The Seakeeping Committee

Final report and recommendations to the 25th ITTC

1. GENERAL

1.1 Membership and meetings

The Committee appointed by the 24th ITTC consisted of the following members:

- Mr. Terrence Applebee (Chairman), Naval Surface Warfare Center, West Bethesda, USA
- Mr. Paul Crossland (Secretary), QinetiQ Ltd, Gosport, United Kingdom
- Dr. Gregory Grigoropoulos, National Technical University of Athens, Greece
- Mr. Greg Hermanski, Institute for Ocean Technology, St. John's, Canada
- Dr. Yonghwan Kim, Seoul National University, Korea
- Dr. Rumen Kishev, Bulgarian Ship Hydrodynamics Centre. Varna, Bulgaria
- Dr. Koichiro Matsumoto, Universal Shipbuilding Corporation, Kawasaki, Japan
- Dr. Jianbo Hua, SSPA Sweden AB, Göteborg, Sweden
- Dr. Jinzhu Xia, Australian Maritime College, Launceston, Australia

Dr Hua resigned during the term of this committee and was replaced by Mr. Dariusz Fathi, Marintek, Trondheim, Norway. Dr. Xia changed companies shortly after his appointment and was unable to participate on the 25th ITTC Seakeeping Committee.

Four committee meetings were held at:

- QinetiQ Ltd, Gosport, United Kingdom, January 2006
- Naval Surface Warfare Center, Carderock Division, West Bethesda, USA, October 2006
- National Technical University of Athens, Greece, May 2007
- Seoul National University, Korea. December 2007

1.2 Recommendations of the 24th ITTC

The following is the specific guidance provided by the 24th ITTC Seakeeping Committee on the work to be undertaken by this committee.

1. Update the state-of-the-art for predicting the behaviour of ships in waves including high speed and unconventional vessels, emphasising developments since the 2005 ITTC Conference,

a) Comment on the potential impact of new developments on the ITTC.
b) Emphasise new experimental techniques and extrapolation methods and the practical applications of computational methods to seakeeping prediction and scaling.
c) Identify the need for R&D for improving methods of model experiments, numerical modelling and full-scale measurements.

2. Update the procedure for experiments on rarely occurring events, 7.5-02-07-02.3.

3. Update the procedure 7.5-02-07-02.1 for model tests on linear and weakly non-linear seakeeping phenomena.

4. Rewrite the procedure 7.5-02-07-02.2 for added resistance and power increase in irregular waves.

5. Update the procedure 7.5-02-07-02.4 for the validation of codes in the frequency domain so that it is independent of the method used.

6. Develop a procedure for the validation of codes in the time domain so that it is independent of the method used.

7. Support the Specialist Committee on Uncertainty Analysis in reviewing the procedures handling uncertainty analysis.

8. Critically review examples of validation of prediction techniques. Identify and specify requirements for new benchmark data.

9. Determine requirements for benchmark tests for seakeeping in oblique waves such that these benchmark tests could be conducted in the future.

1.3 Cooperation with the ISSC

The importance of cooperation with the International Ship and Offshore Structure Congress organisation, specifically, the I.2 Loads Technical Committees, was recognised by arranging a Joint meeting at the National Technical University of Athens in May 2007. The meeting underlined the importance and benefits of the inter-committee collaboration with communication between committee members being recognised as the most basic and important form of contact and information exchange. There was a clear overlap in both committees' mandates and available expertise such that both organisations could benefit from further cooperation, and further collaboration would be advantageous if the participation of the ITTC Ocean Engineering and ISSC Environmental committees is included.

The main task of the Seakeeping Committee is the development of new and existing procedures. Examples of existing ITTC recommended procedures that may be of interest to the ISSC Loads Committee would include:

- Procedure 7.5-02-07-02.1 Seakeeping Experiments

- Procedure 7.5-02-07-02.3 Experiments on Rarely Occurring Events

- Procedure 7.5-02-07-02.4 Validation of Seakeeping Computer Codes in the Frequency Domain.

It may be possible that the Loads committee could review and support the process of updating existing procedures and participate in development of new ones.

Benchmarking and comparative studies were identified as a possible form of joint activities to the extent that both committees could share resources to conduct future joint benchmark and comparative studies. As part of its work the 25th ITTC Seakeeping Committee undertook a task to propose defined requirements for suitable benchmark tests, including information required for the data to be qualified for inclusion in the ITTC benchmark database. The Seakeeping Committee consulted the ISSC Loads Committee on the proposed final description. The ISSC Loads Committee invited ITTC member organisations (members of the Seakeeping committee) to participate in a planned comparative study to calculate lateral bending and torsion moments using the various numerical tools available to members of both committees.

The ISSC takes place a year later than the ITTC and thus the phasing of reports from one committee is not convenient for the other. However, both committees would benefit from the exchange of the list of references from their respective state-of-the-art reviews. ISSC has forwarded a copy of the 2006 ISSC Loads report complete with written discussion and response. It may be possible for committees to review each other reports before their respective Conference submissions but this requires further discussion with the committee's respective parent organisations. A Joint report could also be considered feasible in the future, however, for the time being such a task might be regarded as premature.

For future collaboration some form of continuity amongst the two committees should be ensured; past experience has shown that opportunities for collaboration between both organisations can be lost due to lack of continuity in contacts and/or communication. Thus, the following is proposed to help maintain the continuity of the collaboration:

- Common membership. Both parent organisations should assure that the relevant committees will share at least one common member who could act as a liaison between the two committees. The phasing in the ITTC and ISSC can be utilised to ensure appointment of such a common member.

- Scheduled joint meetings. Propose that the second (or 3rd) ITTC meeting and the first ISSC meeting of their respective committees become permanently scheduled as a joint committee meeting.

2. REVIEW OF STATE-OF-THE-ART

2.1 Developments in Experimental Techniques

New and improved concepts of wave making amenities are being considered to enhance model testing efficiency and accuracy of generated waves in existing and new experimental facilities. Existing and newly developed theories and codes are being used for that purposes.

Naito *at el*. (2005) presents a theory of ship motion analysis of tests conducted in ring waves and focused transient wave generated by an energy absorbing wave maker in a compact circular wave basin. The ring waves are described as multidirectional waves composed of incident waves with the same amplitude and period arriving from all directions. The resultant motions are representing the linear summation of responses to individual incident waves that compose the ring waves. The directional ship characteristic can be obtained in a single run.

Naito (2006) reviews theories of wave generation and absorption and investigates the development of a high-performance absorbing wave-maker for generation of both angular and irregular waves in model test facilities. He also contemplates various configurations of wave-tanks to optimise their performance. Generation of waves in a traditional rectangular basin can be questionable because of problem of reflected waves from the basin walls. The author proposes a concept with an absorbing wave-maker around the tank simultaneously absorbing undesirable waves and generating required waves. Such a tank and wave-maker concepts are described as the Advanced Multiple Organized Experimental Basin (AMOEBA) and Element-Absorbing Wave-maker (EAW) respectively. Generated examples of snapshots of wave amplitudes and long-crested narrow-banded irregular waves show promising results.

Bonnefoy et al. (2006a) presents the first of two papers reporting on the development and validation of a 3D second order numerical wave tank model. The authors present, in Part A, the fully spectral time domain formulation. An extensive verification study of the model accuracy and convergence properties is reported in the context of both local and global quantities. The practical capabilities of the model are reported in Bonnefoy et al. (2006b). Various 2D and 3D complex wave system simulations are compared with experiments.

In some cases numerical and physical tools are being applied to improve existing or design new wave making facilities. Mikkola (2006) describes the use of numerical simulation to solve a design issue in the replacement of wave makers in the long towing tank at the Ship Laboratory of Helsinki University of Technology. Specifically, to select a wedge angle for a plunger type wave maker, a 2D unstructured Finite Volume Method (FVM) was used and then that method was validated against two cases which were similar to the design problem. The comparison with those test cases, from the 2nd ISOPE Numerical Wave Tank Workshop and from simulation of the plunger type wedge wave maker installed at Helsinki University's multi-purpose basin, provided sufficient agreement to be used for the design problem. Three wedge angles were evaluated, 25, 35, and 45 degrees, and the optimal design angle of 35 was selected. Further analysis could then be conducted to provide mechanical and structural design guidance.

Ducrozet at el. (2006) present a novel fully nonlinear potential flow model for simulation of generation and propagation of 2D or 3D gravity waves in finite depth. This new Numerical Wave Tank (NWT) formulation is based on coupling of the fully nonlinear High-Order Spectral Tank (HOST) method with a second order spectral NWT model. For the validation, the formulation results were compared to a highly nonlinear 2D focused wave packet embedded in an irregular wave field, which demonstrated its accuracy and efficiency. The NWT was created to model the Ecole Centrale de Nantes towing tank.

Model experiments are still the most reliable tool for estimates of local and global loads for various types of ship hulls. The segmented models are still the most cost-effective alternative for this type of experiment. The segmented model technique is also applicable to collect other relevant responses. More conventional model experiments are still used to measure motions, pressure distributions and modelling of extreme environments. The goal of these experiments is mostly to obtain reliable data for validation of numerical solutions.

A unique approach to measure loads and responses is presented by Leguen and Fréchou (2007). The authors introduce the new French marine facility at Bassin d'essais des carénes (BEC), and seakeeping experiments performed with a 1:5 scale (length overall of the model = 25 metres) model of a frigate. The structure of the model hull was mechanically similar to the structure of the full-scale ship. The model was built to maintain elastic similarity and proper scaling relation between modes of resonance between the model and the ship. Experiments were conducted at regular waves and speed up to 4 m/s. The model was instrumented to obtain model motions and global deformation of the body in waves. Roll damping at various speeds was measured and whipping and slamming phenomena were observed. The paramount purpose of this unusual experiment was to collect data for validation of design tools for predictions of hull motions and structural responses.

At the same facility Rousset et al. (2005) investigated the effects of slamming loads on ships (vibrations, hull girder fatigue and ultimate strength). The project was established with the joint support of industry and public institutions and included various physical experiments and numerical simulations. This paper presents experiments conducted to study the sensitivity of global and local loads to kinematic parameters variation.

Fonseca et al. (2005) undertook tests with a segmented 4.4m model of a fast ferry to measure the added mass and damping coefficients and structural loads as well as to test for linearity in regular head waves.

Fonseca and Guedes-Soares (2005a) presented a comparison between experimental data and numerical results of the nonlinear wave-induced heave and pitch motions and structural vertical shear forces and bending moments on a containership. The experimental data were obtained from tests in regular head waves with different wave steepness; strong nonlinear effects were detected in the experimental data. The paper focussed on several new aspects of the nonlinear vertical structural loads in regular waves, including the identification and quantification of third harmonic amplitudes, the influence of the regular wave amplitude on the amplitudes of the first three harmonics and on the sagging and hogging peaks, and the influence of the steady structural loads (that exist also with the ship advancing in calm water) on the asymmetry of the vertical loads in waves.

Dessi and Mariani (2005) have used a segmented model to identify the slamming load and to evaluate the ship-beam response (whipping and springing) and they compared these results with full-scale trials. In this paper, the question that the authors intended to answer can be considered as an inverse problem with respect to the past investigation: is it possible to identify the structure of the segmented model and also to obtain information about the loads to which it is subjected, just from the analysis of its vibratory response? In this work, the answer of the above question regarding structure identification is based on the use of the Output-only analysis technique (which seems quite promising for this kind of investigation), whereas the load identification is based on the slender beam theory.

On the other hand, De Jong and Keuning (2005) used a forced 6 D-O-F oscillator and a seven-component segmented model of a frigate to investigate the non-linear effects due to large amplitudes, focusing on combined sway-yaw motions.

The combination of experimental results with appropriate data analysis procedure can produce satisfactory solutions to wave load problems that can also be applied for non-conventional ship hull forms.

Lin et al. (2007a) provided a regression formula to evaluate the design wave load of SWATH vessels, on the basis of the model test results of SWATH vessels. As expected, the formula provides more accurate design wave load that is close to the model test results in the case of lower displacement less than 3000t. Consequently the hull structure weight and fabrication cost will be reduced greatly. They also took into account the mechanical characteristic of SWATH vessels, to propose load combinations and loading manners for transverse strength analysis, torsion strength analysis and overall longitudinal strength analysis of SWATH vessels.

Iseki (2007) presents the bi-spectral analysis applied to nonlinear ship response. Presently, the most often used power spectral analysis is based on linear theory, and is not effective to investigate non-linear aspects of ship responses. The proposed, higher order, bi-spectral analysis is more appropriate to investigate nonlinear ship responses with emphasis on the skewness of the data. The author presents an example of the nonlinear response analysis as a second order Volterra system. The pitch motion response in following sea is characterised by fluctuating skewness and the author concludes that skewness is introduced by the variation in the nonlinear restoring moment of the pitch motion.

Chiu et al. (2007) conducted a study that focuses on the nonlinear behaviour of the pressure responses of the hull surface, especially on the pressures acting on alternately wet and dry areas near the waterline and on the bow zone with high deadrise angles that may be subject to slight impact and water pile-up effects. To clarify the validity of applying Volterra modelling to this problem, a series of experiments in regular and irregular head waves were carried out, and approximate third order and fifth-order Volterra models with the proposed algorithm for finding frequency response functions (FRFs) were applied as a means of validation. In the present article, the first part of the validation was performed using experimental data in regular waves. It was confirmed that the third-order Volterra model has adequate accuracy to simulate deterministically the variation of pressure responses in regular waves of different wave steepness up to wave amplitude to wavelength ratio of 0.01 even for the highly nonlinear pressures acting on the above-mentioned areas of the hull surface.

Minami et al. (2006) present a numerical and experimental study to measure ship responses to extreme wave impact. Experiments were conducted with an elastic model of a container ship (scale 1:141.9), simulations were carried out using the time domain nonlinear strip theory based software SRSLAM, and extreme waves were modelled at a numerical tank NWT2D by superposition of selected regular waves. To conduct the experiments properly, the wave maker and the carriage had to be synchronised for the essential encounter. Results of experiments and calculations are presented.

New emerging technologies are being utilised to measure physical parameters with higher confidence.

Ryu et al. (2006) present an experimental study to measure velocity fields of a plunging wave impacting a structure. As the wave breaks and overtops the structure a large aerated and green water region is formed. The velocity profile of the green water around the structure was measured using bubble image velocimetry (BIV) technique. The measured data and dimensional analysis method was used to obtain a formula for the prediction of the horizontal green water velocity distribution.

Safety concerns are important aspect of many investigations. Parametric roll phenomena frequently observed on large vessels is also a factor for operations of small ships. Globally publicised, the more devastating, large ships disasters are reflected in more research focusing on the associated investigations.

Hu et al. (2006) investigated experimentally and numerically the occurrence of parametric roll resonance in head seas for an ultra large containership whose hull form is easily subject to abrupt changes in transverse metacentric height. Model tests have been performed in a deep water towing tank for different ship forward speeds in regular and irregular head seas. However, in the irregular head seas used in the test matrix, roll instability could not be identified. In addition, the critical role of initial conditions in the temporal evolution of nonlinear system was observed. Numerical analyses encompassing nonlinear seakeeping simulation, time integration of 1-DOF damped Mathieu equation and a Mathieu stability diagram were performed and have been compared with the model test data. Good agreement was found between the model test data and the numerical analyses.

Full-scale measurements are most valuable (although expensive and usually confidential) as a source that can be used to correlate and validate ship design and investigative tools. Fortunately the amount of published full-scale data is increasing. More and more commercial and military ships are equipped with permanent monitoring systems to record ship's operational data and responses to the current environment for the up-to-date decision making and long term improvements to design and simulation tools.

Carrera and Rizzo (2005) carried out full-scale measurements on a 17.5-m FRP pleasure craft in waves to record both its motions and impact structural loads in the bow region. Moersch and Hermundstad (2005) carried out similar measurements with a 21-ft planing craft focusing on the slamming pressures on the bottom of the boat.

Fukunaga et al. (2007) present an onboard installed system to predict height, length and direction of encountered waves using measured ship motion and speed data. The system is one of many elements being developed as an onboard information tool for identification and supporting the decision-making process when operating in heavy seas. The method is based on the comparison between ahead-calculated ship motions using strip theory code and measured ship motions in five degrees of freedom (no surge). The ship motions are measured using a system of six accelerometers. The motions are obtained by double integration of accelerations. The system was tested aboard a passenger/vehicle ferry showing promising results.

Leguen et al. (2007) present a structural monitoring system installed on a French Naval vessel. The system is designed to monitor global, slamming and torsional loads, ship motions, operational and propulsive parameter. The goal of the task is to improve the knowledge base, optimise maintenance process and serve as navigation aids.

Based on data recorded during a long-range transit of a high-speed ferry, Davis et al. (2005) investigate using full-scale measurements to develop vertical plane response amplitude operators (RAOs). Predicting the effect of lifting surface motion damping using model scale testing is difficult at high Froude number because of Reynolds scaling. This problem disappears at full-scale, but developing RAOs from full-scale data is complicated by the precision that encountered wave conditions can be characterised. Issues associated with measuring wave surface and wave direction, as well as problems of obtaining motion displacements from measured accelerations, presented a challenge in the data interpretation in this study. Sea trials data comparisons show consistently larger RAO peaks of pitch, heave and roll than the computed values. The ride control system in the form of stern tabs was limited in its capability to dampen motions, but was most effective in reducing pitch rather than heave. It was also concluded that the action of the steering system produced substantial rolling at high speed and in head seas. Detailed information on state of the environment (sea state and direction) is critical for correct interpretation of full-scale data. Difficulties in establishing proper wave direction due to low frequency swell and high frequency new waves coming from different directions were reported in past.

Yoo et al. (2007) present an approach to obtain wave direction estimated from three-dimensional movements of a buoy. Three GPS receivers fixed on the buoy were used to obtain three rotational angles (yaw, pitch and roll) and calculate correction for the buoy oscillatory motions. The buoy allows also for estimates of wave height. The system was encouragingly tested in static and dynamic on-the-ground dry conditions.

Johnson and Wilson (2005) considered the problem of determining the sea state from measured ship motions from a statistical point of view with the aid of an extensive set of seakeeping trials results. Multiple linear regression was used to deduce the relationship between the RMS ship motions in five degrees of freedom, and the significant wave height measured by a waverider buoy. It was shown that the significant height may be estimated with around 10% error by this method for a wide range of conditions.

2.2 Developments in Theory and Validation

2.2.1 Frequency domain (motion & Loads)

During the last few years, 3-D theories, although still amenable to development, have become standard tools for the calculation of the dynamic loads and responses of ships in waves.

The forward speed of the ship and the inherent hydrodynamic and geometrical nonlinearities remain complicating factors. Strip theories, on the other hand, are used for engineering purposes, since they provide robust and quite accurate results in low to moderate sea states. Thus, the natural trend, described in the respective state-of-the-art review of the 24th ITTC Seakeeping Committee, to move from the frequency domain to the time domain, from strip-theory type to fully 3-D schemes, from linear to nonlinear problems, and also from potential-flow to viscous-flow computations is even more pronounced.

In this section the developments in computational and experimental studies for wave loads and motions of a ship, mainly in the past three years since the last 24th ITTC Conference are summarised. They are categorised according to the domain of calculations (frequency or time domain), the type of singularities used (Green or Rankine sources), the dimensionality of the problem solved (2-D or 3-D) and the order of the problem solved (linear or higher order).

In the case of linear problems, the use of Green singularities permits the automatic satisfaction of both the free-surface boundary condition and the radiation condition at infinity, allowing for the discretisation with panels of the body surface, only.

Du et al. (2005) discuss the influence of the line integral terms in the prediction of three-dimensional seakeeping characteristics of fast hull forms using a boundary integral method employing frequency domain translating and pulsating source Green's functions. They applied the method to Series 60 and NPL hull forms to demonstrate that oscillatory results appear in the predicted values of hydrodynamic coefficients and exciting forces, as a result of the numerical procedure relating to the treatment of the line integral terms in the boundary integral equations. Using the direct potential method instead of the source distribution method can suppress these oscillations, especially when the waterline integral terms are treated properly.

Wang et al. (2007) used a source-sink distribution method to calculate the coefficients of four kinds of twin-hull or multi-hull sections. They applied linear potential theory taking into account viscous effects by a cross-flow approach to predict the motions of catamarans with forward speed in regular waves and to investigate the effect of speed, distance and interaction between the hulls. They compared their results with model tests for a Series 64 catamaran.

Vorobyov and Demidjuk (2007) studied the boundary value problem of radiation and diffraction potentials for a ship travelling in deep water and in regular head waves. The linear theory of surface waves and thin ship model were used. As the boundary value radiation and diffraction problems have an identical structure both solutions are derived simultaneously. The potential function is represented by an exponential Fourier integral transformation in the longitudinal direction and the result is then expanded into the Fourier–Michael integral transformation in the vertical direction. Thus, the boundary value problem is reduced to several second order ordinary differential equations, which are easily solved. The potential function is found in a form of an integral operator with the ship hull equation, vessel velocity and frequency of waves.

Qiu and Peng (2006) and Peng et al. (2007) developed a panel free method to eliminate computational errors of panel methods due to the ship hull geometry approximation, the assumptions regarding the velocity potential or source strength distribution on a panel and the evaluation of singularity terms in the integral equation. In the work, the de-singularised integral equation for a body at forward speed in terms of source strength distribution was developed by removing the singularity due to the Rankine term in the Green function. Non-Uniform Rational B-Splines (NURBS) were adopted to describe the exact body surface mathematically. The regular integral equations were then discretised over the surface body by Gaussian quadrature. The double-body *m*-terms were accurately computed on the NURBS surface from the continuous distribution of the velocity potential. The accuracy of the method was demonstrated by its application to the radiation and diffraction problems of a submerged sphere and a Wigley form at forward speed in the frequency domain. The method was used to calculate motions RAOs for a FPSO and a LNG carrier operating at shallow water. The results were compared to results of model experiments and calculations using the WAMIT code. No quantitative V&V was offered in the paper.

Malenica at el. (2006) discuss the interface between hydrodynamic and structural models since typically each model uses a different type of mesh. The proposed procedure treats hydro-structure interaction in linear seakeeping. The authors assume potential flow and use the boundary integral equation method (based on source formulation) to solve boundary value problems in the frequency domain. Rigid body and hydroelastic body cases are presented.

A typical hydrodynamic mesh contains panels below the mean waterline while the structural mesh follows structural elements of the body. Two main issues in the hydro-structure interaction are: pressure transfer from the rigid body hydrodynamic model to the structural model and transfer of structural deformations back to the hydrodynamic model. In the first case, the recalculation of pressure is recommended instead of interpolation. This is possible because the boundary integral equation used to solve boundary value problems gives the continuous representation of the potential through the whole fluid domain. Coordinates of the structural mesh are then applied to obtain relevant pressures. For the hydroelastic seakeeping analysis the transfer of the modal displacements from structural to hydroelastic meshes is a problem. The authors propose a 6-step procedure to perform the interpolation between the structural and hydrodynamic meshes.

Sutulo and Soares (2004) extended the boundary integral equations method, originally proposed by Young (1973) to solve the 2-D seakeeping problem by direct derivation of the integral equations without recourse to singularity distributions, thus avoiding the presence of irregular frequencies. They used a more sophisticated discretisation procedure, without any symmetry restrictions, assuming deep water. In order to solve the resulting Fredholm equation of the second kind with weak singularity they proposed the piecewise continuous singularity distribution in combination with the integral collocation, to reduce it to a discrete set of algebraic equations of relatively small dimension. Their method results in an improved fulfilment of the body boundary condition, compared to the Frank method. Söding (1993) also aimed towards this goal by distributing discrete sources slightly beneath the body surface in code “Hmasse”; the proposed “patch” method. The current authors applied their method to the S-175 containership and concluded that their method was superior to both the original Frank method and Söding’s method, especially for a small number of panels.

Thomas et al. (2007) conducted model tests in beam and oblique regular waves, using a modified Series 64 model at two demihull spacings to validate catamaran motion prediction methods. They investigated the non-linearity of the roll response by repeating the tests at various wave heights. They compared the results with numerical predictions using two methods: Korvin, a boundary-element method combined with a strip-theory approach, modified for multihulls, and Seakeeper, a modified strip-theory method. Both codes provided accurate predictions, although Seakeeper tended to overpredict the vertical plane motion responses.

2.2.2 Time domain (motion & Loads)

During the last two decades, ship motion analysis in the time domain has significantly increased, replacing frequency domain analysis. Due, mainly, to the trend of building very large ships, there are strong demands for studies related to nonlinear motions and structural loads, and nonlinear analysis in the time domain are essential for such studies. Typical problems include nonlinear wave excitation, the resultant motion, structural loads, green water, slamming and whipping, hydroelasticity (such as springing), sloshing and coupling with ship motion. Furthermore, it is obvious that the application of a time domain approach is getting more popular, and more sophisticated and direct techniques will be introduced in the future.

The time domain approaches for ship motion can be categorised into four representative methods as follows:

(1) Impulse-response-function method: After the pioneering work of Cummins (1962), this method has been used by many researchers to simulate ship motions in time. This method applies the frequency domain solution to compute the impulse response function and/or the retardation function for the radiation forces. Since this method is essentially a conversion of the frequency domain solution to the time domain, there is a strong advantage of reduced computational time. In particular, when the linear problem with an external force is of interest, this method is very effective and efficient. The frequency domain solution can be obtained by any kind of method, e.g. strip or panel methods. Recently there has been some effort to extend this method to nonlinear ship motion problems and to couple the effects with sloshing or other nonlinear loads. In the case of nonlinear ship motion analysis, the application of nonlinear Froude-Krylov forces and nonlinear restoring forces can be combined with the linear diffraction force.

(2) Sectional nonlinear method (nonlinear strip method): Strip theory methods have been extended for use in nonlinear time domain analysis. Lin (1984) solved the nonlinear hydrodynamic problem of two dimensional sections, considering the instantaneous wetted surface with a linear free surface boundary condition, and this concept has been applied for the section based nonlinear ship motion computation. In this method, the hull surface is represented by sections. At each time step, hydrodynamic and restoring forces are obtained at each section, and the total forces are obtained by summing the sectional quantities. This method is also efficient and a higher degree of nonlinearity can be applied than using the impulse response function approach. However, this method still has the limitation of strip theory which is not powerful for low frequencies.

(3) Unsteady Green function approach: This is one of the classical approaches in ship hydrodynamics. This approach adopts the unsteady wave Green function which requires complicated numerical treatment to solve. Despite significant effort, this approach could not become a practical method due to the difficulty in the computation of the Green function. The early versions of TIMIT and LAMP in early 1990 belong to this category.

(4) Rankine panel method: Dawson (1977) and earlier work resulted in the wide-use application of the Rankine panel method for practical wave resistance computations. This method had been extended to unsteady ship motion problems, showing very successful results. LAMP and SWAN is representative of these successes. This method has many of the merits of the three dimensional approach, particularly in the extension of nonlinear analysis and dynamic analysis of structural loads. At the present stage, this method is the leader in time domain and nonlinear ship motion analysis. However, there are still some details to be solved for its more practical use.

(5) Field equation solver: The development of computational resources enables us to apply the field equation solvers for very complicated problems. Particularly, during the last decade, the application of the Navier-Stokes equation solvers for ship hydrodynamic problems has

become more popular, and it is obvious that this trend will continue in the future. So far, the application of CFD tools like FLUENT for seakeeping application is limited to some local problems, but is getting wider use for more global ship flows including ship motion. However, the practicality and accuracy are still beyond the methods based on potential theory at the present stage.

There are a few representative methods in nonlinear ship motion analysis, and a good summary for the linear and nonlinear methods is suggested by Singh and Sen (2007) as shown in Figure 1.

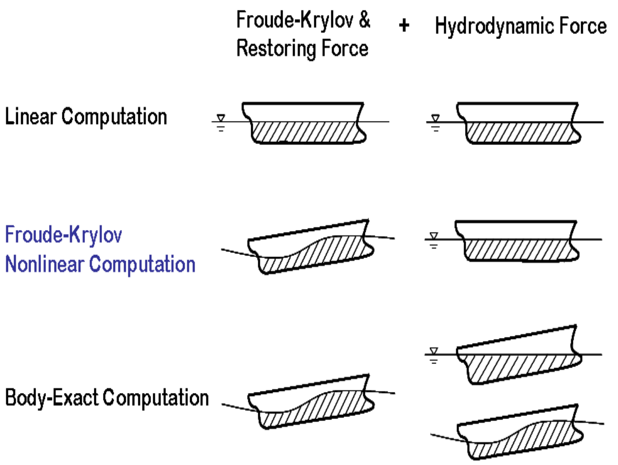


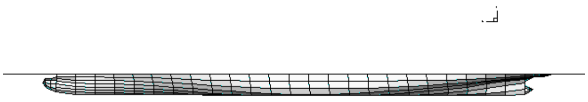
Figure 1: Summary of linear and nonlinear computational methods for ship motion (Singh and Sen, 2007)

In their summary, two nonlinear schemes are characterised, depending on numerical implementation of the Froude-Krylov force, restoring force and hydrodynamic force. The first level is based on the assumption that the primary nonlinearity comes from the incident wave and nonlinear restoring. In this case, the correction of the Froude-Krylov and nonlinear restoring forces on the actual wetted surface is the key for solving nonlinear ship motion problems. At present, this approach, the so-called the weakly nonlinear method, is the most popular for practical ship motion applications. SWAN2 (WASIM nonlinear) and LAMP2 (NLOAD3D nonlinear) belong to this category. On the other hand, stronger nonlinearity can be considered by solving the body nonlinear problem with a linear free surface condition, or fully nonlinear or weak-scatterer problems including the effects of nonlinear free surface flows. In particular, the weak-scatterer approach, e.g. Huang (1998), is a unique approach which is somewhere between a fully nonlinear and weakly nonlinear method. SWAN4 and LAMP4 are such methods. However, this approach requires a remarkable increase in computational time; therefore, its practicality is still limited.

From the viewpoint of the physics involved in nonlinear ship motions, there are two distinct nonlinearities: body nonlinearity and free-surface nonlinearity. The previous method is relatively easy concept to consider, and is effective for most ships. However, the physics involved in nonlinear free surface flows is more profound and harder to be realised in computation. In fact, Figure 1 shows four possible combinations to represent the problem: one linear method and three nonlinear methods. In numerical applications, besides the free surface boundary condition, the primary difference in these methods is in the distribution of the solution grids (panels). In the case of linear and weakly nonlinear methods, the solution grids do not change as time progresses.

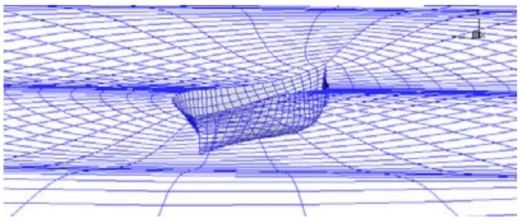
However, the other nonlinear methods require the grids to be updated at every time step; hence a significant amount of computational time is needed. This is the primary reason of using the weakly nonlinear method for practical design applications. Figure 2 shows an example of mesh generation for three different approaches.

Classification societies have led to the development and application of nonlinear seakeeping programs, like WASIM and NLOAD3D. Particularly, the high demand of nonlinear analysis is related to the recent trend of building very large ships such as containerships over 10,000 TEU and LNG carriers over 200,000 cubic metres. Over the last several years, time domain ship motion computations have been based on mostly three methods: the impulse-response function method, the nonlinear section based method, and the Rankine panel method. There are a few papers introducing other methods, but these three methods are the most popular at present.



(a) For linear & weakly nonlinear methods

(b) For body-nonlinear methods



(c) Weak-scatterer methods

Figure 2: Example of solutions grid for three nonlinear methods.

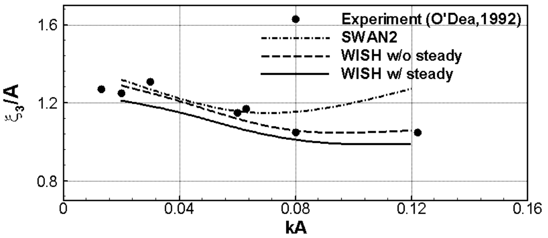
The primary aims of any nonlinear ship motion analysis are the prediction of nonlinear roll such as parametric roll, nonlinear structural loads, coupling with internal or external excitation like sloshing and green water, and to observe hydroelasticity such as springing. The following review focuses on the studies during the last few years.

Some examples of the nonlinear section based method can be found in Fonseca and Guedes Soares (2004), Xia (2005), Mikami and Shimada (2006), Mikami and Kashiwagi (2007). Some of their work has combined nonlinear strip theory and the memory function for predicting ship motion and structural loads. Particularly Fonseca and Guedes Soares (2005a) carried out a systematic experiment, in addition to computation, and the measured data in large wave amplitudes seem very useful for the validation of computational programs.

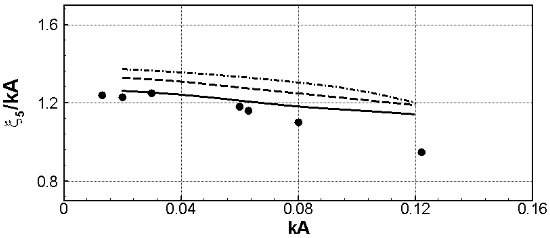
Applications of the impulse response function method have been introduced by Kristiansen et al. (2005), Fan and Huang (2006), Nam and Kim (2006, 2007), Kim et al. (2007d), and others. One of the typical trends in the application of the impulse response function approach is to couple ship motion with internal and external forces, such as sloshing, green water and control devices. For instance, the latter two studies were to couple the ship motion with nonlinear sloshing, and Kristiansen et al. (2005) pointed out that their scheme can be useful when coupled with control algorithms.

The Rankine panel method has been in the main stream of the linear and nonlinear ship motion analysis in the time domain. It has been extended to even more problems in the marine hydrodynamic field. For instance, Zhang et al. (2007a), and Kim and Kim (2008) introduced the extension of the Rankine panel method for multiple body problems, and Zhang et al. (2007b) introduced the application of the desingularised method for large ship motion analysis. A typical application of the panel method was also introduced by Qian and Wang (2005). It is worth noting that Korean shipbuilding companies are developing a computer program called WISH for the nonlinear analysis of wave loads and ship motions in the time domain, Kim et al. (2007a). The aim is to develop a program compatible to WASIM and NLOAD3D, and some successful results have been introduced.

For instance, Figure 3 shows the comparison between experimental, SWAN and WISH results. The authors introduced some technical issues in the nonlinear analysis, and Figure 3 shows the importance of the steady component in the prediction of unsteady ship motion responses.



(a) Heave



(b) Pitch

Figure 3: Comparison of the motion magnitude of the S175 containership with respect to wave slope, λ/L=1.4, Fr=0.275, β=180 deg (Kim et al*.,* 2007a)

Studies based on the transient Green function approach have continued. Datta and Sen (2006) introduced computational results using a higher order distribution of the transient Green function on the body surface. Chuang et al. (2007) have developed an analytical method to evaluate the wave part of the time domain Green function and its derivatives. This scheme is also extended to body nonlinear problems. For instance, Qiu and Peng (2007) adopted this approach to extend to the body nonlinear problem with a linear free surface condition. De Jong et al. (2007) did similar work.

Parametric roll has been of great interest in the design of container ships. Due to the nonlinear behaviour of parametric roll, recent studies have been focused on the simulation of nonlinear roll motion in the time domain. Good examples can be found in Shin et al. (2005) and Ahmed et al. (2006). Additional studies were introduced by Kreuzer and Sichermann (2005), and McCue and Bulian (2007).

CFD applications for the prediction of global ship motion are not yet mature. While used primarily to study local phenomena, there is some work on global ship motion using CFD schemes. For instance, Quérard et al. (2007) presented a two-dimensional approach for obtaining the hydrodynamic coefficients of cylinders swaying, heaving and rolling in presence of a free surface, using a commercial RANS solver. Also Wilson et al. (2006) applied a RANS code for roll motion of a surface combatant.

Luquet et al. (2007) documents the extension of the SWENSE (Spectral Wave Explicit Navier-Stokes Equations) approach, a new method for studying wave-body interactions under viscous flow theory to the simulation of 6 DOF ships in irregular waves. This work has been motivated by the accuracy and efficiency requirements for simulating hulls manoeuvring in waves. Extending the SWENSE method to 6 DOF simulations and irregular waves is discussed in this paper. The validation and verification of the method for a diffraction case is presented and followed by a 2 DOF simulation of a Wigley hull in regular head waves. A first application in irregular waves is illustrated by showing the interaction of a focused wave packet on a TLP. Results show overall good agreement with experiments. The accuracy and effectiveness confirm the viability of the method. Finally, future developments of the proposed approach are discussed.

Building very large ships has meant that hydroelasticity is a big concern to ship designers. Traditionally this problem has been based on frequency domain approaches, but recent studies include some time domain analysis. For instance, Wu and Moan (2005) presented computational results for the SL-7 including hydroelasticity. Time domain analysis is important for fast ships where the motion responses can be strongly nonlinear. Holloway and Davis (2006) applied a strip method for a fast ship, adopting time domain computations, and compared numerical predictions to classical strip theory and experimental results.

2.2.3 High Speed & Multihull Ships:

Recent years have seen the increasing use of a wide range of advanced marine vehicles that include high speed monohulls, multihulls and planing craft for pleasure, commercial and navy applications. This section summarises developments in computational and experimental studies for such vessels.

Fonseca and Guedes Soares (2004) presented a comparison between experimental data and numerical results of the hydrodynamic coefficients and wave-induced motions and loads on a fast monohull model. The GRP model, length 4.52 m, was constructed in four segments connected by a backbone in order to measure sectional loads. The objective of the investigation was to assess the capability of a nonlinear time domain strip method to represent the nonlinear and forward speed effects on a displacement high-speed vessel advancing in large amplitude waves. The numerical method assumed that the radiation and diffraction hydrodynamic forces are linear and the nonlinear contributions arise from the hydrostatics, Froude–Krylov forces and the effects of green water on deck.

Maron et al. (2004) presents the results of an experimental investigation of added masses and damping coefficients of a model of a fast monohull. The GRP model of 4.5m (LBP) was constructed with four segments connected by a backbone. The backbone was instrumented with load cells at the positions of the cuts. This configuration, combined with load cells measuring the force exerted by the forced motion actuators, made it possible to obtain the hydrodynamic coefficients for each of the four hull segments. Nonlinear effects were assessed by conducting model tests for three amplitudes of forced heave and forced pitch motions.

Carrera and Rizzo (2005) carried out full scale measurements on a 17.5m FRP pleasure craft in waves to record both its motions and impact structural loads in the bow region. Moersch and Hermundstad (2005) carried out similar measurements with a 21ft planing craft focusing on the slamming pressures on the bottom of the boat.

Perez Arribas and Clemente Fernandez (2006) presents an assessment of theories that can be used to predict the seakeeping behaviour of high speed craft by considering dynamic forces. These theories are validated by comparing predictions of vertical motions in head seas against seakeeping tests on fast monohull models.

Garme (2005) proposed a method for correcting the lift distribution in order to correctly model the running attitude of a planing craft in waves. The approach is validated in calm water, regular and irregular waves. Simulations of model experiments and comparison with measurement time series are presented.

Nan Xie et al. (2005) used a finite element approach to investigate the hydrodynamic problem of a 3D planing surface. The planing surface was represented by a number of pressure patches whose strengths were constant at each element. The unknown pressure strength was obtained by using the free surface elevation condition under the planing surface and the Kutta condition at the transom stern. The predicted results of the method are compared with other similar work.

Ma et al. (2005) described a new numerical algorithm for solving a 2.5D hydrodynamic theory, based on the high-speed slender body assumptions where the free-surface condition is 3D, but the control equation and body surface condition are 2D. The approach uses boundary integral equations formed in the inner fluid field domain, and outer fluid field domain and matched on a fixed control surface. This paper shows that the matched boundary integral equations can be used to calculate the hydrodynamic characteristics of high-speed displacement vessels with large flare.

Chung and Chun (2007) derived a harmonic function based on the Green function for the limiting case of Froude number tending to infinity to provide a first order potential solution for a flat plate planing at a very high speed, in which the angle of attack varies with speed.

Malenica et al. (2005) examined two different methods investigating multibody interaction using a boundary integral equation method. The first approach is based on the classical direct application of the basic mechanical principles while the second methodology involves the so-called generalised modal approach. The direct method gave good results for a tandem configuration but relatively poor results for side-by-side configuration. The reason for this result was the narrow space between bodies, which can experience a resonant behaviour at some frequencies. This non-potential phenomenon cannot be properly modelled by pure potential theory. In order to improve the method, the authors modified directly the boundary conditions on the part of the free surface and on the bodies. To satisfy those conditions the BIE were modified as well. The authors also presented a mid-field formulation to obtain second order drift loads on the multibody configuration.

Li et al. (2006) presented a numerical simulation predicting the influence of finite water depth on two ships interactions in waves. The developed algorithm solved the zero forward speed free surface Green function for the finite water depth by combining the integral form and John's conventional expansion series form of the Green function. The water depth effects on two ships interacting in waves with forward speed are accounted for by using a 3D panel method based on the zero-speed free surface Green function in a finite depth of water with forward speed correction. Predictions indicate high sensitivity to decreasing water depth, particularly for smaller vessels operating in the vicinity of a larger one.

Inoue and Kamruzzaman (2007) presented a numerical study of hydrodynamic forces and motion responses of a twin Lewis catamaran, with and without a bulbous bow, advancing in regular waves. The authors used the YNU-SEA computer code based on the 3D Green function with forward speed. For the purpose of code validation the added mass and damping coefficients for heave and pitch motions, and pitch and heave responses were calculated and compared to experimental data and previous calculations. After satisfactory comparison, the "validated" code was applied to study the performance of a Wigley hull catamaran, with and without bulbous bow. The authors concluded that the size and the fineness of the bulb are significant in reducing relative wave height for high speed catamaran hulls.

Wei et al. (2007) used a 2.5D theory to predict the motion performance of a displacement trimaran in waves and compared their results with experiments. They also investigated the effect of the transverse distance between side hulls and main hull and the longitudinal position of the side hulls.

Fang and Too (2006) applied a three-dimensional potential flow methodology to analyze the effects of side hull location on a trimaran ship travelling in regular waves. Hydrodynamic interactions between hulls, including added masses and damping coefficients and excitation forces, are used to solve for the six degrees of freedom motions. Comparisons with experimental data are generally good, although some discrepancies, particularly heave at high speed ($Fr = 0.45$), are evident. The technique is then used to evaluate variations in side hull stagger (distance of side hulls from the stern of main hull) and clearance (athwartship distance of side hulls from main hull). Seakeeping performance is shown to be best with smaller stagger and larger clearance.

Subramanian and Gururajan (2004) reported model tests for a series of three planing catamaran hull forms up to speeds corresponding to Fr = 1.12, by varying the length/ breadth of demihull ratios (6.67, 10 and 15.15) and hull spacing (40 to 2). The experimental results are compared fairly well with analytical ones using the SEDOS program (Söding, 1988).

Egorov and Tonyuk (2007) reported a numerical and experimental investigation on trimaran hull motions. The hydrodynamic problem was considered within the framework of linear wave theory. To determine the exciting forces and damping coefficients, Haskind–Newman method was applied where asymptotic values of the radiation potential were used. The damping coefficients were calculated by analyzing the energy transfer from surface waves to the moving ship, using the formula of Haskind–Newman. The generalised added masses were calculated by the Kramers–Kronig equation. Numerical results are verified by systematic testing of trimaran longitudinal motion's hydrodynamic and kinematic properties.

Hart et al. (2007) adapted the time-domain nonlinear LAMP (Large Amplitude Motion Program) code to model the lifting body and a simplified version of a ride control system. Afterwards they carried out seakeeping calculations for the lifting body technology demonstrator *Sea Flyer*, a 48.8 m converted SES with a large lifting body amidships and an aft hydrofoil. They found that their results were in good correlation with available sea trials data.

Bai and Kim (2007) considered the motion control of fully submerged hydrofoils in waves. The change of lift force due to the orbital motion of fluid particles is included as time-varying disturbance in the equation of coupled heave-pitch motion, and the corresponding state space equation is derived. Several control algorithms including PID, LQR, and sliding mode control are applied for regular and irregular wave conditions, and the resultant motion responses are compared. The effectiveness of these algorithms is evaluated via existing experimental data and their robustness checked by motion simulations in various wavelengths and wave heights. PID control is easy to handle, however it exhibits poor performance in irregular waves. LQR control gives robust and stable results throughout all the cases. The results of sliding mode control are remarkable when the information of the wave disturbance is exactly known. However, it was found that the motion tended to diverge as the discrepancy between the real disturbance and the estimated value became bigger.

2.2.4 Rarely Occurring events– Slamming, Whipping & Deck wetness

In significant wave conditions the relative motion of a ship maybe so large that the forefoot and propeller become exposed and the deck submerged on a regular basis. These phenomena occur most frequently at high speed in head seas but are also known to occur in other conditions. If the relative motion is sufficiently high to create instances in time when the body comes back into contact with the water surface above a critical velocity a slam may occur. If a significant length of the keel is exposed then a keel slam usually follows; if the wet deck of a catamaran suffers an impact with the rising water surface then catamaran experiences a wet deck slam. Keel, stern, flare or wet deck slamming can induce excessive vibration within the ship and can ultimately lead to increase in structural fatigue or damage.

Landrini (2006) originally presented as the 2003-2004 Georg Weinblum Memorial Lecture, covers much in the area of water-ship interactions. An overview of three state-of-the-art numerical tools based on potential flow, rotational inviscid flow, and viscous fluid assumptions are outlined and the methodologies compared and discussed. With respect to seakeeping, the author discusses nonlinear phenomena such as water on deck and sloshing. Overall, an excellent treatise on the importance of both experimental and numerical tools in solving highly complex hydrodynamic problems is presented.

Korobkin and Malenica (2005) introduced a new model of water impact and applied it to the two dimensional problem of an asymmetric body entering the water vertically. The model was based on the Wagner theory (1932) of impact and the at-disc approximation but accounted for both the body shape and the nonlinear terms in the Bernoulli equation for the hydrodynamic pressure. The authors applied the Modified Logvinovich Model (MLM), and a simple formula for the evaluation of maximal acceleration magnitude of the inclined wedge dropped onto the liquid free surface, and compared with experimental data. Malenica and Korobkin (2007) provided an assessment of available methods of modelling slamming, starting from the simple von Karman model and ending with fully nonlinear models.

Hermundstad and Moan (2005) presented a method for the prediction of slamming loads on ship hulls and shows validation for a 20-knot, 120-m car carrier. A nonlinear strip theory is used to calculate the relative motions of the ship. The relative vertical velocity and roll rate for a slamming event are given as input to the slamming calculation program, which is based on a generalised two-dimensional Wagner formulation and solved by the boundary element method. Model tests have been carried out in regular head and bow quartering waves of various heights. Slamming on two panels in the upper part of the bow flare has been studied. It was found that the water pile-up around the bow due to the forward speed of the vessel significantly increased the slamming pressures. When the calculated slamming pressures are corrected for 3D effects, they compare well with the measured data.

A similar method was presented by Hermundstad and Moan (2007) and validated for a 290m cruise ship. The nonlinear strip theory method was again used to calculate the ship-wave relative motions which were then input in to the slamming calculation program. To improve the calculation efficiency with minimal loss of accuracy, the method was divided into two separate steps. In the first step, the velocity potentials were calculated for unit relative velocities between the section and the water. In the next step, these pre-calculated velocity potentials were used together with the real relative velocities experienced in a seaway to calculate the slamming pressure and total slamming force on the section. The calculated slamming pressures on the bow flare of the cruise ship agreed quite well with the measured values, at least for time windows in which the calculated and experimental ship motions agreed well.

Wang and Wu (2006) presented an application of an unstructured mesh based finite element method to analyse the two dimensional nonlinear wave interaction with a non-wallsided floating body evoking flare slamming. The fluid motions are described using a velocity potential satisfying the Laplace equation. The generated 2D unstructured mesh was suitable for handling nonlinear geometry shapes. The work focused on the water entry problem of wedge like bodies oscillating with large amplitude in calm water and in nonlinear waves. The results were presented as the hydrodynamic force on the wedge shaped bodies in sway motion and heave motions and were compared to the solution obtained from a second order theory.

The free surface flow generated by a flat plate impacting the water with a constant entry velocity was investigated numerically by Iafrati (2007), for both 2D and axi-symmetric cases. The plate was initially floating on the free surface and was assumed to have instantaneous vertical motion. The liquid was assumed ideal and incompressible, and gravity and surface tension effects were neglected. The work was mainly focused on the development of a numerical procedure that could capture the peculiar features of the free surface dynamics for such flows, and that could provide an accurate estimate of the resulting hydrodynamic loads. The details of the numerical approach were described and differences between the two-dimensional and the axi-symmetric solvers highlighted. Numerical simulations were presented which covered a very wide range of time and length scales. Results were presented in terms of free surface shape, pressure distribution and total hydrodynamic load on the plate and comparisons with theoretical estimates were established where available.

Yang et al. (2007) conducted numerical simulations and wet drop tests to investigate stern slamming of modern containerships and to determine if numerical methods could be used to calculate slamming type impact pressures. The experimental investigation included a drop test with 2D wedges and containership stern sections to evaluate peaks and temporal and spatial distribution of impact pressure distribution in relation to the relative velocity of the body. The data were primarily applied to establish the applicability of CFD codes for slamming simulations. For the numerical drop test, fixed and moving grid systems were applied. The moving grid system was reconstructed at every time step. Grid dependency convergence tests were carried out to identify spatial and temporal grids size independent solutions. The authors conclude that the free fall of a body can be reasonably simulated using a moving dynamic mesh technique and credibly applied for the practical ship design.

Kim (2005) considered the three-dimensional impact problem in the presence of a non-flat, free surface profile. Particularly, this study introduced new 3D impact theories, based on the extended Von Karman and extended Wagner methods. A new numerical technique was introduced that maximised computational efficiency. Numerical computations were carried out by a B-spline Rankine panel method, and the results compared for different wave conditions.

Kim et al. (2007c) undertook computational and experimental studies on the water-entry impact of asymmetric wedges. In the case of the computational studies, two different methods were of interest: a semi-analytic method and a smoothed particle hydrodynamics (SPH) method. The semi-analytic method was extended to solve the generalised Wagner problem of asymmetric water entry. In this method, the evolution of the free surface along body surface was represented by Chebyshev polynomials. To observe violent free surface flows during impact, the SPH was applied. A series of experiments measuring the evolution of the free surface during symmetric and asymmetric drops of 2D wedges with deadrise angles of 30, 45, and 60 degrees had been conducted and compared with those of the semi-analytic and SPH methods. Overall trends of the free surface evolution were consistent in the computation and experiment. In both cases, the splash-up along the body surface with steeper deadrise angle was larger than that of tilted side, but it was found that the measured splash-up along the bodies showed some discrepancy with the computation. Cavity flows were found in the experiment, and SPH provided successful simulation of cavity occurrence.

Viviani et al. (2007) applied two different numerical methods, namely a free surface RANS solver and a SPH method, to the evaluation of slamming loads (global forces and local pressures) on a typical wedge shaped section. Results from both methods are presented and compared with available experiments.

Peseux et al. (2005) dealt with the slamming impact between the ship bow and water free surface by employing numerical and experimental techniques. The hydrodynamic impact loads calculations using numerical methods were conducted within the framework of potential flow theory and Wagner's approximation method of blunt body impact. The numerical analyses were conducted for both rigid and deformable structures. The finite element method was used to solve the set of fluid and structural equations. The experimental investigation included free drop tests of rigid and flexible cone-shaped bodies of varying deadrise angle and compared the measured and calculated pressure in multiple locations which showed satisfactory qualitative agreement.

El Moctar et al. (2005) used a multi-stage approach to predict slamming loads. They used a linear frequency domain, Green function panel method to identify the design wave conditions, a nonlinear code to accurately predict the ship motions, and an extended viscous code to investigate the loads assuming a rigid body. Their numerical results for a Ro-Ro ferry are in close agreement with the measurements of the horizontal force component.

Schellin and El Moctar (2007) presented a numerical procedure to determine wave-induced slamming loads on ships. The procedure was used to predict slamming loads on a modern offshore supply vessel with the area under the bow flare of special interest. The method consisted of three stages. The first stage was running a Green function panel code to determine the environmental conditions causing slamming; the second was the prediction of ship motion under the target wave conditions; the third phase consisted of the application of a RANS code to calculate slamming loads when the previously obtained ship motions were used as input data. The predicted averaged pressure over a selected area was compared favourably to the experimental data.

Singh and Kumar (2007) presented a numerical approach to estimating the slamming impact pressures on a ship hull in regular waves. The method was based on the application of a potential flow method using the 3D transient Green function to calculate ship motions which were used as an input to a RANS solver to obtain slamming impact pressure. In order to validate the method, initial calculations were conducted for a 2D triangular wedge section. The calculations were conducted for three grid sizes to investigate sensitivity of solutions to mesh discretisation and compared to previously published experimental data. The "validated" method was used to calculate slamming pressure on a forward section of a container ship. First, relative motions of the ship were calculated using linear and non-linear programs and applied as an input to the CFD solver. Pressures at the bottom and at the flare points were computed.

Oger et al. (2007) presented a specific study based on the SPH method, and proposed some comparisons between experimental and numerical results for a three-dimensional slamming test case. This study was aimed more at illustrating the large possibilities offered by this meshless method for such applications. The SPH scheme was presented and discussed, and a parallelised SPH model that allowed a reduction in the computational costs of 3D simulations was introduced. In order to allow simulations involving complex 3D geometries, a new method based on the extension of the ghost particle technique for imposing boundary conditions was discussed and tested. As an illustration of these procedures, the case of a complex hull impacting the free surface in the context of imposed motion was treated in a 3D free surface flow computation. For this test case, some experiments had been carried out and were introduced here; numerical and experimental data were compared.

In order to investigate the effects of slamming loads on ships (vibrations, hull girder fatigue and ultimate strength), a French national research project was established with the joint support of industry and public institutions. The project involved different physical experiments and numerical simulations. Rousset et al. (2005) presented the experiments that were aimed at studying the sensitivity of global and local loads to kinematic parameter variation.

Wines et al. (2007) carried out model tests to investigate the effect of weight increase of Royal Norwegian Navy Mine Countermeasures SES Vessel (MCMV) on its performance with respect to slamming on the wet deck. They determined that the increase in the wetted surface and the significant growth in the number of slamming incidents, and gave indication about the liable locations of slams.

The primary objective of Fu et al. (2007) was to obtain full-scale qualitative and quantitative wave slamming data of the *Sea Fighter* (FSF-J), a high-speed multihull vessel. These data included measurements of the ambient environmental conditions, the incident waves impacting the ship, ship motions, and visual documentation of the free surface/wave field surrounding the ship during slamming events. This reference described four of the typical wave slam events, which occurred during the field test.

Davis and Whelan (2007) developed a computational model for catamaran wet deck slamming on the basis of the variation of added mass as the hulls enter the water. The computational model introduces a soft connection between the water added mass associated with the slam and the hull. The method has been evaluated by comparison with 2D model drop tests in terms of the maximum forces and acceleration imposed on the hull, the variation of velocity during the slam event and the depth of penetration into the water.

Lin et al. (2007b) presented a numerical simulation method for predicting the wet deck slamming of a high speed catamaran. The numerical simulation method was built upon the framework of a time domain potential flow panel code that solved the 3D wave-body hydrodynamics and rigid-body dynamics problems with consideration of external forces.

An extension of the wet deck slamming hydrodynamic approach of Ge et al. (2005) had been added to predict wet deck slamming within the time domain simulation. A validation study of the numerical simulation method was carried out, which compared predicted motions and wet deck slamming pressures to measurements from recent model tests and full scale sea trials for the catamaran *Sea Fighter*, FSF-J. Comparisons were made in the time domain with wave-by-wave response for individual runs and this overall numerical simulation method, the mathematical formulation of the wet deck slamming approach, details of the *Sea Fighter* model test, full-scale trials results of the validation study, and several outstanding issues related to the numerical simulations method were discussed.

Ge at al (2005) reported a comparison of experimental and theoretical impact loads and global response due to wet deck slamming on a high speed catamaran in regular head seas is studied. An instrumented segmented model was tested in the Ocean Basin at the Marine Technology Center in Trondheim in 1996. The data compared well to the predicted vertical motions, vertical shear forces and bending motions as presented earlier. The authors extended the data comparison to the predicted slamming and impact loading resulting in fair agreement. Uncertainty and error analysis of both experiment and numerical simulation point to the importance of accurately measuring trim angle and incident wave elevation along the physical model, and accounting for the side hull interactions in the prediction model.

Stenius et al. (2007) modelled hydroelasticity in water impacts of the ship hull bottom panels using explicit finite element methods. The technique enabled the modelling of the instantaneous fluid-structure interaction. Hydroelastic effects on the panel response were systematically studied for different impact velocities, boundary conditions and structural mass. The work was compared with other published work concerning hydroelasticity in panel-water impacts.

The stern form of certain types of ship, which can be characterised by a flat bottom and shallow draft, can be subjected to frequent emersions followed by an impact resulting in stern slamming. The subsequent vibrations can contribute to the global vertical bending moment and could compromise comfort levels in the aft part of the ship. Luo et al. (2007a) presented a combined seakeeping and decoupled vibration method to simulate whipping responses induced by stern slamming loads in following waves and proposed a formulation for stern slamming force. Numerical and test results of pressures, whipping component, and total vertical bending moment (VBM) were found to be in fair agreement. They carried out sensitivity analysis using a simplified model on the time period of slamming force, dynamic sinkage and trim and ship speed. They also provided guidelines to the captain to reduce whipping responses induced by slamming in following waves.

Luo et al. (2007b) presented a study on stern slamming using a segmented model technique. The goal of the study was to demonstrate that the stern slamming phenomenon might have significant impact on the global VBM in following seas for a vessel operating at low forward and zero speed. The study confirmed the severity of stern slamming loads and showed an increase in midships VBM of 34% for a specific sea state and zero speed.

Dessi and Mariani (2006a) presented extensive experimental investigations on bow and stern slamming loads, using segmented models. Critical conditions for bow bottom and flare slamming in head seas as well as for stern slamming in following seas have been identified as a function of forward speed. Confirmation of results based on full scale onboard observations was demonstrated.

Dessi, and Mariani (2006b) also attempted to combine two approaches, Wagner's and Von Karman's models, to predict slamming loads. The goal was to use simple and efficient numerical methods to compute impact loading and ultimately ship whipping. Their results are then compared to seakeeping tests conducted at INSEAN of a segmented model representing a fast ferry. The combination of the two generalised solutions does appear to represent more accurately the measured loads, and provides a satisfactory prediction of the maximum bending response.

Dessi et al. (2007) presented an experimental investigation into the VBM response to stern slamming loads on a large modern passenger ship employing a segmented model approach. The model experiments were performed in head and following irregular waves, at various sea states and speeds. The analysis focused on the determination of the criteria for slamming to occur, and on the global responses. The analysis was conducted using spectral and wavelet transforms techniques. Criteria for slamming occurrence were determined using the Ochi and Motter (1973) approach based on ship relative motions and relative velocity. The criteria were established for bow bottom (relative displacement and velocity) and flare (relative velocity) and stern slamming (relative displacement).

Chen and Xiao (2007) studied the effect of speed and sea state on the slamming probability of ships on the basis of the seakeeping standard series. They selected five differently sized ships. The results showed that the severity of the sea state affects the slamming probability at the bow in a monotonic way, while the respective effect of speed depends on the sea state. With respect to the slamming problem, low, middle and high sea conditions could be bounded by the ratio of significant wave height and ship length of 0.02 and 0.03.

Storhaug and Moan (2007) presented a procedure for evaluating the impact of wave-induced vibrations on ship fatigue life. The proposed approach was demonstrated by experimentation using a segmented flexible model of a bulk carrier. The slowly varying wave frequencies and high frequency loads were considered. Experiments were conducted at several selected sea states and vessel operational speeds; the effects of involuntary speed reduction, ballast and cargo drafts and trim on measured fatigue damage were investigated.

Cusano et al. (2007) presented an experimental and numerical investigation into the effects of bow flare and stern slamming on large modern passenger vessels in order to assess whipping responses and develop a practical tool for designers for these types of ship. The experimental data, primarily collected for validation of the numerical approach, were rigid body motions, impact pressure. The theoretical procedure included calculation of rigid body motions, evaluation of slamming pressure and vibration analysis of the ship structure. For the rigid body motions a linear frequency domain code based on the 3D Green function was employed. To predict impact pressure associated with bow flare slamming a 2D BEM code was applied. Two approaches were adopted for whipping analysis. To evaluate the whipping contribution at the ship design stage when the structural information is not sufficiently complete, a 1D FEM was used. The 1D structure was modelled by a series of beams with proper inertia, stiffness and mass distribution. For more detailed analysis, a 3D FEM model was used. In the model all structural elements were modelled using shell and beam elements. To account for payload, machinery and equipment on-structural masses were appropriately distributed. The predictions were successfully compared to experimental data. The authors indicated the usefulness of 1D whipping simulations for preliminary ship structure analysis in the early stages of the design process.

Rosén (2005) presented a method to reconstruct the momentary pressure distribution in hull-water impacts. Measurements of the propagating pressure pulse in one position of the hull at a particular instant of time were associated with measurements in other positions at other instants by a set of assumptions and interpolation techniques. Hereby, the complete pressure distribution was reconstructed with the use of only a limited number of transducers. The method was evaluated with data from full-scale trials of a planing craft in waves. Reconstructed pressure distributions were applied as loads in a finite element model of the hull.

A green water incident occurs when the bow becomes submerged and water is shipped onto the foredeck. The resultant deck loads can cause significant damage to exposed structures, including the superstructure, exposed cargo etc, as well as impacting on the ability to perform tasks requiring access to the foredeck area.

Establishing the correct mathematical model of green water phenomenon can be difficult, especially in the way the non-linear wave motion, hull form at the bow, spray generation and water flow on the deck are coupled.

Kishev et al. (2005a) undertook to verify a modified probabilistic approach for deck wetness intensity estimation that treats the phenomenon as a joint probability of occurrence of freeboard exceedance and its duration. This served to distinguish between spray generation and green water on the deck. Experimental data were obtained from specially tailored model tests with a range of ship types in heavy irregular seas. Results from these tests have been generalised along with other similar results from previous model tests and full-scale observations to enable the processing of a large statistical database concerning the influence of sea waves and ship motion parameters on deck wetness intensity, This allowed the formulation of limiting "threshold" values for statistical estimates for the frequency and duration of the deck wetness process, enabling direct comparison of theoretical predictions with real onboard observations.

A fundamental experimental investigation into the phenomena of water shipping on the bow of a modern containership was undertaken by Fonseca and Guedes Soares (2005b). The results were used to study the physical process by which the water came onto the deck and to validate mathematical models simulating the green water on deck loads. The data analysis indicated that pitch and relative motion responses are significantly nonlinear in regular waves. Since the presence of water on the deck is highly dependent on those responses, the linear approach to solve such a problem is not adequate. Tests in irregular waves indicate that the relationship between water height on the deck and impact pressure and force are also very scattered due to the complexity and nonlinearity of the water shipping phenomenon.

A hybrid technique was developed by Varyani et al. (2004) using a time domain code based on a nonlinear strip method developed by Crossland and Johnson (1998) to analyse problems involving green water on the deck and to set up threshold values to identify the occurrence of green water. Varyani et al. (2004) then used a waterjet model, in preference to the dam-break model, to represent the green water flow on deck of a ship with forward speed. Furthermore, model tests were used to empirically specify the shape of water elevation on deck to provide initial conditions for the CFD model to estimate the resulting deck loading.

Figure 4 (Varyani et al. 2004) shows the comparison of the horizontal load measured on the fore deck with the two CFD models. Clearly, the dam-break model with initial velocity (waterjet) replicates the experiments better.

The CFD model was described in more detail by Pham and Varyani (2005). The CFD model (so called waterjet model) was developed from the dam-break model including an initial velocity to determine both the horizontal and vertical loading following green water events, and compared predictions with experimental results. The comparison showed that the modified model of the dam-break with initial velocity was required to represent water flow when investigating green water loading on ships with forward speed.

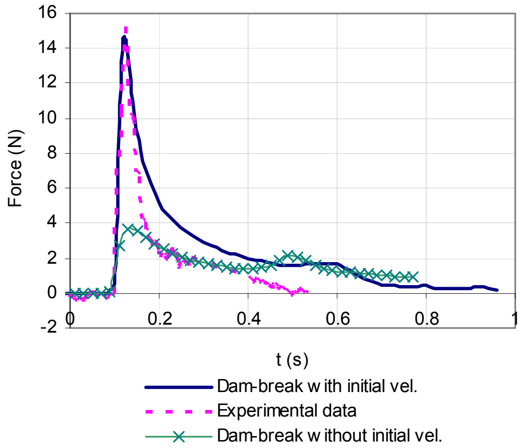


Figure 4: Comparison of horizontal load for an S-175 container ship at Fr = 0.3, H = 8.0m and T = 12s. Varyani et al. (2004).

This CFD model was used by Varyani et al. (2005) to review the phenomenon of green water on container ships coupled with the time domain method based on a nonlinear strip theory for predicting the occurrence of green water. The simple CFD hydrodynamic model (waterjet model) was developed to represent the green water flow on deck. Comparisons of the predicted horizontal green water load (acting on a vertical structure) and test data were made. The work also looked at the presence of breakwaters in reducing the load effects of green water.

Wemmenhove et al. (2005) described a study of the simulation of green water loading on the deck of a ship. The numerical model was developed as a one-phase model initially, but later extended to take two-phase flow effects into account. The method used for the simulations is based on the Navier Stokes equations, with the model discretised using a finite volume method. The incompressible two-phase flow model has been validated on a dam break problem.

Gomez-Gesteira et al. (2005) analysed wave overtopping on the decks of offshore platforms and ships within the framework of the SPH method. SPH has been shown, in literature, to be a suitable qualitative method to model wave motion. The authors were able to show that SPH could provide good quantitative predictions that can permit comparisons between numerical and experimental results. The theoretical method was able to reproduce the main features observed when a wave hits a horizontal platform. The work demonstrated that the presence of a fixed horizontal deck above the mean water level strongly modifies the wave kinematics. In particular, the flow in the wave crest is split into two, showing a different behaviour above and below the deck.

Liang et al. (2007) carried out model tests to better understand the mechanism of green water events and the resulting damage on a moving FPSO. During the experiments, parameters closely related to green water, such as water height on deck, green water induced loads and motions were measured. In addition they used RANS CFD and a finite element code to simulate green water on a FPSO in a numerical wave tank. In the numerical simulation, a dynamic boundary condition was used to generate the incoming wave and the Volume of Fluid (VOF) method was employed for capturing the free surface. Wave reflection was handled properly by setting up a wave absorption zone. The highly nonlinear wave-body interactions, including large amplitude ship motion and green water on deck, were modelled successfully when compared with experiments.

A numerical method was developed by Yamasaki et al. (2005) to predict the water impact pressure caused by the green water phenomena. The density function method was employed in the framework of a locally refined overlapping grid system. The simple problem of a rectangular body placed in regular waves was considered and the simulation results were compared with tank experiments. It was demonstrated that this method could be extended to a moving body problem, in which the body was free to undergo heave, pitch, and surge motions.

Wist et al. (2006) presented a nonlinear probability distribution for the prediction of green water load and volume using a model developed by Ogawa (2003). The Ogawa model was developed assuming that the crest heights were Rayleigh-distributed. This model, however, does not include nonlinear effects that make wave crests larger than half of the wave height. The nonlinear effects were introduced to the Rayleigh distribution using second order wave theory described by Marthinsen and Winterstein (1992). Predictions from the upgraded nonlinear model were compared to results of model tests. The nonlinear model overpredicts the experimental pressure data but agrees well with the green water volume.

McCue et al. (2007) presented a relative comparison of topside shape in their analysis of parametric rolling. The effects of a tumblehome design, compared to more traditional wall-sided or flared topsides, is a larger reduction in the mean GM as a wave passes midships so that parametric rolling can occur at lower forward speeds. Modelling regions of instability using the Mathieu equation, the reduced GM effect was confirmed for this hull design. The effect of lowering KG (increasing GM) to improve dynamic stability may also improve roll magnitude and parametric resonance, but this remains to be confirmed.

2.2.5 Sloshing

Sloshing is a strongly nonlinear phenomenon, where the highly distorted free surface may be associated with wave breaking and air trapping. CIP (Constrained Interpolation Profile) - based methods, initially proposed by Yabe and Wang (1991) are currently used to cope with these kind of flows. There are two important key points in the CIP method: (1) a compact upwind scheme with sub-cell resolution for the advection calculation and (2) a pressure based algorithm that can treat liquid, gas, and solid phases, irrespective of the flow being compressible or incompressible. The algorithms incorporating the latter feature are denoted as C-CUP (CIP Combined and Unified Procedure).

Kishev et al. (2006) applied a new computational fluid dynamics simulation approach based on the CIP method to tackle the violent sloshing problem. The authors studied the 2D sloshing phenomenon in a rectangular tank, viewing the sloshing problem as a multiphase problem that includes water and air flows. A stationary Cartesian grid is used and the free surface is solved by an interface capturing method. The C-CUP scheme was adopted for the flow solver, and both the CIP scheme and the CIP conservative semi-Lagrangian with cubic interpolation polynomial (CIP-CSL3) scheme were used for interface capturing. For validation of the numerical method, a physical experiment was conducted with a rectangular tank for several frequencies and filling heights. A convergence check was first performed for the method. The numerical simulation results on violent sloshing show that the use of the CIP-CSL3 scheme as an interface capturing procedure gives much better results for the pressures and the free surface profiles than the conventional CIP scheme.

Colagrossi et al. (2006) presented research work which combines 2D sloshing experiments performed in a rectangular tank and the 2D SPH solver. By varying the excitation period of the sinusoidal horizontal motion of the tank, and by increasing its amplitude of oscillation, some peculiar phenomena were observed for excitation periods near the linear sloshing natural period, i.e. an asymmetric behaviour of the wave elevation along the tank, as well as alternation of the breaking phenomenon at the two tank sides.

Colicchio et al. (2007) studied a very peculiar phenomenon that can appear during sloshing flow in a partially filled tank: the flip-trough event. A 2D sloshing flow inside a tank, which is forced to oscillate horizontally, is studied experimentally. From the experimental point of view, a novel free surface tracking is used to characterise the details of the flip through dynamics while impulsive wave loads are measured by using an *ad hoc* distribution of miniaturised pressure sensors. The extremely local character of the phenomenon investigated is used to highlight capabilities and limits of the numerical algorithms proposed: a Level Set technique to solve the Navier Stokes equations, and a SPH method to solve the Euler equations. A suitable domain decomposition strategy is proposed to study the evolution of the air bubble entrapped during the development of the flip-through event.

Sueyoshi et al. (2005) used the MPS (Moving Particle Semi-implicit) method introduced by Koshizuka and Oka (1996) to simulate violent sloshing flows. Most of previous computational work for sloshing has adopted field equation solvers, but the present study used a particle method. It is shown that the violent flows including wave breaking can be simulated well, but it is found that impact pressure is hard to predict.

Kim et al. (2007d) applied numerical methods for violent sloshing flows and compared their results. To this end, two different approaches were implemented for cases where experimental data are available. The methods considered were a finite volume method based on the hybrid VOF scheme and a finite difference method based on the SOLA-SURF algorithm. The hybrid VOF scheme was developed by combining a volume capturing VOF method with the Level-Set re-initialisation procedure. This scheme improves numerical smearing effects accompanying the conventional VOF method especially for the regions on violent flows or poor grid resolution. The application of the SOLA-SURF scheme is based on the assumption that the sloshing-induced impact loads are dictated by global fluid motion. According to experimental observation, despite the occurrence of overturning, splashes, bubbles, and other complicated physical phenomena, the magnitude of sloshing-induced impact pressure seems to be dictated by the global motion of fluid volume. When this is the case, the simulation of the global flow is key in the prediction of impact occurrence. From the perspective of computational efficiency, such a concept has a strong advantage by ignoring some complicated physical issues, as long as it does not affect the global flow. The aforementioned numerical methods were applied to the rectangular tank model with three different liquid filling level conditions (30%, 50%, and 70%) near natural frequencies. The hydrodynamic impact pressures on the side wall and top corner of the tank and violent free-surface flows were compared with the experiment.

Akyildıza and Unal (2006) undertook a numerical and experimental study looking at the pressure variations and 3D effects on liquid sloshing loads in a moving, partially filled, rectangular tank. A numerical algorithm based on the VOF technique was used to study the nonlinear behaviour and damping characteristics of liquid sloshing. Several configurations of both with and without baffles in the tanks were studied and comparisons showed good agreement for both impact and non-impact type sloshing loads in the cases investigated.

Nam et al. (2006) solved the linear ship motion coupled with nonlinear sloshing problem. In particular, an impulse response function is adopted for the time domain analysis of ship motion. For simulating nonlinear sloshing flow, the numerical method used by Kim (2001, 2002) is applied. This method concentrates on the simulation of global fluid motion, including impact occurrence during violent sloshing. The developed scheme is verified by comparing the motion RAOs with the frequency domain solution. The nonlinear effects of the coupled problem are observed in the roll motion of a modified S175 hull equipped with a rectangular passive type anti-rolling tank. Their analysis shows that the nonlinearity of sloshing flow is an essential part in the coupled analysis. A similar conclusion was derived by Kim et al. (2007d) who used the same method to analyse ship motion and a finite difference method to simulate the nonlinear sloshing flow. The sloshing-induced forces and moments were added to wave excitation forces and moments, and then the corresponding body motion was obtained.

Kyoung et al. (2005) obtained a numerical solution for the wave impact load on the structure due to excessive sloshing in an LNG or FPSO tank by imposing the exact nonlinear free surface conditions.

Nam and Kim (2007) considered the motion responses of a LNG-FPSO in waves, coupled with sloshing in cargo. When a floating body with liquid cargo is under excitation in ocean waves, its ship motion is affected by both external wave excitation and internal sloshing-induced forces and moments. The authors used a model of an LNG-FPSO with two tanks to carry out a series of experiments to validate the numerical scheme introduced by Nam et al. (2006). The motion responses in regular waves have been measured at a range of frequencies at different tank conditions and wave amplitudes. The measured motion RAOs were compared with computational results and a fair agreement was found.

Lee et al. (2007a) investigated the coupling and interactions between ship motion and inner tank sloshing using a time domain simulation scheme. For the time domain simulation, the hydrodynamic coefficients and wave forces were obtained using a frequency domain 3D diffraction/radiation panel program. The corresponding simulation of motions in the time domain is carried out using the convolution integrals. The liquid sloshing in a tank is simulated in the time domain by a Navier Stokes solver. The developed schemes are applied to a barge type FPSO hull equipped with two partially filled tanks. The time domain simulation results show similar trends when compared with experimental results.

Lee et al. (2007b) undertook a series of sensitivity studies on LNG tank sloshing loads using a computational fluid dynamics (CFD) program. The sensitivity of impact pressure is checked through numerical simulations parameters, such as fluid viscosity, liquid–gas density ratio, ullage pressure and compressibility and verified against experimental results.

Rognebakke and Faltinsen (2005) studied high filling sloshing-induced impacts by experiments as well as by use of theoretical and numerical models. A two dimensional flow is assumed in the theoretical treatment and aimed at in the experiments. The tank shape is rectangular. The idea in the experiments was to use high speed cameras and particle image velocimetry technique to capture the details of the impact flow. Pressures were measured in the impact zone.

2.3 Added-Resistance & Powering in Waves

Commercial ship design is usually conducted on the basis of its resistance and powering performance in calm water. But ships normally operate in a range of environmental conditions such as wind and waves, not solely in calm water. The design of ships, therefore, should be conducted considering such wave and wind effects. At the design stage, such effects have so far been considered as an allowance of the resistance or necessary power in the ship. This quantity is called the "sea margin" and it has customary been a constant value, e.g. 15%. This sea margin, however, must be varied depending on ship routes, environmental conditions, ship size, shape, kind of ship, etc.

Due to the increasing awareness of global ecology and soaring fuel oil prices, the development of energy saving measures on ships to reduce greenhouse gases and fuel consumption are recent issues discussed at IMO and other organisations. For saving energy at sea, i.e. in wind and waves, not only improvements to the hull form, main engine or propeller, but also improvements to ships operations such as weather routing, are necessary. Any information on ship performance in waves is crucial for ship owners to assist in procurement. The improvement in ship performance at sea is also an important issue for ship designers.

Under the above circumstances, the accurate prediction method of ship performance in waves, e.g. added resistance and power increase in waves is necessary for both of purchasers and designers of ships.

The added resistance in waves is normally estimated as a combination of 2D strip theory based on Maruo's theorem and the component due to wave diffraction at the bow. The theory of the latter component is for example Fujii-Takahashi's or Faltinsen's equations.

Perez Arribas (2007) compared some 2D theory results with model tests of container ships and a ferry. He showed the application range of the momentum and energy method, the integrated pressure method and the radiation energy method.

Fang and Chen (2006) compared the 3D pulsating source distribution method with the 2D calculation and model test results for the series 60 model. The 3D method showed better prediction for mean lateral drift force in waves, but for added resistance the 2D method was superior.

These 2D or 3D methods can calculate the hydrodynamic forces acting on ship's hull shape only at its calm waterline and below. But recently it has been noted that the effect of the hull shape above the calm waterline on added resistance in waves can not be neglected.

Hirota et al. (2005) showed, using model test results, that the sharpness of the bow shape above the calm waterline could reduce the added resistance in head waves. They also confirmed its effect by comparing the measurements from two bulk carriers at sea, where one has the sharpen bow shape above the calm waterline (refered as "Ax-Bow".) and the other has the ordinary blunt bow.

Figure 5 shows the comparison of speed loss in waves obtained from full-scale measurements at sea.

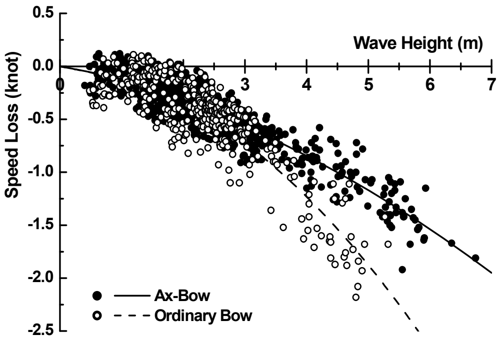


Figure 5: Comparison of speed loss at sea

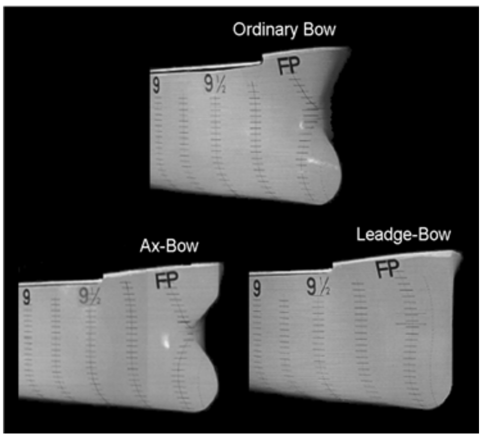


Figure 6: Comparison of bow shapes

As seen, the vertically sharpen bow (referred to as the "LEADGE-Bow") shows less added resistance in waves, but even the bow sharpened only above water line can reduce the added resistance from the ordinary bow. Figure 6 shows these bow shapes.

Kihara et al. (2005) developed a 2.5D time domain method for the hydrodynamic forces in head waves. The focus of their approach was on the influence of the above water hull form on the added resistance. They compute the added resistance in regular head waves for very large crude oil carriers (VLCC) with different bow flare angles, whose body plans are given in Figure 7. The effect of bow shape above the water on the added resistance obtained from their computations is given in Figure 8.

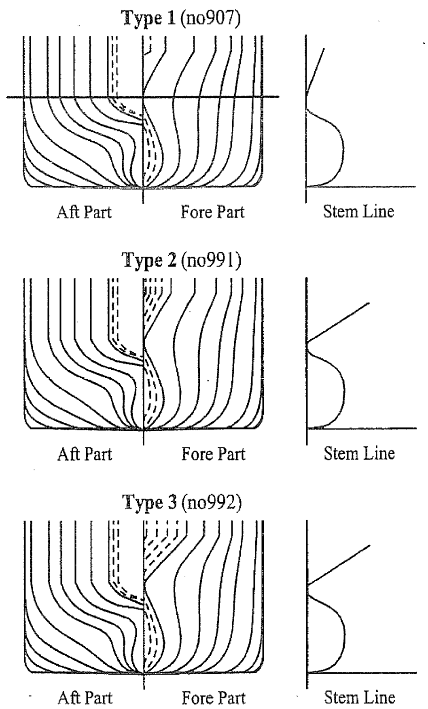


Figure 7: Body plan of VLCC variants

Sato et al. (2006) applied a CFD code named WISDAM-X to estimate the surface pressure on a VLCC in regular head and oblique waves. Orihara et al. (2005) and Orihara (2006) applied WISDAM-X to simulate surface pressure and the resultant ship motions and added resistance in regular head and oblique waves on a container ship and a VLCC for their fully loaded conditions and ballast condition. This code can predict the surface pressure distribution on the ship in motion in waves, which means it can also consider the difference of the hull shape above the calm waterline.

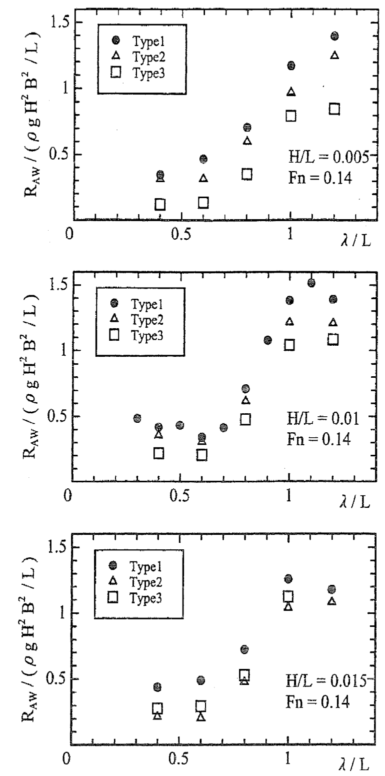


Figure 8: Influence of above-water bow forms on computed added resistance.

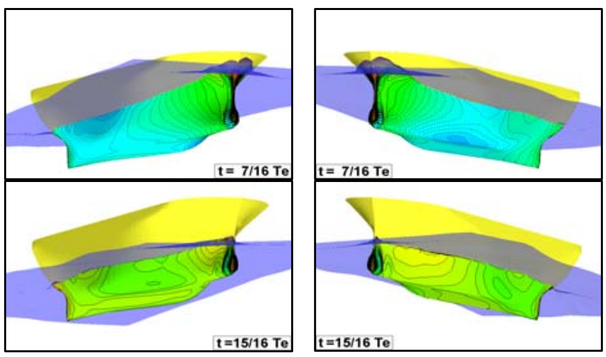


Figure 9: Computed pressure distributions on a container ship, Fr=0.25, χ=120deg, λ/L=1.0

This type of CFD seems promising for the detailed design of ship resistance and powering performance at sea in the future. Figures 9 to 11 show the computed surface pressure distributions on a container ship and a VLCC in regular waves. Figures 12 to 14 show the comparisons of added resistance in regular waves between computation and model test results.

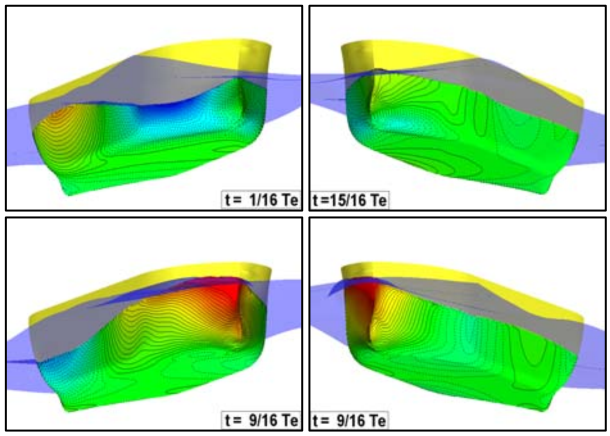


Figure 10: Computed pressure distributions on a VLCC (Full load condition), Fr=0.15, χ=120deg, λ/L=0.5

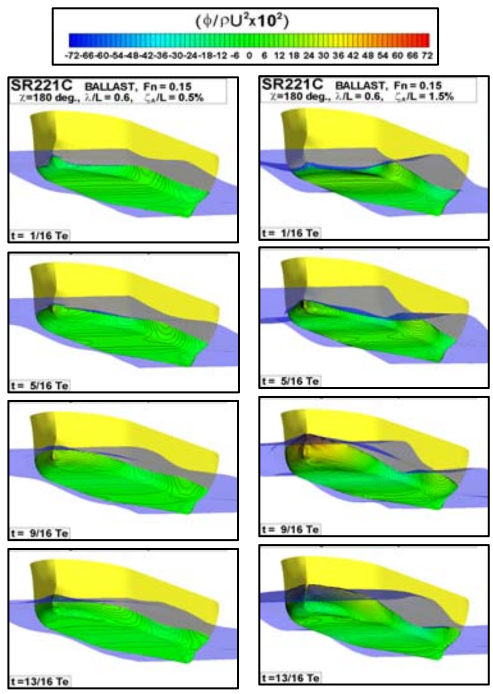


Figure 11: Computed pressure distributions on a VLCC (Ballast cond.), Fr=0.15, χ=180deg, λ/L=0.6

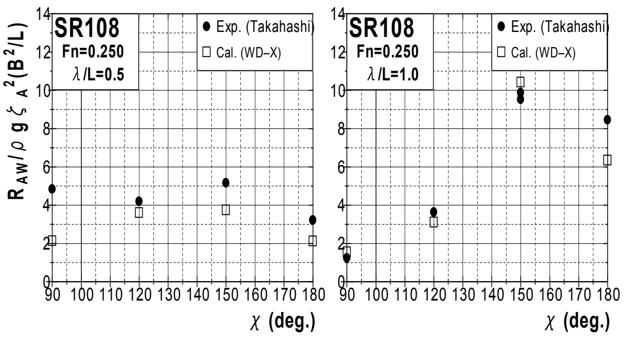


Figure 12: Added-resistance coefficients for a container ship, λ/L=0.5 and 1.0

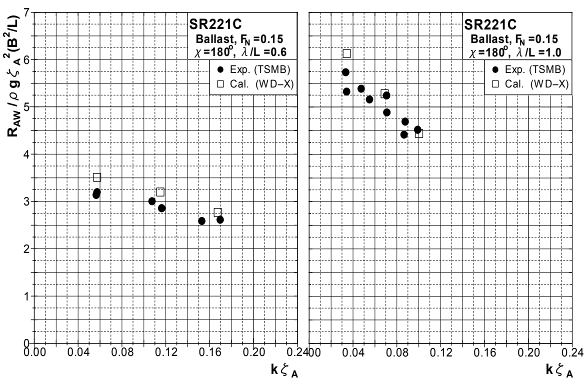


Figure 13: Added-resistance coefficients for a VLCC (Ballast cond.), Fr=0.15, χ=180degλ/L=0.5 and 1.0 vs. wave slope

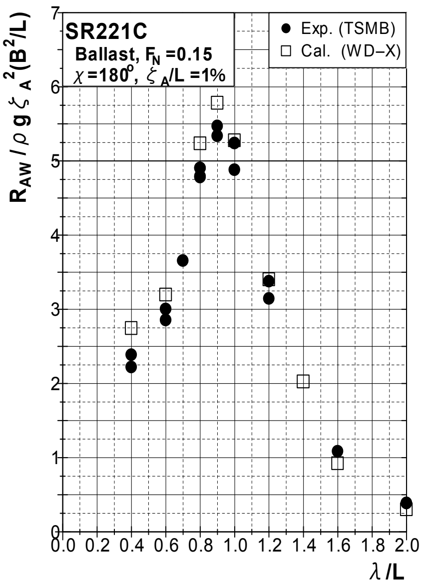


Figure 14: Added-resistance coefficients for a VLCC (Ballast cond.), Fr=0.15, χ=180deg

For the purpose of predicting power increase in realistic seas, conducting self-propulsion tests in irregular waves is the most direct and simplest approach. However this is not, in general, a satisfactory solution, because the results are less precise than those obtained in regular waves, and apply only to the particular wave spectra for which the experiments were carried out.

In order to design ships or to analyse measured data from ships 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 the basic data on the ship's response functions in regular waves. In particular, by using these data and the irregular wave spectra, power increase in a range of irregular waves can be calculated and evaluated.

Several methods have been proposed and are in broad use at various laboratories to predict power increase in irregular waves from response functions obtained from model tests in regular waves and using the basic results from performance tests in calm water. The applicability of these four methods is evaluated.

These methods are:

- Direct Power Method (DPM)
- Torque and Revolution Method (QNM)
- Thrust and Revolution Method (TNM)
- Resistance and Thrust Identify Method (RTIM)

All these methods have been described in previous ITTC proceedings. In order to evaluate these methods, comparison of the calculation results has been conducted for model test data from three ships as summarised in Table 1.

Ship Identification		SR125	SR244	
Ship Type		Containership	VLCC	
Test year		1970	2002	
Test place		Osaka Univ.	Akashi Ship Model Basin Co., Ltd.	
Loading Condition		FULL	FULL	BALLAST
Scale		1 : 43.75	1 : 43.716	
Model Scale	Lpp	4.000	7.320	
	B	0.5847	1.3267	
	Tmean	0.2076	0.4415	0.1967
	Cb	0.568	0.803	0.757
	Prop Dia, Dp (m)	0.150	0.215	
	ζa	0.040	0.0286	
Fr		0.25	0.15	

Table 1. Ship particulars for added power comparison

The available model test data for these ships are those from resistance tests, self-propulsion tests and open propeller tests in calm water, and resistance tests and self propulsion tests in regular head waves. For the six irregular wave conditions given in Table 2, the power increase in irregular waves is predicted. The following Pierson-Moskowitz type ISSC 1964 long-crested wave spectrum is used for the prediction:

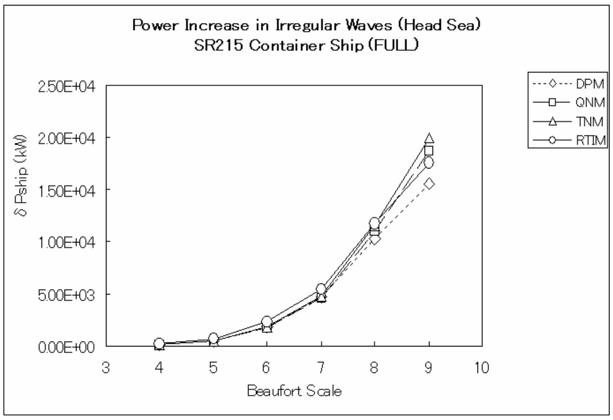
$$S(\omega) = 0.11 \cdot H_{1/3}^2 \cdot \frac{T_0}{2\pi}\left(\frac{\omega \cdot T_0}{2\pi}\right)^{-5} \cdot \exp\left\{-0.44 \cdot \left(\frac{\omega \cdot T_0}{2\pi}\right)^{-4}\right\}$$

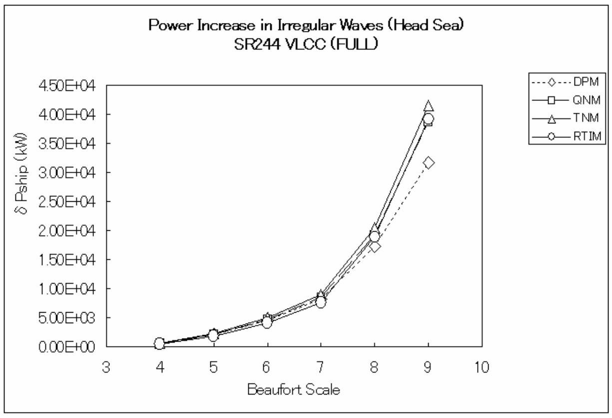
BF	4	5	6	7	8	9
$H_{1/3}$ (m)	1.0	2.0	3.0	4.0	5.5	7.0
T_0 (s)	3.9	5.5	6.7	7.7	9.1	10.1

Table 2. Irregular wave conditions (Beaufort scale)

The comparison results of predicted power increase in irregular waves with respect to the irregular wave conditions are given in Figure 15. Comparisons of each calculation method given in Figure 15 shows that all methods but DPM give similar results for the full load condition for both ships. DPM gives slightly smaller values of added power.

For VLCC in ballast condition, DPM and RTIM methods show smaller values than the others. But, for evaluating methods for ballast condition, more test data are desirable.





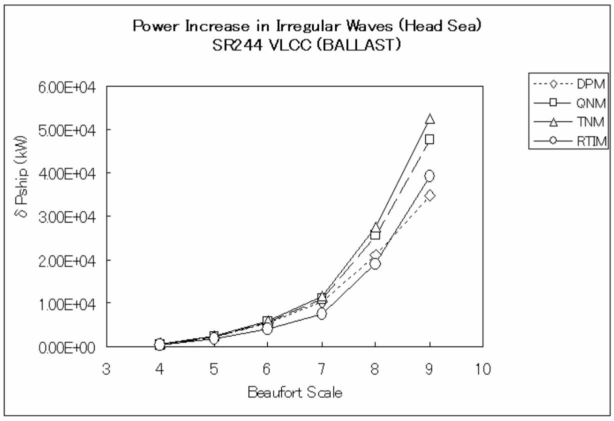


Figure 15: Comparison of power increase in irregular waves between four methods

2.4 CFD Applications in Seakeeping

During last two decades, the development of CFD schemes has been remarkable with the help of the improvements in computational resources. In the field of seakeeping, the use of CFD techniques has increased dramatically over the last several years. The present review focuses on the overall trend of recent studies but the detailed numerical schemes are not described here. It should also be noted that CFD in this review means the numerical methods to solve the field equations and boundary element methods are not considered.

There has been a strong demand and expectation of simulating the violent flows in ship hydrodynamics. Besides the accuracy of physical modelling and computational results, the colourful post-processors and capability of simulating strongly nonlinear free surface flows are very tempting to researchers and engineers. At this stage, there is still doubt about the accuracy of CFD tools, but the application is getting more and more popular.

There are two parts of the numerical scheme for problems with a free surface: the scheme for the field equation solver to compute velocity and pressure, and a scheme for tracing the movement of the free surface. The first part is common in many engineering fields, but the second part is special only for the evolution of the free surface. The accuracy of the computational results depends on the accuracy of both parts. The computational schemes have been getting diverse, but most numerical methods for the evolution of the free surface can be categorised into a few representative techniques. Those are particle tracing, volume of fluid (VOF), and using a surface height function such as SURF and Level-Set. Each scheme has strengths and weakness, depending on the physical problem to be considered. Yet there is no scheme which is clearly more efficient and accurate than any other. Recent studies clearly show such diversity with no significant dominance of any one numerical scheme.

Recent studies in the field of seakeeping are more focused on the application rather than the development of computational schemes. It implies that CFD tools are getting closer to a mature status for practical use. A good example is FLUENT which has successfully expanded its commercial market over the last several years. In fact, during this time, many commercial programs have become commercially accessible.

It is very noticeable that some of the CFD programs are coupled with FEM analysis for structural response, e.g. DYTRAN. Such programs enable the user to observe local fluid-structure interaction to a rough degree.

The most significant trend in recent studies, particularly from the viewpoint of methodology, is probably the application of particle methods. Since its first applications, the SPH method has been extended to include various physical problems, from large deformation solid mechanics to compressible/incompressible fluid dynamics. In this method, the fluid domain is represented by distributing a number of particles, and the particles are accelerated or decelerated by pressure gradients which are obtained by differentiating the, so-called, smoothing function or kernel function. Each moving particle carries this kernel function with it, and the whole computational domain is interpolated by summing up the physical quantity of neighbouring particles with proper weighting factors. SPH has been adopted for simulating wave-breaking around the ship's bow during the early stages of SPH development, but nowadays more applications can be found including strongly nonlinear local flows in seakeeping problems. Furthermore, more diverse particle methods, e.g. the MPS method, have been introduced. The weakness of particle methods is in the computation of hydrodynamic pressure. Due to its assumption of weak compressibility of fluid, hydrodynamic pressure shows very spiky behaviours in time and space. Therefore, so far, particle methods are still of limited practical use.

Recently many trials have been introduced to solve the global motion of ships in ocean waves. Due to the large domain size for such problems, the application is very limited and the results are relatively poorer than potential theory, at this stage. However, eventually CFD computations will be the mainstream of global seakeeping analysis. It should be noted that some meaningful results to obtain the hydrodynamic coefficients, such as rolling damping or viscous coefficients for ship manoeuvring, have been introduced during the last a few years. This kind of application will obviously increase in frequency of use.

There are a significant number of CFD applications for green water problems. Greco et al. (2005) introduced a domain-decomposition method for nonlinear air-water interface during green water occurrence. BEM and Level-Set techniques are combined for the decomposed domains. Wemmenhove et al. (2005) have used a 3D finite volume method, Gomez-Gesteira et al. (2005) have used the SPH method, and Hu and Kashiwagi (2006a) have applied CIP for green water and ship motion problems. A more detailed review is described in a separate section for green water. Figure 16 shows some computational examples of green water.

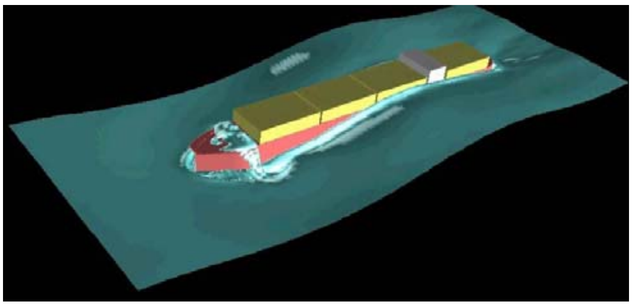


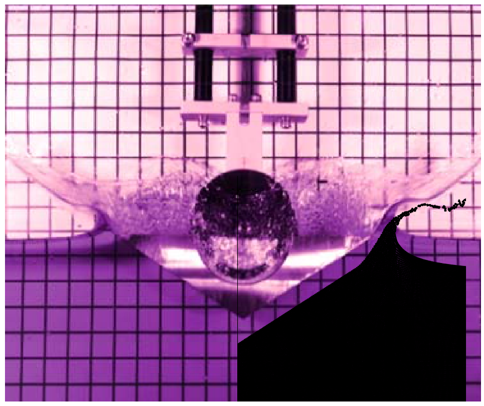
Figure 16: Hu and Kashiwagi (2004)

Many studies have focused on CFD computation to simulate violent sloshing flows. Sueyoshi et al. (2005) have applied the MPS method, a kind of particle method, for a two-dimensional tank. Nam and Kim (2005) introduced the application of SPH, and Kishev et al. (2006) have applied a CIP scheme. Level-Set and SPH methods have been applied by Colicchio (2007) for flip-through phenomena during sloshing flows and compared with experimental results. Kim et al. (2007b) also compared the computational results between VOF and SURF schemes, and experimental data, particularly focusing on sloshing-induced impact. Kim (2007) described experimental and numerical issues in sloshing analysis, and the comparison between the SPH and SURF schemes has been introduced. Shibata and Koshizuka (2007) also introduced the results of a particle method for green water on the ship deck, comparing with experimental results. More details can be found in the section on sloshing.

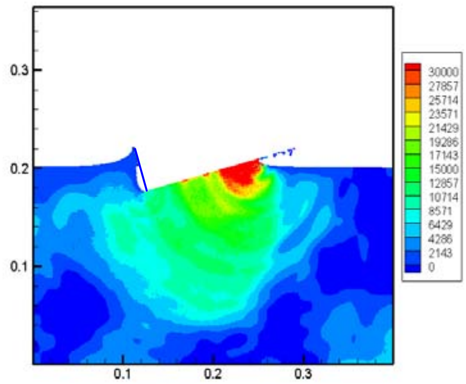
CFD tools are not generally useful for the slamming problem. The water entry problem with impact occurrence is strongly nonlinear, and regarded as a non-memory problem, and the impulsive pressure variation is involved like the sloshing-induced impact. There have been numerical computations performed using finite difference (and volume) methods, but the results show too large a sensitivity to grid resolution and time segment.

Recently this problem was tackled by using SPH. Good examples can be found in the work of Oger et al. (2006, 2007) which solved 2D and 3D water entry impact problems. Kim et al. (2007c) also applied the SPH method for the water entry of wedges, and free surface evolutions have been compared with experimental results. Particularly, SPH has been applied for simulating both the non-cavity and cavity flows during impact. Figure 17 shows examples of their results.

Many computational results for ship motions were introduced during the last few years. Hu and Kashiwagi introduced the results of SPH computation for ship motion from 2004, as nicely shown in Figure 16. Their study has been extended and more results were introduced recently (e.g. 2006b).



(a) Symmetric drop



(b) Asymmetric drop with cavity flows

Figure 17: Examples of SPH computation for water-entry problem with and without cavity flows (Kim et al., 2007a)

Sato et al. (2006, 2007) showed computational results of ship motions using a density function approach for the free surface, particularly focusing on a trimaran hull (2007). Carrica et al. (2006) solved viscous flows involved in large amplitude ship motions using the Level-Set technique. El Moctar et al. (2006) combined a boundary element method and a Navier-Stokes equation solver for ship motion and coupled with FEM for ship structural analysis. Very recently, Hosseini et al. (2007) presented the results of a RANS-based computation and compared them with experimental results for validating extreme motion prediction. This study focused on

ONR's tumblehome hull form. In addition, Yang et al. (2007) showed the computational results of a VOF method for the motion of an FPSO in severe ocean conditions.

2.5 Benchmark Data

Tasked with determining the requirements for benchmark seakeeping tests in oblique waves, with emphasis on data of high-speed vessels, the 25th ITTC Seakeeping Committee continued with the work begun previously by the 24th ITTC Seakeeping Committee. It became apparent that references from previous ITTCs that were listed as benchmark data should be reviewed and that the ability to practically utilise or to accurately reproduce the results was problematic. It was concluded that the definition of benchmark data is the first step in determining what is appropriate for inclusion in the ITTC Procedures. In the request for guidance from the Advisory Council, and from discussions within the Seakeeping Committee, a working definition was adopted and a set of criteria selected.

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

Criteria: The following set of parameters represents a minimum set of information needed to be reported in order to accurately reproduce the experiment.

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

Ship – Ship speed and heading.

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

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

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

Using this definition and criteria, much of the existing benchmark data referenced in the Procedures was found lacking. The availability of non-proprietary, high speed vessel data suitable for benchmark consideration is extremely limited, particularly in oblique waves. This is understandable given the limited extent of basins that can generate oblique waves and the large number of passes a high speed model would be required to perform to meet the minimum number of wave encounters. In addition, high speed hull designs are often proprietary and seakeeping data are restricted.

2.6 Uncertainty analysis

Uncertainty in the precision of data presented at symposia, or in papers, discussions, and reports is often unaddressed. It has long been recognised that sources of error, from instrumentation, measurement technique, experimental methods, facility limitations, etc., can affect the accuracy of data. Yet the inclusion of error bars around data points associated with uncertainty is seldom found in the literature. When assessing the suitability of benchmark tests and data, the inclusion of uncertainty analysis provides confidence that the process and resulting data have been thoroughly examined and is trustworthy. It also provides a better framework in which to repeat any model tests or compare with numerical simulation. It is, however, recognised that practical restrictions, such as the cost or schedule for conducting and reporting model tests can limit the application of uncertainty analysis techniques. The work being performed by the Specialist Committee on Uncertainty Analysis will be important if methods and principles are developed that can be practically implemented for seakeeping experiments.

3. ITTC RECOMMENDED PROCEDURES

3.1 ITTC Procedures 7.5-02-07-02.1, Seakeeping Experiments

Apart from several minor changes mostly related to ensuring that text and formulae meet ITTC standards and some editorial changes, the following modifications have been made:

- Chapter 2.13 now includes discussion and recommendations for cut off frequencies of the idealised spectrum used for generating irregular waves, duration of the test run in irregular waves, and the time between test runs.

- Following the updated definition of benchmark data, references that were referring to numerical calculations were removed from the validation reference list in Chapter 4.

- No changes were made to Appendix A1, Examples of Uncertainty Analysis, due to an expected recommendation by the Uncertainty Analysis Specialist Committee changing the general approach to the uncertainty analysis subject.

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

The recommended procedure for predicting power increase in irregular waves from model experiments in regular waves using DPM (Direct Power Method), QNM (Torque & Revolution Method), and TNM (Thrust & Revolution Method) is provided by the 24th ITTC Seakeeping Committee.

In this report the above three methods together with an additional RTIM (Resistance & Thrust Identify Method) were evaluated by comparing their prediction results against ship model test results. Among these, QNM, TNM and RTIM give almost identical results but DPM was found to give different results.

Thus, this procedure has been updated to remove the DPM as a means for predicting power increase in irregular waves from model experiments in regular waves. Comparisons of the advantages and disadvantages of these procedures are also summarised in this procedure.

3.3 ITTC Procedures 7.5-02-07-02.3, Experiments on Rarely Occurring Events

This procedure has been extensively updated to covers tests on a rigid body model (not a segmented or elastic model) to define extreme motions, extreme motion-related phenomena and local loads but not aimed at quantifying global hull loads. The procedure is related to extreme behaviour in head waves concentrating upon deck wetness, slamming and propeller emergence.

The procedure refers to the seakeeping test procedure **7.5-02-07-02.1,** for providing data relating to model construction, limitations on the relationship between the tank geometry, the model size and wave parameters with regards to the interference effects.

All sections have been expanded to include the current practice, including;

- Measurement techniques for each phenomenon
- Run duration
- Parameters to be measured
- Data presentation

The committee suggests that the procedure for Experiments on Rarely Occurring Events should be extended to include the measurement of global loads .

3.4 ITTC Procedure 7.5-02-07-02.4, Verification and Validation of Linear Seakeeping Computer Codes.

The procedures provided by the 24th ITTC Seakeeping Committee for the validation of the seakeeping codes in the frequency and the time domain were revised, restructured and combined to a common procedure for the validation and verification of *linear* seakeeping computer codes.

A clear distinction has been made between the **verification** and the **validation** of a seakeeping code and the activities associated with each of these tasks.

The scarcity of fully documented benchmark data necessitates the thorough implementation of the proposed procedure.

The procedure is aimed at the validation in the linear regime but should be extended to the nonlinear regime in due course.

This procedure has been developed to replace the previous procedure Validation of Seakeeping Computer Codes in the Frequency Domain 7.5 – 02 07 - 02.4

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The Seakeeping Committee has updated four Procedures as mentioned in Section 3; the two procedures relating to verification and validation of frequency domain seakeeping codes and verification and validation of time domain seakeeping codes have been combined to form one procedure.

The state-of-the-art of research activities in the field of seakeeping have been reviewed by this committee. A review of the research work on sloshing has been added to the tasks by this committee because of the potential impact on the work of future committees.

The specific requirements for future research have been identified as a result of this review. A detailed review of the existing ITTC seakeeping benchmark data has been made; the drawbacks of the existing would-be benchmark data and the future requirements for the benchmark data have been identified.

4.1.1 Experimental techniques

Model experiments are becoming less extensive but more sophisticated. Basic tests are being successfully replaced by numerical models. Often the tests that are required need more preparation effort, innovative, complex and precise instruments but possibly less tank time. A number of tests are specifically designed to produce benchmark data to be used for verification and validation of computer codes with the ultimate aim of replacing tank testing.

There is however a niche that still requires the traditional approach. Knowledge on global and local loads and responses need to be further enhanced using, mainly, traditional methods. The physics and the effects of slamming loads and other nonlinear phenomena are not completely understood and are in need of more research. Designs of modern and unique hull forms also need to be tested using conventional facilities.

Innovative concepts of wave making and absorbing mechanisms and circular tank shapes, combined with unique post-processing techniques are proposed to improve accuracy and efficiency of experimental facilities. Existing facilities are being upgraded and numerically modelled to create tools for more proficient utilisation. New post-processing techniques are being invented and tested to improve interpretation of experimental outputs.

There is a trend to carry out testing using larger models and to conduct experiments in a natural environment. Not fully understood Reynolds scaling effects can be overcome by experimentation using large scale models or full-scale measurements. Most valuable are full-scale measurements that provide information that can be used to correlate and validate ship design and assessment tools. Hopefully the data will become less proprietary and more available since the number of commercial and military craft outfitted with monitoring systems is increasing. Relevant and accurate information on the environment in addition to ship operational and response data is crucial. Progress in this field is observed as well.

Aspects direct related to, like parametric roll combined with stability and capsizing problems, are also being investigated. New technologies have been implemented into the conventional test environment (e.g., bubble image velocimetry) to augment the present capability of testing facilities.

The development of facilities and experimental work nowadays is driven by the need to validate numerical codes; to design and evaluate performance of modern unconventional hull forms, such as high-speed and multihull ships; to investigate highly nonlinear global and local loads related to incidents like slamming, whipping, springing or sloshing; to model 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 urgent as ever. It is important to design experiments so that the completeness of model information and quality of collected data meet the requirements presented in the ITTC definition of benchmark data.

Development and improvements to new measuring technologies/devices (BIV, PIV, distribution of pressure on surfaces) allowing for the measurement of parameters not available from traditional technologies is required and recommended.

More research into direct safety related subjects (e.g., parametric roll) is encouraged. Information on factors that trigger parametric roll (environment, speed, heading and initial conditions) is crucial for full and better understanding of physics of the phenomenon.

The value of sea trials is indisputable and the recognition of the need for full-scale data is escalating. More and more commercial and military craft are permanently instrumented or outfitted with monitoring systems to collect information used to optimise design and performance of theses vessels. Even though overcoming the proprietary and confidentiality issues can be very difficult, publication of the data is essential and desirable.

With the new process of acquisition introduced by the military in many countries, commercial facilities experience opportunities to conduct experiments with hull forms that previously were tested in dedicated tanks only. Submarine hull forms are being tested in commercial facilities. These, very often, unclassified projects provide the opportunity to publish the data and exchange practical knowledge. Procedures for conducting such new experiments may be required very soon.

4.1.2 Loads and Responses in Waves

During the last three years, work has been done mainly in the treatment of the 3D problem using Green sources. Papers have been presented on the interaction of hydrodynamic and structural models, the extension of hydrodynamic models to multihull vessels and the solution of the 2D problem avoiding irregular frequencies. However, only limited experimental verification of the numerical results was reported.

The current stage of linear and weakly nonlinear ship motion analysis is at a sufficiently mature stage to be applied to real ship design issues. Any of the impulse response function approaches combined with strip or 3D panel methods, nonlinear time domain strip methods, and Rankine panel method has a strong capability to predict weakly nonlinear problems in which the incident waves and body nonlinearity play the most important role. In the longer term, it is expected that the Rankine panel method will be the most popular for engineering problems over the next ten years, and Navier-Stokes equation solvers will be extensively tackled for strongly nonlinear ship motions. In particular, WASIM (SWAN) and NLOAD3D (LAMP) have proved the practicality of the Rankine panel method, and the development of similar programs like WISH will no doubt continue.

The time domain analysis of ship motion is being extended to more complicated problems, including multiple body problems, motions in shallow water, coupling with sloshing, slamming, and green water. Furthermore, predicting hydroelastic behaviour of the hull girder in waves is undertaken by coupling with time domain ship motion analysis. Such extensions will make the time domain analysis more widely used for research and practical purpose.

When nonlinear ship motion responses and global structural loads are the primary concerns, the strip based method with the correction for instantaneous wetted surface can be very efficient. However, there are limitations to the 2D approaches, and full 3D approaches are desirable for better accuracy of computational results. In particular, when the dynamic load analysis including pressure mapping on the hull surface for structural analysis is the aim, at present, the Rankine panel method seems a proper choice.

A parametric and/or collaborative study would be a beneficial means of comparing the advantages, disadvantages, and accuracy of various time domain methods. The committee proposes that such a study, in the form of an international symposium or workshop, should include nonlinear structural loads and hydrodynamic pressure as well as motion responses. A comparative study would provide a means to compare and contrast different nonlinear methodologies which is crucial in the verification part of the V&V process. A comparative study that includes experimental data would not only provide benchmark data but would provide the means to validate computational techniques. Furthermore, the outcome from such a workshop would aid the extension of the time domain procedure to include non-linear ship motion.

There available a few sources of motion response data and global structural loads of well known hull forms (e.g. Wigley and S175 hulls) but most of them have been prepared for the validation of frequency domain codes. At this stage, systematic experimental data to validate time domain computations are few.

The accuracy of time domain solutions depend on detailed numerical methods such as the treatment of the transom, spatial and temporal discretisation, Fourier transformation, coefficients involved in the autopilot or soft spring, the definition of instantaneous position, and so on. The detailed description about such parameters and schemes should be included in any report of such work, but the existing studies with such information are very rare. It is strongly recommended that the detailed numerical schemes and computational parameters be included when the computational results are introduced.

CFD computations have had limited application so far, but it is obvious that more trials will be conducted and will gain popularity in the future. To shorten the period before their widespread use, understanding of the physics involved in ship motion is crucial. Especially, increasing the accuracy of the memory effects in the ship motion, i.e. wave propagating due to radiation and diffraction, will be the key to success of CFD simulation.

4.1.3 Sloshing

Several CFD techniques have been used to simulate violent sloshing flows in tanks. They belong to one of the following types: CIP, including optionally the CUP feature, SPH, MPS, hybrid VOF and finite difference schemes to solve Navier-Stokes equations. Attempts have also been made to couple the effects of the linear ship motion in the time domain with nonlinear sloshing. Finally, model tests have been carried out using modern techniques such as PIV. It can be concluded that the pressures and the free surface profiles are predicted with reasonable accuracy.

The proposed numerical schemes should be extended to cope with 3D problems. Their numerical accuracy and stability in time-marching should be further validated via reliable experimental results both for 2D and 3D problems.

If the finite difference scheme is employed for solving the Navier Stokes equations, the numerical diffusion originating from the computation of advection equations is unavoidable, especially in long time simulations. A conservative form of the CIP scheme looks promising by exhibiting less numerical diffusion, but validation of this work and the extension to 3D problems must be carried out. Particle methods (MPS and SPH methods) might be better than finite difference methods in that no numerical diffusion exists and the conservation of mass is perfect. However, the computation time will be enormous especially for 3D problems. Although some ideas have already been proposed, more advanced techniques must be developed for reducing the computation time significantly.

4.1.4 Slamming, Deck Loads and Whipping.

Numerical techniques for investigating rarely occurring events such as slamming, deck loads and whipping are developing rapidly. The general approach to the whole range of these phenomena is one of using a multi-stage approach whereby traditional techniques for predicting the motion of the ship are used to derive occurrences of the rare events; then advanced CFD techniques are utilised to understand the result of a rare event occurring.

For example, in deck wetness (or green sea loads) traditional methods(both linear and non-linear) can be employed to determine the relative wave height at the bow; then once a freeboard exceedance is predicted a CFD technique is then employed to predict the vertical and horizontal loading due to that event. Recent work has shown that for vessels with forward speed, using RANS to represent a dam break model with a forward jet super-imposed is a useful approach to adopt for predicting both horizontal and vertical local loads due to green sea events.

Smooth Particle Hydrodynamics models have been shown to be capable of treating violent free-surface flow and have been applied to predictions of green seas loading and impact loads due to slamming events.

As reported by the previous ITTC Seakeeping Committee, Constrained Interpolation Profile (CIP) based methods appear to provided a very robust approach for strongly nonlinear wave-body interactions. There does not appear to be much literature in the present review detailing the progress of these techniques.

4.1.5 High Speed Vessels and Multihull Ships

Several model and full-scale tests with high speed vessels have been reported in this period. Monohull tests in large amplitude waves have been conducted to enable assessment of the capabilities of nonlinear seakeeping codes. Systematic tests of planing catamaran hulls are also reported.

Both 3D Green function and Rankine source methods, as well as 2.5D theory, have been applied to high-speed and multihull problems. Many of these have been compared with model test results (mostly in head seas). A 3D finite element approach for planing craft has been presented and compared with similar work.

There are still little data relating to the behaviour of multihull vessels in oblique waves. Therefore, it is recommended that efforts should be devoted to obtaining suitable benchmark data for use within the ITTC.

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.

4.1.6 Added Resistance & Powering in Waves

Several methods of determining added resistance & powering in irregular waves from response functions obtained from model tests in regular waves (in addition to using basic results from performance tests in still water) have been proposed and are in broad use at various laboratories to predict power increase in irregular waves. Four kinds of methods were investigated by this committee. Comparison of results obtained for various ships by these four methods shows that all methods except the DPM (Direct Power Method) give almost the same results in the case of full load condition. Because of this result, DPM has been removed from the present procedure. From the practical viewpoint, QNM (Torque & Revolution Method), TNM (Thrust & Revolution Method) and RTIM (Resistance & Thrust Identify Method) show very compatible results. These three methods are recommended in the procedure for use in predicting power increase in irregular waves from model experiments in regular waves.

This recommendation is a somewhat practical, decision reached on the basis of comparisons of the estimated results with each other. The comparison of these estimations with self-propulsion test results in irregular waves would be desirable, even though the tests in irregular waves are, in general, less precise than those obtained in regular waves. The agreement of the three methods is good for the fully loaded condition, but not good enough for the ballast condition. The amount of data at a ballast condition is limited.

Further evaluation of these prediction methods based on the accumulation of comparisons for various model tests including the self-propulsion tests in irregular waves and tests in ballast conditions is recommended. In TNM and RTIM, open propeller characteristics and self-propulsion factors in calm water are used for predicting the power increase in waves. It seems the hypothesis is that these factors in calm water are almost the same as those in moderate wave conditions. The applicability of this hypothesis should be confirmed.

The final aim of any calculation is the accurate prediction of the power increase of a ship in an actual seaway. From the viewpoint of considering the various added resistance components, such as those due to waves, wind, manoeuvring, hull aging or fouling, RTIM is the most practicable method because it takes all the components of added resistance into account. An equilibrium equation for powering with the various components of added resistance due to the various environmental conditions should be established. Prediction results should be evaluated by comparing with model test results in such environmental conditions, and with the full-scale measurement results. For obtaining full-scale ship performance data, standardisation of the measuring procedure, measuring system and analysis procedure should be discussed and established.

4.1.7 Computational Fluid Dynamics

During the last few years, very significant effort in CFD computation for seakeeping analyses has been made. CFD applications are making it possible to analyse strongly nonlinear free surface flows such as violent sloshing flows, green water simulation, and water entry with high speed. At present, CFD applications seem to be at the early stage of practical use, but eventually will be widely used for many free surface problems.

There has been a significant number of ship motion analyses using CFD methods. Most of the work is based on finite difference/volume methods solving the Navier-Stokes equation, and the CIP method has also been applied. Most work is also aimed at large amplitude ship motions in severe wave conditions. Such applications could show the capability of simulating strongly nonlinear waves and ship motions, but more systematic and thorough validation like Hosseini et al. (2007) seem essential for practical application. Verification through comparison with the solution of potential theory is strongly recommended in various wave conditions, and the comparison should include ship motion in small and large incident waves, wave profiles, pressure and structural loads. Time-consuming computation is hard to avoid at present, and the effort to reduce the computational time should be continued.

Particle methods are becoming popular in the analyses of violent free surface flows. Recently, many studies have adopted the SPH method for green water, sloshing, and slamming problems. The particle methods are relatively easier to develop into computer programs than field equation solvers, but many technical issues are currently unsolved. Particularly, it is hard to avoid the spiky time signal of hydrodynamic pressure in the particle method. This weakness should be overcome by developing a new scheme. On the other hand, some research showed that hydrodynamic force integrated surface pressure is not as spiky as pressure.

4.1.8 Benchmark Data

It is suggested that the definition of benchmark data and review criteria proposed by the Seakeeping Committee be adopted. Further, that the effort continues to review existing and new test results for applicability and appropriateness. In addition, a long range goal is recommended to establish an accessible database (perhaps via a website) where members can obtain necessary information with respect to model test particulars, and can retrieve and use digital data from these experiments.

4.1.9 Uncertainty Analysis

The Seakeeping Committee conclude that the work of the Specialist Committee on Uncertainty Analysis be continued until practical and useful techniques are provided for assessing and reporting experimental uncertainty.

4.1.10 Cooperation with ISSC

At the request of the ITTC Executive Committee and the ISSC Standing Committee, the ITTC Seakeeping and ISSC I.2 Loads committees organised a joint meeting to discuss feasibility, concepts and time frame of collaboration between the two groups. This meeting took place on May 9, 2007 at the

National University of Athens and was attended by 15 members of both committees.

Regular communication between committees' members was recognised as the most basic and important form of contact and information exchange. Names of all members with contact particulars were exchanged between attendees. This exchange should be considered in future committee.

The two Committees discussed the overlap in committees' mandates and available expertise and concluded that participation of ITTC Ocean Engineering and ISSC Environment (I.1) committees would also be advantageous for the future collaboration. The cooperation between ISSC Loads and ITTC Ocean Engineering Committees is of vital importance, due to the shared offshore structures interests.

Benchmarking and comparative studies were identified as an example of the fundamental form of potential joint activities. The ISSC Loads Committee will invite members of the ITTC Seakeeping Committee to participate in a planned comparative study to calculate lateral bending and torsion moments using various numerical tools available to both committee members.

Both the ITTC Seakeeping and ISSC I.2 Loads Committees acknowledged that the collaboration continuity needs to be ensured in the future. Past experience shows that opportunities for collaboration between both organizations were lost due to lack of continuity in contacts and communication. The meeting proposed the following to maintain the continuity of the collaboration:

- Common membership, with at least one member serving on both committees

- Scheduled joint meetings.

4.2 Recommendations

Adopt the revised procedure No. 7.5-02-07-02.1 Loads and Responses, Seakeeping, Seakeeping Experiments

Adopt the revised procedure No. 7.5-02-07-02.2 Loads and Responses, Seakeeping, Predicting the Power Increase in Irregular Waves from Model Tests in Regular Waves

Adopt the revised procedure No. 7.5-02-07-02.3 Loads and Responses, Seakeeping, Experiments on Rarely Occurring Events

Adopt the new combined procedure No. 7.5-02-07-02.4 Loads and Responses, Seakeeping, Verification and Validation of Linear Seakeeping Computer Codes

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5.2 Nomenclature

FAST	International Conference of Fast Sea Transportation
HSMV	Symposium on High Speed Marine Vehicles
ISOPE	International Offshore and Polar Engineering Conference
IWWWFB	International Workshop on Water Waves and Floating Bodies
NAV	International Conference on Ship and Shipping Research
OMAE	International Conference on Offshore Mechanics and Artic Engineering
PRADS	International Symposium on Practical Design on Ships and Other Floating Structures