1.0 (b) λ/L=1.2 (c) λ/L=1.4

Figure 32 Heave (upper) and pitch (lower) motion responses (Fn=0.20, β=180°)

the running sinkage and trim. This was a clear inconsistency in the comparative study in which in some cases the hogging and sagging correction was applied at the mean water level for the specific running sinkage and trim and in some case it was not- making direct comparison difficult.

The most popular data sets adopted by the individual authors were as follows.

For motions:

- Vertical and lateral plane RAOs
- Harmonic analysis
- Variation of response with wave steepness

For loads:

- Vertical and lateral plane RAOs
- Variation of response with wave steepness
- Exceedance probabilities

The 26th ITTC seakeeping committee has updated procedure 7.5 – 02-07 - 02.5 to include the verification and validation of weakly nonlinear seakeeping codes. The basis for weakly nonlinear computations, which represents the most popular approach at the moment, is not dissimilar to that for linear computations. The hope is that the outcomes of this workshop can be used in extending the procedure further to include fully non-linear.

Weakly nonlinear methods have been developed to predict the primary nonlinear effects due to the incident wave and variation in the instantaneous restoring force due to the body motion. This method is effective and efficient, particularly when the ship is slender. The V&V approach is not so different to that for linear codes except that additional aspects should be checked throughout the process; the procedure still recommends comparison with linear responses in addition to full non-linear responses. The nonlinear solution is dependent upon the formulation of nonlinear components, incident wave amplitude, and body geometry above the still water level and so these items should form part of the V&V process.

One outcome from the workshop and the comparative study is that verification activities are not explicitly discussed in papers; this activity is seen as something very specific for the software developers and not generally discussed in open literature papers. This committee recommend that verification activities are explicitly demonstrated by those who develop these types of computer codes.

The verification process for linear and weakly non-linear is clear from the procedure and is based upon verification of the initial conditions and boundary conditions but also based upon the assumptions and relationships embedded in the methodology. For example, comparing the diffraction forces and moments obtained by the integration of pressure with those determined by the Haskind relations and comparing the viscous contributions to roll damping against the empirical data are two forms of verification that are appropriate for weakly non-linear codes but will not be appropriate for fully non-linear CFD type approaches. The verification activities for fully non-linear approaches appear to include with grid resolution studies to quantify the grid error; grid studies appear to be targeted towards 2D comparisons with analytic solutions and the linear RAOs. Verification for three dimensional problems includes breaking down the output to provide confirmation of matching the boundary conditions.

In practice, validation activities for fully non-linear codes will follow those for weakly non-linear as a result of the type of data available. However, CFD does provide the opportunity to validate computations against velocity data, as opposed to pressure data for weakly non-linear.

## 4. UNCERTAINTY ANALYSIS AND BENCHMARK DATA

Need for uncertainty analysis in measurements, and verification and validation of numerical codes does not have to be emphasised over and over. The V&V process requires benchmark data that meets criteria specified by ITTC 2008. Benchmark data could be obtained from properly conducted either model scale experiments or full-scale trials. Full-scale data is particularly valuable as it by passes all scaling concerns relevant to model experiments.

Uncertainty in measured seemed to be matured and with transformation of ITTC 2009 approach to ISO method in line with the ITTC international community expectations. However, not all presented experimental results are yet published together with uncertainty calculations. This is particularly dissatisfactory when the data is used in process of numerical code validation. V&V of numerical codes is mostly limited to qualitative comparison of calculation with measurement (simplified validation). Fortunately interest in improving understanding of V&V methodology and procedures is growing.

Irvine, Longo and Stern (2008) present towing-tank experiments of coupled pitch and heave motions for a surface combatant advancing in regular head wave. The test program was undertaken to provide a validation data set for unsteady RANS and other CFD codes, including rigorous uncertainty assessment of the experimental results following standard procedures. Results indicate that the regular head waves are linear with second- and third-order magnitudes consistent with third-order Stokes waves. Pitch and heave responses and phases show expected trends for long and short wavelengths and are linear. Maximum response occurs for frequency of encounter equal to pitch and heave natural frequencies and Lpp/λ =0.75.

Eça, Vaz, and Hoekstra (2010) provide an overview and discussion of procedures for Code Verification, Solution Verification and Validation. Examples of the three types of procedures are presented for simple test cases demonstrating the advantages of performing Verification and Validation exercises.

Grochowalski and Jankowski (2009) present a methodology for validation of computer software for simulation of ship motions and capsizing in extreme waves. The requirements for dedicated model experiments are defined and the validation phases of the software are explained. Examples of the validation of certain parts of the computer program as well as the whole software package are included.

Huijsmans *et al.* (2010) present results of a benchmark exercise consisting comparison of results obtained from 12 various state-of-the-art numerical codes and model test results of a modern container ship. The authors found that the panel method based on the disturbed steady flow, leads to acceptable transfer functions for ship motions. The CFD approach used in this study also produces acceptable motion transfer functions. However the results from the CFD computation for the internal load transfer functions do show a larger scatter when comparing with the results from model test.

Hydroelastic behaviour of hull-girder structure is getting more important as the size of modern ships becomes larger and voyage speed becomes faster. Kim *et al.* (2010) introduced a new numerical method, which adopts a fully coupled BEM-FEM in time domain. In the study, this numerical method has been applied to real ship models, including large LNG carriers and containerships, and the computational results are compared with towing-tank experiment for validation. Furthermore, extension to nonlinear problem is introduced.

Kim, Yu and Hong (2010) provide an overview of a recent study to investigate the nonlinear wave loads acting on large container carriers using segmented model tests and numerical analysis. Under the Wave Induced Loads on Ships (WILS) JIP, extensive model tests were undertaken to measure the nonlinear wave-induced extreme and springing loads. The authors selected the most critical test cases are selected and compared with numerical results from the nonlinear seakeeping analysis. From this comparative study, the numerical analyses are successfully validated.

Results of model scale experiments are frequently applied to validate numerical codes. Simulation results are typically presented in full-scale values. However it is still unclear if numerical codes formulations are appropriate for simulations at full-scale Reynolds number. Atsavapranee *et al.* (2008) performed a full-scale calm water roll decay trials to investigate if RANS codes can produce reliable full-scale results. The main thrust of the trial was an examination of the viscous flow field through the collection of particle image velocimetry (PIV) data. To help in the understanding of the overall flow field and associated forces, strain gage measurements of the bilge keel lateral force were also made. Other data collected includes measurement of the local environment (wave and wind), ship motions and ship speed through water.

## 5. ITTC RECOMMENDED PROCEDURES

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

An editorial modification to chapter 4.1 was introduced to reflect ITTC 2008 change in general approach to experimental uncertainty analysis.

The only substantial change made to the procedure was modification to the committee approach to experimental uncertainty analysis that is included in the Appendix. The committee follows ITTC 2008 recommended internationally recognized ISO GUM approach. The committee provides definitions of Type A and Type B uncertainty as well as formulae for their calculations. Sources of both types of uncertainty are identified and explained, and simple samples presented. Concepts of standard uncertainty, combined uncertainty and expanded uncertainty are discussed and confidence level factors provided. Examples of standard and combined uncertainties estimated based on a seakeeping experiment with model of a submarine operating on surface is given.

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

In this procedure three methods for predicting power increase in irregular waves from model experiments in regular waves, i.e. QNM (Torque & Revolution Method), TNM (Thrust & Revolution Method) and RTIM (Resistance & Thrust Identify Method), are evaluated based on the comparison of their predicted results. The comparison of these results should also be compared with the measured power increase in irregular waves obtained from the direct irregular wave tests such as resistance tests or self-propulsion in irregular waves.

But the full set of data obtained from model tests in still water, in regular waves and in irregular waves for the same ship model were not found, which are necessary for the comparison of power increase in irregular waves between the prediction from model tests in regular waves and the irregular wave tests. Instead of the above, the comparison of resistance increase, propeller torque and revolution increase in irregular waves between prediction from regular wave tests and the irregular wave test results is performed.

According to the above comparison results, the prediction accuracy for resistance increase is acceptable, but that for propeller torque and revolution is not good. This means that RTIM seems applicable for the prediction of power increase in irregular waves in the reasonable prediction accuracy rather than QNM or TNM. However, the amount of data use for the above evaluation is limited and further investigation is necessary.

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

This procedure has been reviewed by the committee which only addressed minor corrections.

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

This procedure has been updated to include the V&V activities required for weakly non-linear seakeeping analysis, focussing on weakly or weak-scatterer-based nonlinear time domain analysis. In addition to the V&V activities that are required for the development of linear seakeeping codes, further step are recommended that are specific for these types of nonlinear methods. Mandatory requirements are provided for the representation of the input and output data.

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

This new procedure has been written to outline the methods by which measurements of global wave loads can be made. The procedure describes the design of the experiment, the set-up of the model and instrumentation, the test, and the analysis. This procedure expands the existing seakeeping procedure (7.5-02-07-02.1) by outlining the additional considerations required for the measurement of global loads using the various options for model construction and experimental designs.

## 5.6 ITTC Procedure 4.2.4-01 Standard Format for Exchange of Seakeeping Data on Computer-Compatible Media

This procedure was reviewed by this committee and recommended that it should be withdrawn since procedures relating to the presentation of results and formatting of data is usually covered by the particular procedure.

## 6. CONCLUSIONS

### 6.1 General technical conclusions

Imperfections in the waves that are generated in model tests are recognised as the major source of uncertainty in experiments of this nature; developments in techniques aimed at quantifying and/or reducing these effects are recommended. The development of experimental facilities continues to be driven by the need to validate numerical codes, design and evaluate performance of modern unconventional hull forms such as high-speed and multihull ships, investigations into highly nonlinear global and local loads related to incidents like slamming, whipping springing or sloshing, and modelling of extreme sea conditions. The need for more experimentation within these areas is vital for all ranges of operational and environmental conditions.

The need for quality benchmark data is as great as ever, particularly relating to the measurement of non-linear motions and global loads from tests on a modern hull form; more often experiments of this nature are undertaken as part of Joint Industry Projects which means that data may not be released in open literature.

Full-scale data provide the most robust form of validation in terms of the realism of the data that are collected. In many cases the data, usually, have an unacceptable level of uncertainty mainly as a result of the inability to control and quantify the ocean environment. Increasing numbers of ships are fitted with monitoring systems to collect a wealth of data that could be used for design; there is a need to further develop the techniques that reduce the uncertainty in full-scale data.

Frequency domain analysis still represents the chosen approach when considering rapid evaluation of prototype designs. However, there are few developments in this area, except in the area of coupling frequency domain methods with structural models (thus representing an efficient means of evaluating global loads for concept designs).

The popularity of time-domain methods for seakeeping analysis is increasing as a result of the advantages that time domain analysis brings in the extension to nonlinear motion and structural loads, and coupling with external or internal forces. Therefore, the importance of verification and validation of such computational methods is high. For the community involved in time-domain computation, the demonstration of verification activities is recommended. When nonlinear ship motions and structural loads are considered, the asymptotic behavior at small wave amplitude, i.e. the recovery of the linear solution, can be observed as one form of verification. The validation of the computer program should be done systematically by comparing with experimental data and/or frequency-domain solutions. The generation of data, from tests on modern hull forms, that are suitable for validation is required particularly for nonlinear seakeeping tests. The time-histories of ship motions or structural loads (for rigid and hydro-elastic bodies) are required for subsequent analysis in validation activities.

Hydro-elasticity is of great interest to the maritime community; particularly, in recent years, a great deal of evidence has been observed that springing and whipping phenomena contribute significantly to fatigue damage in very large commercial ships. Therefore, it is strongly recommend that more activity on this issue is addressed by the research community. A more precise description of the experimental model and/or numerical model is recommended. Crucial information such as sectional properties and the method of modeling the backbone should be described in detail. Since bench-mark-test cases are very limited in the field, more comparative or collaborative studies are highly recommended.

Very large ships with a rather flexible structures and low natural frequencies in various structural response modes are prone to whipping. The combination of the "regular" (rule based) wave loading on the ships combined with the additional loads due to the whipping effects have been found to result in significantly higher loading being predicted than is presently asked for in the rules. These hydro-elastic effects are more and more an area for concern and so it is recommended that the research targets this problem.

In recent years, the capacity and length of LNG carriers have increased dramatically. Such increase results in the high risk of structural damage due to sloshing-induced impact loads, and recent damage cases have been already reported. Moreover, the LNG tanks of offshore structures such as LNG-FPSO and FSRU are exposed to a much higher possibility of severe sloshing-induced impact loads than ships, since restriction for filling height cannot be imposed. Therefore, the engineering demand for the accurate prediction of sloshing pressure is increasing.

There are little or no suitable data of the behaviour of high-speed planing craft in oblique waves. The theories are usually derived for vertical plane responses only. Efforts should be devoted to establishing a suitable test procedure for the response of high speed planing craft in oblique seas with a view to obtaining suitable benchmark validation data. Finally, there are very little criteria available for understanding the performance of high speed craft and the committee recommend that research should be targeted towards this aspect.

This committee has endeavored to evaluate the applicability of the various methods, DPM (Direct Power Method), QNM (Torque & Revolution Method), TNM (Thrust & Revolution Method) and RTIM (Resistance & Thrust Identify Method) for predicting the power increase in waves by comparing these methods with the direct irregular wave tests. However, a full set of experimental data, containing results from propeller open water tests, resistance and self propulsion tests in still water and regular and irregular wave tests, for the same design has not been found. Therefore, as an alternative, comparisons were conducted for added resistance, propeller torque and revolution increase in irregular waves between those estimated from model test results in regular waves and direct irregular wave test results using data obtained from published papers. According to the comparison results, the agreement between the methods appears consistent for added resistance (RTIM), but not good for propeller torque and RPM increase (QNM). The discrepancies of propeller torque and revolution increase may be due how the propeller differs in severe irregular wave conditions compared with mild sea conditions. Further investigations are necessary to compare and evaluate the three prediction methods by undertaking irregular and regular wave tests for various hull forms, loading conditions and wave conditions; in order to evaluate the reliability on the applicability of these methods.

$CO_2$ emissions from ships have become a crucial issue in the shipping and shipbuilding industry putting more emphasis on the understanding of the fuel consumption throughout the life of the ship. The procedures of estimating and verifying $CO_2$ emission from ships are under intensive discussion at IMO/MEPC and it may be beneficial for the ITTC to cooperate with the IMO during this discussion . In order to estimate and evaluate $CO_2$ emission from a new ship at the design stage, the Energy Efficiency Design Index (EEDI) has been agreed for use in design. For calculating EEDI, power increase or speed loss in an actual seaway has to be predicted by model tests or theoretical calculations. At the present time, there is a coefficient $f_w$ in calculation of EEDI that describes the ratio of ship speed in waves and in wind to that in still water is currently taken 1.0, because its reliable simulation procedure is not available yet.

## 6.2 Recommendations to the Full Conference

Adopt the updated procedure No. 7.5-02-07-02.1 Testing and Extrapolation Methods - Seakeeping Experiments.

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

Adopt the updated procedure No. 7.5-02-07-02.3 Testing and Extrapolation Methods - 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 new procedure No. 7.5-02-07-02.6 Testing and Extrapolation Methods - Global Loads Seakeeping Procedure.

Withdraw the procedure No. 4.2.4-01 Standard Format for Exchange of Seakeeping Data on Computer-Compatible Media

## 6.3 Proposals for future work

It is recommended that the current V&V procedure should be extended to include the outcomes of the ITTC Seakeeping Workshop. In particular, the procedure should look to address specific aspects of the verification of hydro-elastic computational codes.

The Seakeeping committee has updated seakeeping experiments procedure to include the uncertainty analysis as recommended by ISO-GUM. This committee recommends this work be extended to include the other procedures of this committee.

As a result of the high cost associated with the testing of a hydro-elastic model, much of the experimental testing is undertaken as part of European and Asian Joint Industry Projects (JIPs) such as TULCS and WILS II. The data derived from such tests are usually commercially protected, however, it is recommended that the ITTC engage with recent and on-going JIPs where the outcomes from such joint projects are valuable for the development/revision of ITTC procedures and collecting bench-mark data. At the very least this might involved targeting JIP related open workshops.

More facilities are developing the capability to assess numerically and experimentally sloshing in tanks. It is recommended that the ITTC reviews the experimental procedures currently in place that have been developed by the class societies and recommend a unified procedure for development at a later stage. This process should also consider the extrapolation methods used to estimate loads at full scale.

It is recommended to collaborate with ITTC Ocean Engineering Committee and/or ISSC Loads and Responses and Environment Committees to share the information relating to nonlinear motion and structural loads and to understand the impact of projected changes in the sea wave environment and the influence the types of wave spectra have in seakeeping experiments. Where there is such overlap with these committees, then collaboration will be valuable.

Both the ITTC and ISSC acknowledge the benefit of continuing, therefore, it is recommended that the next ITTC Seakeeping Committee participate in a joint workshop with the ISSC, based on uncertainty in the measurement and prediction of wave loads and responses, to be held around September 2012.

It is also recommended to extend this collaboration to include the ISSC Impulsive Pressure Loading and Responses Assessment Committee in respect of its current work on slamming-whipping problems – particular a technical survey on hull-girder hydro-elasticity.

Past experience shows that opportunities for collaboration between both organizations are improved significantly if continuity across committees is maintained. One way of securing this continuity is to consider common membership where practicable.

It is recommended that the ITTC establishes a numerical and experimental process for estimating the coefficient $f_w$ in the calculation of EEDI.

Regarding the $CO_2$ emission during ship operations, there is another index, i.e. the Energy Efficiency Operating Indicator (EEOI) which is also under discussion by IMO/MEPC. EEOI is the index describing the actual $CO_2$ emission from ships measured at actual sea, which is directly related to the consumption of bunker fuel oil, per unit of transport work. It is recommended that the committee should understand the type of data (and the quality of the data) that should be recorded during full scale monitoring trials.

## 7. REFERENCES AND NOMENCLATURE

CFD – Computational Fluid Dynamics

ISOPE - International Offshore and Polar Engineering Conference

IWWWFB - International Workshop on Water Waves and Floating Bodies

PRADS - International Symposium on Practical Design of Ships and Other Floating Structures

RANS - Reynolds Averaged Navier–Stokes

SPH - Smooth Particle Hydrodynamics

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