The Seakeeping Committee

Final Report and Recommendations to the 24th ITTC

1. INTRODUCTION

1.1 Membership and Meetings

The Committee appointed by the 23rd ITTC consisted of the following Members:

- Prof. Hiroshi Kagemoto (Chairman). University of Tokyo, Japan.
- Mr. Terrence Applebee (Secretary). Naval Surface Warfare Center, U.S.A.
- Mr. Adolfo Marón. Canal de Experiencias Hidrodinámicas de El Pardo, Spain.
- Mr. Paul Crossland. QinetiQ, United Kingdom.
- Prof. Jian-Min Yang. Shanghai Jiao Tong University, China.
- Dr. Jianbo Hua. SSPA Sweden AB, Sweden.
- Prof. Masashi Kashiwagi. Kyushu University, Japan.
- Mr. Jean-François Le Guen. Bassin d’Essais des Carènes, France.
- Professor J.A. Keuning. Technical University Delft, The Netherlands*.

The Committee acknowledges the contribution of the Stability in Waves Committee to the discussion relating to Parametric Rolling.

Four Committee meetings were held, respectively at:

- QinetiQ, United Kingdom, January 2003.
- Canal de Experiencias Hidrodinámicas de El Pardo, Spain, September 2003.
- Shanghai Jiao Tong University, China, May 2004.
- Naval Surface Warfare Center, USA, January 2005.

1.2 Recommendations of the 23rd ITTC

The following is the specific guidance, provided by the 23rd ITTC Loads and Responses Committee, on the work to be performed by 24th ITTC Seakeeping Committee:

Recommendations. Review the state-of-the-art, comment on the potential impact of new developments on the ITTC and identify the need for research and development for predicting the behaviour of ships with forward speed in waves, including high-speed and unconventional vessels such as planing boats and catamarans. Monitor and follow the development of new experimental techniques and extrapolation methods.

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* Due to circumstances beyond his control, Professor Keuning was unable to participate on the 24th ITTC Seakeeping Committee.

Review the ITTC recommended procedures, benchmark data, and test cases for validation and uncertainty analysis, and update as required. Identify the requirements for new procedures, benchmark data, validation and uncertainty analysis and stimulate the research necessary for their preparation.

Tasks.

1. Review the first attempt of the Loads and Responses Committee of the 23rd ITTC to develop procedures for the validation of seakeeping computer codes in the frequency domain.
2. Develop a procedure for the validation of seakeeping codes in the time domain.
3. Review methods to determine impulsive pressure loads taking the characteristics of the structure into account. Develop experimental and numerical procedures for the prediction of bow and stern slamming, deck loads and loads on bow visors.
4. Develop a procedure for model experiments to determine whipping loads.
5. Develop a procedure for predicting the risk and magnitude of parametric rolling.
6. Review available seakeeping operability criteria.
7. Continue work to develop standard procedures for predicting added resistance and added power in waves.

From these guidelines, the 24th ITTC Seakeeping Committee developed the following task structure:

Task 1: Review the state-of-the-art, comment on the potential impact of new developments on the ITTC, and identify the need for research & development for predicting the behaviour of ships with forward speed in waves, including high-speed and unconventional vessels such as planing boats and catamarans. (see Chapter 2)

Task 2: Monitor and follow the development of new experimental techniques and extrapolation methods. (see Section 2.1)

Task 3: Review the ITTC recommended procedures, benchmark data, and test cases for validation and uncertainty analysis, and update as required. In particular, ITTC Procedures 7.5-02-07-02.1, Seakeeping Experiments (see Section 2.3)

Task 4: Review the ITTC recommended procedures, benchmark data, and test cases for validation and uncertainty analysis, and update as required. In particular, ITTC Procedures 7.5-02-07-02.2, Predicting the Power Increase in Irregular Waves from Model Experiments in Regular Waves (see Section 2.2)

Task 5: Review the ITTC recommended procedures, benchmark data, and test cases for validation and uncertainty analysis, and update as required. In particular, ITTC Procedures 7.5-02-07-02.4, Validation of Seakeeping Computer Codes in the Frequency Domain (see Section 2.2)

Task 6: Develop a procedure for the validation of seakeeping computer codes in the time domain (See Section 2.2)

Task 7: Develop experimental and numerical procedures for the prediction of bow and stern slamming, deck loads and loads on bow visors. Develop a procedure for model experiments to determine whipping loads. To be reported as part of the ITTC Procedures 7.5-02-07-02.3, Experiments on Rarely Occurring Events (see Section 2.2)

Task 8: Review methods to determine impulsive pressure loads taking the characteristics of the structure into account (see Section 2.2)

Task 9: Review available seakeeping operability criteria (see Section 2.4).

Task 10: Develop numeric and experimental procedures for predicting the risk and magnitude of parametric rolling. [To be reported as part of the Stability in Waves Committee report.]

Task 11: Discuss the philosophy and value of uncertainty analysis, leading to a proposal for procedural development (not reported).

The results of the two recommendations to the Seakeeping Committee can be found in Chapter 2, and the results of the recommended tasks can be found in Chapter 3. The following provides an outline of the rest of this report:

- Chapter 2, Review of state-of-the-art.
- Chapter 3, ITTC Recommended Procedures.
- Chapter 4, Conclusions and recommendations.
- Chapter 5, References.

2. REVIEW OF STATE-OF-THE-ART

2.1 Developments in Experimental Techniques

New Experimental Facilities. Detailed survey of new experimental facilities, including those that can be used for seakeeping experiments, is summarized in the report of the Resistance Committee (Section 2).

New Experimental Techniques and Extrapolation Methods. Validation by model tests is necessary for time domain seakeeping computer codes, in order to achieve reliable analysis of strongly non-linear dynamic problems of ships in waves such as slamming impact, the slamming-induced acceleration, large roll motion in quartering and following waves, course-keeping and broaching-to problem in quartering waves etc. For this purpose, Garme and Hua (1999) have developed a model test arrangement together with an extrapolation method. The originality of this method is that the wave motion around the running model is extrapolated from the measured wave and expressed in terms of the equation of wave elevation. The initial condition for the time domain simulation is then obtained from the measured model motions, and the determined equation of the wave elevation is used as the excitation source. Thus, the simulated motion time series can be directly compared with the measured ones. The validated result shows that the wave elevation determination procedure works satisfactory not only for regular wave but also for long-crested irregular wave and crossing wave. Two validation cases for the motions of a RoRo-ship free-running in a regular and an irregular heading, respectively, are presented for a time-domain computer code.

This validation procedure is also applied to the calculated wave-induced surge, sway and yaw forces of a patrol boat in following and quartering regular waves and two component irregular waves, see Hua (2002). A semi-captive test arrangement was developed for this purpose. The same model test technique has also been applied for determination of the complex (amplitude and phase) motion response operators of a ship in irregular waves composed of regular waves of five wave frequencies so that only one test run can provide the five corresponding complex response operators.

A model test technique of deterministic wave for safety analysis is developed; see Clauss and Janou (2004). Special waves such as wave packets, extreme wave, storm seas, random seas with embedded high wave sequence, regular waves with embedded high wave group, etc. can be generated in the model tank. Different capsizing scenarios can then be tested in these tailored wave trains.

To investigate the impact pressure distribution on a planing craft in waves, a model was instrumented with pressure transducers and towed in calm water, head and oblique regular and irregular waves, see Rosén and Garme (2004). The matrix of transducers was concentrated in the forebody to capture the impact loads and an aft matrix to follow the pressure in the transom area. In waves, the propagation of the pressure enabled a reconstruction of the impact pressure distribution time history from the transducer signals. The impact loads determined as the integrated reconstructed pressure were compared with the inertia forces determined from the accelerometer signals.

Instantaneous wave profiles associated with green water loading events were investigated by Drake (2001) for a stationary vessel heading into long-crested random waves. Comparisons are made with the profile predicted by a transient wave packet that has been specially formulated to produce the most probable time history of extreme linear relative motion at the bow.

An investigation of the heel-induced effect on the hydrodynamic forces on the directional stability of a ship in following waves was conducted by means of captive model measurement with various heel angles up to the 50 degrees, see Hashimoto et al. (2004). The details of nonlinear heel-induced hydrodynamic forces with respect to the heel angle in waves are presented.

Erwandi and Suzuki (2001) used a CCD camera to measure the diffraction waves generated by a ship operating in regular waves. The results are evaluated by making some transverse cuts on the image data in the y-direction (transverse cut). The obtained Kochin functions are compared with the longitudinal cut results based on Ohkusu method (1980), and also with theoretical results based on slender body theory.

2.2 Developments in Theory and Validation

Loads and Responses in Waves. Owing to the presence of forward speed of a ship and inherent hydrodynamic and geometrical nonlinearities, seakeeping computations are still far from a state of mature engineering science. Strip methods, which are based on 2-D linear potential-flow computations in the frequency domain, have been used for engineering purposes, because they are very efficient, robust, and relatively accurate in low to moderate sea states. However, in recent years, attention tends to be focused on 3-D effects and nonlinearities in rough seas. Thus, as a natural trend, seakeeping computations seem to transfer 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.

This section summarizes developments in computational and experimental studies for wave loads and motions of a ship, mainly in the past three years since the last 23rd ITTC Conference. A review of the seakeeping computations up to the year 2000 is provided in the last ITTC report (2002) and by Beck and Reed (2001).

In what follows, the computational tool developments for seakeeping analysis are described according to the kinds of calculation methods with the potential-flow assumption. The developments in viscous-flow computations are covered later in this section.

Described first is the 3-D Green function methods in the frequency and time domains. These are basically for the linear problems, and thus the free-surface boundary condition and the radiation condition at infinity are satisfied automatically. Therefore, only the body surface needs to be discretized with panels; which is advantageous from computational and practical viewpoints. For the zero speed case, the frequency-domain approach is very successful and requires less computation time than the time-domain approach, since the latter needs to be time-marched to evaluate convolution integrals related to the memory effects. For the forward speed case, however, the frequency-domain Green function is very complicated and needs much care and computation time, whereas the inclusion of the forward speed term in the time-domain Green function needs minor changes and thus the numerical burden is almost the same as that for the zero speed case. Other advantages of the time-domain approach are the ability to deal with large amplitude body motions (the so-called body-nonlinear formulation), non-constant forward speed, nonlinear restoring forces, and so on.

Some developments in the time-domain nonlinear strip method are also described. In this method, the ship hull is assumed to be slender, and thus the 3-D fluid flow near the hull is simplified as a flow in the 2-D planes of transverse sections. With this strip-theory approximation, numerical computations become much efficient and robust at the sacrifice of genuine 3-D and forward-speed effects. Because this is a time-domain approach, some nonlinearities in large-amplitude ship motions may be taken into account, including bow-flare slamming and green-water impact on the deck.

To surmount limitations in the time-domain Green function method dealing with only the linearized free-surface condition, Rankine panel (or source) methods have been developed since the beginning of 1990s. There are several variations in this method depending on the way of satisfying the radiation condition at infinity and the time-marching schemes for the free-surface condition and the equations of ship motions. The Rankine panel method is versatile in that it can deal with different kinds of free-surface conditions that may include nonlinear terms. However, this method is generally time-consuming and hence unlikely to be routinely used at least in the near future by industry.

Frequency-Domain Green-Function Method: For the zero forward speed case, the 3-D panel method using the free-surface Green function has been established as a reliable and efficient numerical tool for routine use. However, for the nonzero forward speed case, the corresponding free-surface Green function in the frequency domain involves a number of numerical difficulties which hinder the Green function from being practicable in panel methods. In fact, numerous studies have been done on the free-surface Green function at forward speed and some numerical calculation methods have been developed in the past two decades.

Noblesse and Yang (2003, 2004) derived a new Green function which is considerably simpler than some expressions for the free-surface Green function that have been used in the literature and thus relatively easy to compute. This new Green function satisfies the radiation condition and the linearized free-surface boundary condition in the far field but only approximately in the near field. This feature may not be of fatal defect and, on the contrary, can be advantageous in taking account of near-field effects in the free-surface boundary condition due to the steady disturbance of a ship.

Guilbaud et al. (2001, 2003) and Maury et al. (2003) studied panel methods using two different expressions of the free-surface Green function; a conventional expression with the complex-valued exponential integral function and the single-integral expression of Bessho (1977). It is shown that inclusion of the so-called line-integral term and the removal of irregular frequencies are crucial for a solution without numerical oscillations with respect to the frequency. Computed results were compared to test results for Series-60 models of $C_B = 0.6$ and 0.8.

Chen et al. (2001) also developed a panel method using a new expression of the “super” Green function derived by Chen and Noblesse (1998) and a higher-order description of the ship hull by bi-quadratic patches. Numerical solutions are obtained by applying a Galerkin scheme, and verification and validation are performed by comparison with the semi-analytical solutions for a sphere obtained by Wu (1995) and experimental results for a Wigley hull measured by Journée (1992).

Through a number of studies done up to date, we are confident that the frequency-domain Green function can be computed very accurately over the whole calculation domain. However, some numerical problems seem to still exist in solving the integral equations for the source strength or the velocity potential itself on the wetted surface of a ship. In particular, there must be a precise numerical cancellation between the singularities from the line-integral term along the water line and from the surface-integral term in close proximity to the free surface, but probably this numerical cancellation is not achieved to the level of satisfactory accuracy.

Because of these numerical difficulties and necessity of a complex numerical evaluation of the free-surface Green function with forward speed, the recent trend to make use of a Rankine panel method or time-domain Green function method as will be described in the next section.

Time-Domain Green-Function Method: The hydrodynamic problems can be solved by either the frequency-domain or the time-domain approach. For the linear problem, the frequency-domain and time-domain results are related by the Fourier transform. For the zero speed case, the frequency-domain approach requires less computational time than the time-domain one, since the latter needs to evaluate convolution integrals. However in the case of forward speed, the time-domain approach may be advantageous, since the time-domain free-surface Green function can be evaluated with minor changes from the zero-speed case.

For this reason, Kara and Vassalos (2003) studied the steady and unsteady hydrodynamic problems in the time domain using the time-domain free-surface Green function. The boundary integral equation is derived on the basis of the source distribution formulation, and a numerical solution is obtained by a constant-panel collocation method. Computed results show fairy good agreement with experimental and other published numerical results for a Wigley hull. Kataoka et al. (2001) also developed a linear time-domain calculation method using the time-domain free-surface Green function, and applied the method to one of the four modified Wigley models for which experiments were conducted by Journée (1992) and a Series-60 (C_B=0.6) model.

The time-domain approach is advantageous to study nonlinear problems even in the framework of the free-surface Green function method. There may be several levels of approximations in treating nonlinear problems. The simplest one using the time domain Green function is that the Froude-Krylov and restoring forces are computed exactly but the radiation and diffraction forces are retained as linear. This approximation does not increase the computation time as compared to the linear formulation and accounts for dominant nonlinearities in ship motions in large-amplitude waves. Along with this approach, Sen (2002) performed computations of large-amplitude 3-D ship motions with forward speed. Attention was mainly focused on the difference between linear and nonlinear results, and computations were performed for a Wigley hull and a Series-60 model over a variety of wave and speed parameters. It is shown that a considerable influence of nonlinearities exists in predicting the instantaneous location of the hull in waves, which is crucial in determining the keel emergence and deck wetness.

The so-called "body-exact" (body-nonlinear) formulation for the radiation and diffraction problems is the next higher level of approximation for nonlinearities. In this formulation, the transient free-surface Green function is used and thus the free-surface boundary condition is linear, but the body boundary condition is satisfied on the instantaneous wetted surface under the undisturbed free surface. Therefore, the computation time in the body-nonlinear formulation enormously increases as compared with the linear problem. Commercial codes based on this formulation are available at present, an example of which is LAMP (Large Amplitude Motion Program) version-4 developed initially by Lin and Yue (1991). Independent of this commercial code, Kataoka et al. (2002, 2003) published a series of papers on the 3-D body-nonlinear problem in the time domain. Although the formulation is the same, Kataoka et al. improved the numerical scheme to reduce the computation time, particularly in the development of a fast calculation scheme for the transient free-surface Green function. Then, they used the method to study geometrical nonlinear effects of the ship hull (such as bow and stern flares) on the hydrodynamic pressure and wave-induced ship motions. Through comparisons with experiments and other calculation methods for Wigley models with and without flares above the still water level, they found that the amplitude of heave motion near the resonance and the peak value in the added resistance are markedly reduced by the flare effects and that the change in pressure due to nonlinear effects originates largely from the hydrostatic restoring-force term.

Time-Domain Nonlinear Strip Methods: More practical nonlinear calculation methods in the time domain which can be applied to actual ships may be based on strip theories. Several nonlinear strip theories in the time domain have been developed, earlier work of which was done by Yamamoto et al. (1978) and Jensen and Pedersen (1979), then followed by some others. In 1997 and 2000, the ISSC Technical Committees carried out comparative studies and recommended that improved methods should be developed and further comparative research should be done. A common part in various methods based on the nonlinear strip method is that the Froude-Krylov and hydrostatic forces are computed over the instantaneous wetted surface of a ship under the profile of incident wave, and some differences exist in the treatment of components of hydrodynamic forces.

The method adopted in Fonseca and Soares (2002) is essentially the same as that in a previous work by Fonseca and Soares (1998) and evaluates the radiation forces in the linear framework, which are represented by the convolution of memory functions. The scattering part of the incident wave in the diffraction problem is kept as linear, but nonlinear forces due to green water on deck are evaluated using the momentum theory and incorporated in the motion equations. Computed results were compared with existing experimental data for the S-175 container ship, particularly the data by O'Dea et al. (1992) for the influence of wave steepness on the vertical motions and accelerations and the data by Watanabe et al. (1989) for the influence of bow flare on the shipping water and on the asymmetry in the wave-induced vertical bending moment. Although not perfect, the method was successful in reproducing the main nonlinear effects, such as a general experimental fact that the sagging moment is larger than the hogging moment.

Qiu and Hsiung (2001) and Takagi and Yoshida (2003) developed, respectively, practical nonlinear calculation methods, which are similar to that by Fonseca and Soares (1998). In the method by Qiu and Hsiung a direct solution scheme was applied to obtain the impulse response function, and in the method by Takagi and Yoshida, the memory-effect functions in the radiation problem were calculated by means of the frequency-domain EUT (Enhanced Unified Theory) developed by Kashiwagi (1995), calculating the surge mode and the bow wave diffraction with 3-D and forward-speed effects incorporated in a rational way by modifying the unified theory proposed by Newman (1978).

The time-domain nonlinear strip method adopted by Wang et al. (2001) involves prediction of the sectional green-water force (which is the vertical force per unit length due to green water on deck in a longitudinal position x and at a time t) using the momentum theory. Computed results were compared with experimental data by O'Dea et al. (1992) for both heave and pitch motions and bow accelerations of the S-175 container ship. Comparisons were also made for vertical bending moments of a Panamax container ship and a VLCC. The agreement between computational and experimental results looks good, and nonlinear effects are significant for the container ships considered, whereas not significant for a VLCC.

Almost all of the studies cited above are nonlinear modifications of some kind to the conventional strip theory in the time domain. As one of the new efforts in this direction, Gu et al. (2003) presented a nonlinear hydro-elastic simulation method for the prediction of wave-induced loads on ships with large amplitude motions. By means of a Timoshenko beam theory, flexible modes of the ship hull girder are accounted for. In addition, the effects of bow flare slamming, bottom impact, and green water on vertical bending moments were taken into account. The coupling effect between higher-order harmonic frequencies and the whipping components of vertical bending moments were verified by numerical calculations. Good performance and high efficiency were confirmed in comparison with experimental and other theoretical results for the S-175 container ship with two kinds of bow flare forms.

The work by Wu and Hermundstad (2002) also took account of structural hydro-elastic effects but the computation time could be significantly reduced by partitioning the flexible modes into dynamic and quasi-static ones. Validation of the method was carried out using experimental data of the S-175 container ship provided by O'Dea et al. (1992) and Watanabe et al. (1989). Because of very good efficiency, the method was extended to the calculation of the long-term probability of exceedance in nonlinear responses. With these calculation methods, it may be feasible to evaluate extreme wave loads and other nonlinear responses in ship design and to develop a rule formula of design wave loads in the near future.

Other Methods in the Time Domain: The time-domain analysis is a natural avenue to deal with extreme wave problems. The fully-nonlinear approach may be ranked as the highest level, but this approach for 3-D ship motions is still in an elementary state of development. Shirakura et al. (2002) made efforts to establish a 3-D fully-nonlinear numerical wave tank, but when the forward speed is present, numerical solutions based on the Mixed Eulerian-Lagrangian (MEL) method tend to be unstable in the time marching. Unfortunately the computational requirements in this MEL method are still too heavy and its capability to deal with arbitrary geometries is too limited to be routinely used in ship design. Linear and weakly-nonlinear approaches by means of Rankine panel methods are more efficient.

Colagrossi et al. (2001, 2002) solved the linear problem by a Rankine panel method using the time-domain boundary integral equations. To recover the efficiency of strip method, a transient-test technique developed for experiments to study the response to wave packets was applied to numerical computations and the Response Amplitude Operator (RAO) of a ship could be determined by overnight computations on a PC with Pentium III 600 MHz.

Yasukawa (2001, 2002) developed a 3-D Rankine source method in the time domain, which is a sort of the "body-exact" formulation but the free-surface condition includes the 2nd order terms with respect to unsteady quantities identified by the Taylor expansion around $z=0$. To accelerate the computation of free-surface influence terms, two different types of the free-surface meshes were employed; ship-fitted mesh for the near field and space-fixed regular mesh for the far field. Computed results of hydro-dynamic forces on and wave-induced motions of a modified Wigley hull and the S-175 container ship were compared with experiments and strip-theory results. The agreement was fairly good, but the amplitude of incident wave and resulting ship motions was relatively small and thus applicability to large-amplitude problems should be validated.

Hermans (2004) also introduced a time-domain Rankine panel method developed at the University of Delft, which can be a nonlinear solver but is limited to several kinds of linearized formulations at present. The method was implemented to predict the added resistance in waves of a blunt ship.

Lin and Kuang (2002, 2004) tried to solve fully nonlinear seakeeping problems by a pseudo-spectral method, combining a local flow analysis near the ship boundary with the global flow analysis by a spectral method. Main interest seems to be placed on wave-wave nonlinear interactions, and validation of the method needs to be done in a more systematic way.

A hybrid calculation scheme, using a Rankine source method for the near field and the time-domain free-surface Green function method to satisfy the radiation condition at a far field, was studied by Kataoka et al. (2004). This hybrid scheme is essentially the same as a commercial code LAMP version-4, but the analysis in the far field is carried out in a space-fixed coordinate system, which makes the scheme more stable at the expense of numerical efficiency. Validation of the scheme is care-fully performed through comparisons with other calculation methods and experiments and through sensitivity studies of several parameters involved in the method.

Liut et al. (2002) reported an extension of LAMP version-4, with investigation of water-on-deck effects on ship motions and structural loads. 3-D green-water events on ship platforms were simulated by solving the equations of conservation of mass and momentum with a finite-volume method and shallow-water assumptions. This calculation method was validated with available experimental data and successfully incorporated into the latest LAMP system as an additional module.

Other Methods in the Frequency Domain: Although the free-surface Green-function method at forward speed has been studied since 1980s, complexity in evaluating the Green function and in obtaining a precise solution from the boundary integral equation has hindered to establish the Green-function method as a reliable tool for seakeeping computations. As an alternative, the Rankine panel method has been studied and various schemes for this method have been proposed.

Bertram and Yasukawa (2001) applied a fully nonlinear, 3-D Rankine panel method to the prediction of local pressures, motions, and added resistance of a VLCC and the S-175 container ship. The steady flow contribution is captured completely by solving the fully nonlinear problem first and then linearizing the unsteady problem around the steady-flow solution. They proposed using rectangular grids with cut-outs for the hull of blunt ships with block coefficient above 0.7 rather than to use conventional quasi-streamlined grids. Owing to the way of satisfying the radiation condition, frequency-domain Rankine panel methods are currently limited in practice to approximately $\tau = U\omega / g > 0.4$. To surmount this practical limitation, a hybrid method matching an inner Rankine panel method to an outer Green function method may be a promising approach. Concerning the way of satisfying the far-field radiation condition, Du et al. (2003) proposed a new matching method using two arrays of fundamental singularities placed inside the ship hull.

Nechita et al. (2001) developed a 3-D Rankine panel method, which is very similar to that by Bertram and Yasukawa (2001), taking account of the effects of fully nonlinear steady-wave field on the free-surface and body boundary conditions. Validation of the method was performed for a Series-60 ($C_B = 0.8$), particularly a comparison of the wave field between computed and measured results. To check applicability of the Rankine panel method to practical ships, Matsunami et al. (2001) also applied the method developed at the University of Tokyo to the prediction of wave-induced loads on a VLCC and a large container ship. Through comparisons with experimental results obtained by themselves, 3-D effects were investigated on ship motions, bending moments, and unsteady pressures. They concluded that the Rankine panel method may be used in the structural design of practical ships.

Experimental Studies on Loads and Responses: Some of the papers reviewed above include experimental data that were obtained newly by the authors to validate the calculation method developed.

For the purpose of providing experimental data for validation of RANS CFD codes (see Section 2.2.6), Gui et al. (2001) conducted an experimental study using a model-scale naval surface combatant, DTMB Model 5512. The added resistance, heave force, pitch moment, and free-surface elevations were measured for a fairly wide range of test conditions.

Nonlinear effects on the wave loads in rough seas were studied experimentally by Mizokami et al. (2001) for a container ship, and the results were compared with time-domain linear and nonlinear strip methods developed in the past. They observed significant nonlinear effects on the vertical bending moment and the wave-induced pressure especially near the water surface.

Miyake et al. (2001) also studied experimentally nonlinear effects on the ship motions and wave loads using a VLCC model and a container ship model. The six-degree-of-freedom motions, vertical and horizontal bending moments, and hydrodynamic pressures were measured for a wide range of incident angles, frequencies, and wave heights of the incident wave. Although various nonlinear effects are observed, they note that nonlinearities in the wave loads on the VLCC model are relatively small especially in quartering seas as compared to those on the container ship model.

In addition to the above, there are useful experimental data for well-documented ship models (Series-60 and S-175) which can be used for validation of computer codes and a comparative study. For details, the reader is referred to Section 2.3 on benchmark data and uncertainty analysis.

Added Resistance and Added Power in Waves. It has been indicated so far that the added resistance in waves predicted by the conventional numerical methods based on a linear potential theory is sometimes significantly smaller than the corresponding experimental results in short waves.

Recently some nonlinear numerical calculations of the added resistance in waves have appeared. Hermans (2004) reviewed the work of Bunnik (1999) and Raven (1996), which used the Rankine panel method to show that the added resistance in waves is underestimated if the water surface due to a uniform flow or that due to a double-body flow is used as the steady water-surface profile on which the free-surface boundary condition for the unsteady potential is imposed. However, if the water surface due to a complete nonlinear steady flow is used as the steady water-surface profile, the added resistance in waves could be estimated quite accurately.

Other than the panel methods, which are based on a velocity-potential theory, numerical computations based on CFD (Computational Fluid Dynamics), which directly solves the equation of motions of water particles (Navier-Stokes Equation) and those of a ship simultaneously in their exact nonlinear forms by a finite-difference scheme while discretizing the flow volume around the ship into 3-D grids, have been appearing (Kinoshita et al., 1999, Orihara and Miyata, 2003, Hu and Kashiwagi, 2004). Although the available results of added resistance in waves obtained by the CFD computations are still quite limited, those published so far, e.g., Orihara and Miyata (2003), show that the CFD computations agree reasonably well with measured results.

An interesting fact commonly indicated by the numerical computations mentioned above is that the bow form of a ship above the calm-water surface affects the added resistance in waves quite significantly. This fact is further confirmed in the papers of Matsumoto et al. (1998, 2000) and Yamasaki, et al. (2003), in which it is shown (independently from the above theoretical work) as an experimental fact that the added wave resistance of a blunt-bow ship could be reduced by as much as 20-30%, while having little effect on other aspects of performances such as the calm-water resistance or the motions in waves, by modifying the blunt bow above the calm-water surface into a forward projecting sharpened bow.

In Kashiwagi et al. (2004), a new system, developed by the group of shipyards and universities organized in the Shipbuilding Research Association of Japan, automatically calculates, for appropriate ship-form data, various performance measures for the ship in real seas, such as the ship motions, speed reduction characteristics in waves, propeller and engine dynamics, manoeuvring motion responses, and global wave load. In this system for the calculation of added resistance, what is described as Enhanced Unified Theory (EUT), a modified Unified Theory accounting for the bow wave diffraction (Kashiwagi, 1997), is used.

High-Speed Vessels and Multihull Ships. Recent years have seen the increasing use of a wide range of advance marine vehicles that include high-speed monohulls, multihulls and planing craft. In order to optimize these designs to meet specific performance requirements there is a need to have the validated tools available to understand the design issues. At higher Froude numbers the heave RAO exhibits some resonance, with values in excess of unity, which is not usually captured by linear strip theory. Also, 2-D strip theory calculations are not able to sufficiently quantify the full interaction effects of the multihull ships which points towards full 3D techniques. The main requirement has been the development of valid 3D theories to account for multihulls and their extension to account for the higher range of Froude numbers.

This section summarizes developments in computational and experimental studies for high-speed vessels including monohulls, multihulls and planing craft.

Prediction of ship motions are usually formulated around a fixed frame of reference, moving with the ship, which then requires the forward speed terms to be included in the free surface boundary condition. Holloway and Davis (2002) developed a time domain based strip theory method in a fixed spatial frame of reference which is valid for higher Froude numbers. The Green function solution is described and the integration of the motion is undertaken by an averaging method to ensure stability of the solution. Davis and Holloway (2003) presented comparisons of this theory with experimental results from tests over a range of hull forms (and hull types) for Froude numbers around 0.8-0.9. The paper concluded that by providing a modest allowance for frictional damping there is good agreement between computed and measured vertical plane RAOs.

Bruzzone et al. (2001) presented a comparison between two numerical methods for determine the vertical plane responses of high-speed marine vehicles. One method applies a Rankine source distribution on the discretized hull and free surface, the other uses Green function formulation, with and without forward speed, on the hull surface. The paper shows numerical predictions of a deep-V and a round bilge monohull and compares them with experimental data for Froude Numbers up to 0.635. Ship motions evaluated by both the Green function method (with forward speed) and the Rankine Source method show different results to the traditional strip theory method.

Sclavounous and Borgen (2004) developed a 3D Rankine panel method to predict the motions of a high-speed, foil assisted, monohull vessel (Fr=0.6). In this paper the SWAN-2 (Ship Wave ANalysis) Rankine panel method is extended to include the effects of lifting appendages and in particular passive hydrofoils.

Ballard et al. (2001) used a convolution integral method to describe the radiation and diffraction terms to investigate the response of a fast hull form, both monohull and catamaran configuration, at Fr=0.5 in regular head waves. The impulse response functions are calculated from two different singularity methods – the first a pulsating source method and second a travelling, pulsating source method. Both methods used a panelled representation of the mean underwater surface of the hull. The non-linear incident wave and restoring forces are calculated using a representation of the instantaneous under-water hull form. It was found that the impulse response function determined from the pulsating source method was generally inferior to those determined from the translating pulsating source method.

Assessment of the response of high-speed vessels in waves from all directions is particularly important in the design process. Hudson et al. (2001) used 3-D potential flow theory to predict the heave, pitch and roll in regular oblique waves and compared with experimental measurements. This paper presents predictions of the motions of a high-speed catamaran in regular oblique waves using a translating pulsating source method. The unsteady potentials were determined, for the mean underwater wetted surface of the hull, using a boundary element method. This paper demonstrated that the translating pulsating source method provided better predictions than the pulsating source method.

Pastoor et al. (2004) studies the behaviour of a frigate-type trimaran in regular waves for a range of headings. This paper uses a 3D boundary integral method using the free surface Green function to calculate the influence coefficients on the wetted hull surface. The paper conjectured that the hydrodynamic interaction effects maybe justifiably neglected by the fact that the outriggers are small, the separation from the main hull is large and the forward speed is high. Thus, the pressure distribution on the main hull will be unaffected by the waves generated. However, results are presented showing comparison between the linear 3D frequency domain panel code and experiments.

Renilson et al. (2004) summarized a series of hydrodynamic trials on the trimaran research vessel, RV Triton. These trials included an extensive series of seakeeping runs made at fixed speeds in “star” patterns to ensure that all headings relative to the predominant wave direction were conducted. The sea environment was recorded through an onboard wave radar system giving full directional wave field, a omni-directional bow mounted wave height recorder and a fully directional wave buoy.

In waves, planing craft will respond in much the same way as any ship, in that they will experience motion in six degrees of freedom, surge, sway, heave, roll, pitch and yaw. The combined effects of the vertical plane motions have implications on the structural design of the vessel and are generally regarded as the most important. Hence most of the experimental and theoretical data relating to the performance of planing boats in rough weather is confined to vertical plane motions in head waves and more rarely following waves. There appears to be little or no data pertaining to performance in oblique seas, including sway, roll and yaw motions. Yet these motions have significance in the stability of the craft and overall performance in real sea conditions.

Suitable benchmark data are reported by Fridsma (1969), who performed a study on a systematic series of planing boats in irregular head waves. The study looked at the effects of deadrise, trim, loading, speed, length/beam ratio, bow section shape and sea state on the performance of a series of prismatic planing craft. For a given boat the designer should determine displacement, overall length, average beam, average deadrise, speed, smooth water trim and a sea state from which design charts, derived from the experimental data, can be used to predict full scale performance. Clearly, this form of assessment can only be used if the parameters of the boat under consideration fall within the limits of the design charts. Extrapolating is not recommended. Further-more, Fridsma varied the significant wave height during the tests but it is not clear if the modal period remained constant over the wave heights tested. If modal period did remain constant then extrapolation to other modal periods (if one was interested in a different sea area for example) would be unsatisfactory. If the modal period was change so that the significant wave height was matched with the most common modal period, then interpolation between wave heights becomes a problem.

Akers et al. (1999) describes a series of experiments to measure the responses of a planing craft by driving the boat through a Kelvin wave pattern generated by a displacement boat. The planing craft was instrumented with accelerometer packages and gyroscopes. The paper compared the measured motions with time domain predictions using commercially available software. The program is based on an extended version of the low aspect ratio strip theory developed by Zarnick (1979). In typical calculations of this nature the added mass and damping terms are evaluated at infinite frequency (or at least where the terms reach an asymptote).

Rosen and Garme (2001) presented a simulation model based on 2D potential theory that by though updating the hydrodynamic coefficients at each time step is non-linear. From the motion calculation 3D pressure distributions are formulated at each time step and applied as load cases in FEA.

Blake and Wilson (2001) looked to solve the equations of motion in the frequency domain using a linear theory and in the time domain using non-linear hydrodynamic coefficients. The hydrodynamic lift is derived from the consideration of the unsteady perturbed potential flow associated with the motion. Through a slender body theory analogy, the total vertical forces and moments are derived. To aid in validating any theoretical prediction, also shown is a novel video method of determining the wetted areas, spray generation and blister sheet information. The construction of the linear model leads to two first order differential equations in heave and pitch (surge is neglected). Representing these equations in the frequency domain leads to a quadratic equation in $i\omega$. Solving this equation gives four roots. If there is a complex pair of roots to this equation, the crafts' response is considered oscillatory.

By assessing the comparative performance of the two approaches the importance of non-linear effects can be investigated. In Blake (2000) from which the 2001 paper was derived, the following conclusions were included:

- In the non-planing region where $\frac{V}{\sqrt{L}} = 2$, heave and pitch motions are linear with wave height.
- In the intermediate region where $\frac{V}{\sqrt{L}} = 4$, heave and pitch motions depart from their linear behaviour especially around the resonant frequencies. Any discrepancy around resonance usually means inconsistencies in the treatment of the damping terms.
- In the planing region where $\frac{V}{\sqrt{L}} = 6$, heave and pitch motions are clearly non-linear.

Caponnetto et al. (2003) described three methods to simulate planing craft in waves. One based on Wagner's theory of hydrodynamic impacts, the others used a RANS solver applying different computational grid to the boat motions. Comparisons are made with experimental results for Fr = 4.

Slamming, Deck Loads and Whipping. *Shipping of Green Water:* A green water incident occurs when water immerses the deck as a result of the ship submerging into a wave or due to a large wave hitting the side or the bow of the ship. The velocities and volume of the water which covers the deck can be significant and can damage exposed structures, including the superstructure, along the deck, together with affecting the operability onboard Floating Production Storage and Offloading

(FPSO) vessels. Similarly, for vessels operating at high-speeds, such as container vessels, naval vessels, etc., green water is the lurking threat which not only puts exposed containers at risk, but also affects deck machinery and causes inconvenience to manning on deck, or, in the extreme, loss of human lives overboard.

The green water problem is of increasing concern as the number of permanently moored FPSOs is on the increase. These facilities stay at their position during a storm and can therefore be subjected to very large waves. Leonhardsen et al. (2001) summarized the green water incidents reported in Norwegian waters on FPSOs and concluded that the frequency of green water incidents is high and that it is an important factor in the risk analysis of an FPSO.

Buchner and Voogt (2000) investigated experimentally the green water at the bow of weather-vaning FPSOs with different bow flare angles. From the observation, the flow onto the deck for a full elliptical bow shows, in general, a strong resemblance to the theoretical dam breaking problem (Stoker, 1957). From the theory, it is found that the freeboard exceedance is linearly related to the water height on deck, and that the velocity of the waterfront over the deck is proportional to the square root of the freeboard exceedance at the fore perpendicular. These relations are confirmed by experimental data, almost independent of the underwater hull shape, the wavelength and the wave direction. From the character of the green water impact flow, the load of the water on the structure is not due to a solid impact as is the case for slamming, but due to a jet with an increasing height. It is concluded from the momentum theory that the peak impact load is proportional to the maximum water height on deck and the square of the waterfront velocity over the deck, yielding a quadratic relation between the impact loads on structure at the deck and the freeboard exceedance. With an increase of the bow flare angle, a decrease of the water height and impact pressure, and an increase of the water velocity on deck are observed.

Ogawa et al. (2001) conducted a series of model tests to measure the green sea loads acting on the deck and hatch covers of a bulk carrier model due to shipping water. The tests were carried out in irregular waves in several combinations of wave heading and ship speed conditions. It was confirmed that the deck wetness and green sea loads will be reduced considerably if the wave heading is altered to quarter or beam seas or the ship speed is reduced. Ogawa et al. (2002) conducted model tests in regular and irregular waves to measure the green water loads on the deck of a model of the generic cargo ship. After the experimental results of the cargo ship were compared with that of a bulk carrier, it was concluded that the green water load on the deck of a cargo ship is smaller than that of the bulk carrier and that the green water load in the regulation should be different for different ship types.

Stansberg and Nielsen (2001) carried out a model test with a turret-moored FPSO in head seas in scale 1:55. Investigation of the measurements has shown that green sea events occur as the combined result of energetic wave events and bow-down pitch motion. Most of these events include some of the largest waves characterized by steep and energetic single waves overtopping the bow; a few events are observed as groups of succeeding large waves (still with high energy envelope peaks), in which one of the succeeding waves may become critical. It is also concluded that the nonlinearity of the incoming waves should be taken into account and, in general, a second-order irregular wave model is a consistent model that includes the leading nonlinear effects and is convenient for practical use in simulating 3-hour (full-scale) records.

Schonberg and Rainey (2002) developed a new tool for the calculation of water velocities on the deck of a ship as a result of green water incidents. This tool models the flow by simulating a 2D shelf moving vertically up-and-down into a pool of water originally at rest. The flow of water is modelled using a numerical method, which applied potential theory and uses de-singularized boundary integral equation method combined with an implicit time-stepping procedure. The results from this new calculation procedure are compared with the results from the standard procedure, which indicates that the standard approach is conservative.

Buchner and Garcia (2003) discussed the practical design considerations related to the green water problem. For a particular structure at a specific location, the different ways to solve the green water problem are:

- Design the vessel and structures on the deck against the predicted green water impact load levels.
- Optimize the bow shape (underwater shape and above water bow flare).
- Increase the freeboard height such that green water is prevented completely.
- Increase the freeboard height such that the green loads are reduced to acceptable levels and design for these load levels.
- Optimize the structures on the deck to minimize the green water impact loads.
- Use protecting breakwaters in front of critical structures on the deck.

Vassalos et al. (2003) derived a model for estimating bow relative motions and deck wetness based on a comprehensive model-testing programme in severe sea states (Vassalos et al., 2001). The output of this model, in conjunction with empirical relationships inferred from model test measurements, yield the parameters of appropriate probability distributions selected for modelling green seas loads events on hatch covers and can be used to determine the extreme value distribution of those events. The procedure in conjunction with non-linear FEM analysis was used to assess the level of risk implicit in current design standards for hatch covers of bulk carriers, on the basis of which the cost effectiveness of eventual changes to those standards were preliminarily considered.

Barcellona et al. (2003) reported an experimental study regarding water-on-deck caused on a restrained model at zero speed in head waves by using a transient-test technique. A single water-shipping event is induced by the wave packet, and the severity of the interaction is controlled by the wave-packet steepness. Three different bow geometries are considered, and on each model a vertical wall is placed at a certain distance from the forward perpendicular to mimic the presence of deck structures. Velocity of the shipped water along the deck, pressure field on the deck, and horizontal impact force on the wall are measured. The main fluid-dynamic aspects of the green-water phenomenon are highlighted. For the tested cases, water shipping starts always with the free surface exceeding the freeboard, plunging onto the deck, and forming complex cavities entrapping air inside. The geometry of the air cavity depends on the hull form and the wave steepness. Then the water propagates along the deck. In general, the waterfront is strongly three dimensional because of the water entering along the deck contour. The interaction of the shipped water with the vertical structure consists of impact, run up-run down cycle, and backward plunging of the water onto the deck, still wetted. The evolution of the pressure field follows that of the waterfront. Pressure peaks are associated with the impact against the vertical wall, and by the backward plunging of the water on the deck, at the end of the run up-run down cycle of the water. It is shown that both these stages can be of importance from the structure point of view.

Greco et al. (2004) investigated experimentally and numerically the shipping of water on deck of a vessel in head-sea conditions and zero-forward speed. Through the experimental observations the main stages of the fluid-dynamic phenomenon are identified. For the considered conditions, water shipping initiates with waterfront overturning onto the deck, entrapping air, and then flowing along the initially dry deck to impacting against vertical superstructures. Numerically, the water-on-deck phenomena are studied by considering a simplified 2D potential flow problem. Through comparison against experimental data, it is shown that the potential-flow model suffices to give a robust and efficient estimate of green water loads until large breaking phenomena, usually following impact events, are observed. A boundary element method with piecewise-linear shape functions for geometry and boundary data is used for the numerical solution. The fluid-structure interaction is studied by coupling the nonlinear potential flow model with a linear Euler beam to represent a portion of the deckhouse under the action of the shipped water. The loading conditions related to violent fluid impacts and air cushion effects are discussed. Upon considering realistic parameters, the occurrence of critical conditions for structural safety is discussed. The role of hydro-elasticity is addressed in the case of fluid impacting against a vertical wall.

Nielsen and Mayer (2004) used Navier-Stokes solver with a VOF free surface capturing scheme to numerically model green water loads on a moored FPSO exposed to head sea waves. Two cases: green water on a fixed vessel and a full green water incident, including vessel motions, are investigated. The resulting water-height on deck and impact pressure on a deck-mounted structure are compared to the experimental data and very favourable agreement was obtained. The investigation shows that the VOF model captures most of the green water flow physics, including the flow on deck, and that both 2D and 3D give very similar results which indicates that 3D effects are not dominant.

Stansberg et al. (2004) described the prediction of critical loads and responses from green water on FPSO in random storm waves. Physical mechanisms leading to water on deck and bow flare slamming and the resulting responses are analyzed. A numerical engineering tool for prediction of green sea loads on deck and bow structures of an FPSO in irregular waves was reviewed. Critical inflow parameters predicted by this tool are addressed. In particular, the incident wave particle velocity and the relative height above deck are considered. Model test data from two tests with a turret moored FPSO in steep storm sea states are used to demonstrate the role of these parameters in events leading to impact loads on deckhouse and bow flare. A comparison to VOF-based CFD simulations of a water-on-deck event is also shown. The water propagation on a forecastle as well as the resulting impact load on a deckhouse shows promising comparisons to model test data and to CFD simulations.

Pham and Varyani (2004) studied two generic designs of breakwaters, i.e. the V-shape and the vane-type breakwaters, to reduce green water effect at the initial stage and act as a shield to protect deck machinery and containers. To achieve this objective, a computational method using CFD (standard Fluent package) as a tool was used to investigate the effect of generic variation of geometric parameters on the change in performance of the breakwater against green water. Conclusions are drawn based on the merits of such variation on each type of breakwater.

Wave Impact and Slamming: Hermunstad et al. (2002) presented a practical method for the prediction of slamming loads and structural responses in bow of a FPSO. Incoming waves are simulated by a second order wave model, which describes the water elevation and kinematics. Vessel motions are calculated by linear analysis. Relative motions are estimated by combining the linear vessel motions, second order incoming waves and linear diffraction. The relative motions and velocities at the bow are used as input to numerical slamming calculations. The generalized Wagner-method (Zhao et al., 1993, 1996) for 2D sections is used to calculate the slamming load, and quasi-static finite-element model of the bow is used to calculate the structural responses at each time step using the exact pressure distribution from the slamming calculations. Measurements on a 1:55 scale model of a FPSO are used for validation of the bow slamming calculations and good agreement was achieved.

Faltinsen (2002) analyzed the water entry of a rigid wedge by matched asymptotic expansions. A jet domain, inner domain at the spray roots and an outer domain, are defined. The new contributions are: (a) an inner domain solution at a spray root valid for any angle between the body surface and the horizontal surface, (b) a solution for gravity-free water entry of a general 2D body shape that is applicable for larger local deadrise angles than the solutions obtained by previous authors, and (c) a generalization of the water entry analysis to time varying entry velocity that gives information about the flow at the spray root. It is discussed how the inner domain solution at the spray root can be used in further development of numerical methods for nonlinear wave-induced motions and loads on a ship. Also discussed is how the results can be used to predict sloshing damping due to tank roof impact.

Tanizawa et al. (2002) studied the hydrodynamic impact forces acting on the bulbous bow both theoretically and experimentally. For theoretical study, shape of the bulbous bow was approximated by an ellipsoid, and von Karman's momentum theory was applied to estimate the slamming impact loads with given impact velocity of the emerged bow to the free surface. Wagner's impact theory was also applied to study the effect of the free surface swell up. An estimation method of the impact loads was proposed and an experiment of a self-propelled container ship model was conducted to validate the method. The vertical and lateral shearing forces and bending moments at the root of the bulbous bow were measured and presented in the paper.

In Ogawa et al. (2002), a practical prediction method for the probability density function of the impact pressure on the bow flare was derived based on model tests. In the derivation, the combination of Chuang's method of impact pressure estimation and the probability density function of relative water height was used. Chuang's method uses the relative speed and the angle between ship and wave to estimate the impact pressure, while in the estimation of probability density function nonlinear effect of the ship hull was taken into account. It was confirmed that this method gives a good estimation for the probability density function of impact pressure on bow flare after comparing it with experimental data.

Howison et al. (2002) reviewed and extended theories for two classes of slamming flows resulting from the violent impact of rigid bodies on the initially planar boundary of an inviscid fluid. The two configurations described are the impact of smooth convex bodies, and of non-smooth bottomed bodies, respectively. In each case, theories were presented first for small penetration depths in finite-or infinite depth fluids (Wagner flows), and secondly when the penetration is comparable to the fluid depth (Korobkin flows). Three dimensional Wagner and Korobkin flows, and the transition from Wagner flow to Korobkin flow, were also discussed. Some of the most interesting open questions and some new solutions were briefly described.

Greco et al. (2003) made an analysis of the local hydro-elastic responses of a Very Large Floating Structure (VLFS) with shallow draft. The method of analysis is based on a 2D fully nonlinear potential-flow model to solve the problem by BEM. The boundary value problem of the velocity potential φ and the similar problem for its derivative $\partial\varphi/\partial t$, which is necessary in the calculation of the pressure on the body surface, are solved simultaneously. The very shallow draft of a barge-type floating airport implies that bottom slamming will occur. Air-cushion formation is also accounted for. Structural consequences of bottom slamming are studied by coupling a simple Euler-beam model with fluid-dynamic solver.

Jensen and Mansour (2003) proposed an approach to estimate the effect of impulsive loads like slamming and green water on deck on the wave-induced bending moment by a semi-analytical method. The impulsive loads leading to transient vibrations are described in terms of magnitude, phase lag relative to the wave-induced peak and decay rate. These loads can be due to flare slamming, bottom slamming or green water loads as they all can be characterized by a short duration relative to the wave cycle. The magnitude of these loads is estimated by published theoretical or experimental results. The results are given in closed form expressions and the required information for the procedure is restricted to the main ship dimensions: length, breadth, draft, block coefficient and bow flare coefficient together with speed and heading. The formulae make it simple to obtain quick estimates in the conceptual design phase and to perform a sensitivity study of the variation of the ship's main dimensions and operational profile.

Cusano et al. (2003) described both the full-scale and model test monitoring campaigns and the most significant collected data, referring to the occurrence of slamming events. A comparison of these measurements with results derived by a combined hydrodynamic-structural numerical calculation procedure developed by CETENA is also presented. Both the full-scale and model test investigations were carried out on the MDV3000 monohull fast ferry and characterized by V-shaped bow lines. The full-scale data on ship motions, slamming pressures and global and local strains of the hull girder were collected by a proper structural monitoring system. A fibreglass model with scale ratio of 1:30 was developed by representing the actual hull shape with a segmented model, subdivided into six independent parts. The elastic behaviour of the ship was reproduced by means of an elastic girder that constitutes the backbone of the ship model, rigidly connected to each of the six hull segments, representing the real distribution of the bending stiffness along the ship length. Numerical investigation of the structure by FE models produced the required dimensions of the backbone girder. The hydroelastic tests were carried out in the towing tank where it was possible to reproduce recursive slamming events followed by whipping phenomena in severe operative conditions.

Scolan and Korobkin (2003) developed a coupled model to analyze the hydroelastic effects during the impact of a conical shell onto a free surface of liquid. The hydrodynamic problem is formulated within the Wagner theory and the structural problem is formulated within the linear elasticity theory for thin shells. Only axi-symmetric configurations are studied. The boundary value problem is formulated in terms of the displacement potential and the shell deflection. The modal-based method is used, and the resulting coupled boundary value problem is written as a linear differential system for the amplitude of each mode. It is shown that the elasticity exhibits a substantial influence compared to the rigid case.

Takagi and Dobashi (2003) described an approach to a distorted plate penetrating calm water surface as a flow model of the water impact in rough sea. The hull structure was modelled as a tandem mass and spring system with two degrees of freedom. One of the degrees corresponds to the global hull response, and the other corresponds to the local structure response. A sequence of circular hollows was used as the bottom shape of the body instead of the surface shape of the short crested waves to solve the fluid impact problem. The results show that the model-scale ship experiences much larger stress at the local structure because of the influence of trapped air.

Bow impact loading on floating offshore structures is related to steep waves occurring in random seas. Voogt and Buchner (2004) proposed a design evaluation method to predict the bow slam loading problem from the input (scatter diagram) to the output (predicted load and response levels) based on a clear description of the bow slam physics. The method is based on second order wave theory describing the wave steepness and an empirical relation between the wave steepness and the local impact. The position of this impact follows from a coupled time domain analysis of the ship motion. The method assumes long-crested waves which are considered as a worst case scenario.

Wu et al. (2004) analyzed the hydrodynamic problem of two-dimensional wedge entering water through free fall motion based on the velocity potential theory. The gravity effect on the flow is ignored as the interest is over a short period of time. When the tip of the wedge touches water the flow is assumed to be similar. The problem of this similarity flow is solved by a boundary element method together with an analytical solution for the jet based on the shallow water approximation. This is then used as the initial condition for the subsequent solution which is obtained by the same boundary element method in a stretched coordinate system together with the time marching technique to follow the body motion and the free surface deformation. An auxiliary function is introduced to decouple the mutual dependence of the hydrodynamic force and the body acceleration. Experimental study is also undertaken, and the numerical prediction is found to be in good agreement with the measured data for wedges with different weight, dead-rise angle and entry speed.

Whipping: Due to the lack of reference material and experience, it seems that it is premature to provide a standard procedure for whipping experiments at moment. However, the following items/descriptions might be a useful starting point.

1. Definition: Whipping is the response of the ship structure due to an existing force generated by the shock of an impact (slamming). Whipping can amplify strain and increases the structural damages due to the fatigue. Whipping occurs in severe seas. Whipping can be characterized as the response of a dynamic system.

2. Model design and construction: Be-cause hydro-elasticity is of great importance for whipping experiments, the models should be considered to be hydro-structural similitude, or models segmented either on a rigid beam or on a non-rigid beam. At present, the model set-up on non-rigid beam is the most commonly used to perform whipping experiments.

   Hydro-structural models are not segmented. Such models have roughly the same structure than the real ship. Their hull girder has the same main characteristics as the real ship (decks, bulkheads and stiffeners), providing structural similarity with regard to the strain at any cross section over the model length. Extrapolation laws must be studied very carefully, in particular due to the materials which are usually the same as in full-scale. The hydro-structural models are expensive and there design and fabrication is time consuming.

3. Segmented model: Loads or strain usually measured are, basically, forces applied on a part of the ship. A segmented model is cut in several independent components. Two types of segmented models exist depending on the type of beam connecting the various segments: rigid or elastic beam.

Typically the horizontal gap between the segments is around 5 to 10 mm for a 6-meter model. Geometrical hull shape must take into account this gap (i.e., the length of the model must not be change by the length of the gaps). The important parameter is the ratio of length between perpendicular (Lpp) and the total length of the segments. It is preferably that the gaps be sealed to ensure water-tightness.

Data outputs are loads, shearing forces and bending moments (vertical and/or lateral), and, more rarely, torsional moment. Those outputs can be obtained directly, or after post-processing due to inertia forces correction.

Rigid segmented models use a rigid beam that must have sufficient rigidity to be considered as infinite (high frequency of the set-up). The model shape does not change in waves at the studied frequencies. Bending moments can be directly evaluated by measurements. For the frequencies where the model can be considered as rigid, results for loading can be used as input for a numerical analysis of the structure. These computations can capture the effects of whipping. The computations can either be 2D (representation of hull girder) or 3D.

For elastic segmented models, each segment of the model must have the same inertial properties as the corresponding segment in the real ship. Ideally, the neutral axis of the backbone for the induced moments under investigation should match, or be as close as possible, to that of the real ship.

Some important point must be reported in the experimental reports:

a) For elastic segmented model experiments, performed to determine a response in one or several specific modes, it is thus mandatory to identify the structural damping of the tested structures. Even if the damping at full-scale is unknown, experimentally the structural damping should be measured. Kapsenberg et al. (2002) writes in his articles that if a succession of impacts is observed, the structural damping is important, especially when a second impact is considered. The response to the second impact can be increased or decreased by the effect of the first impact, which is not totally damped. Typical structural damping used in calculations is 1 to 3% of critical damping.
b) Typically, only the first vertical mode is experimentally simulated (sometimes the second). This prevents local deformation of the structure from being simulated (for example, superstructure mode). Additionally, there is the issue of how representative is the mode shape of a segmented model composed of a finite and weak number of segments, and with a finished and weak number, with regard to the reality. This should be studied numerically, even with a simple 2D girder representation. Comparison between segmented model mode shape and a numerical estimation of the full-scale mode shape should be performed in order to check the validity of model design.
c) Usually the signal is filtered using a low pass filter to eliminate setting up a frequency of resonance and hull girder resonance. Then it is possible to determine the contribution due to waves using spectral analysis. The part due to whipping is determined using temporal analysis (on a signal which is not filtered at the resonant frequency of the girder), producing the Weibull parameters.
d) From experiments (mainly experiments on rigid segmented model) forces can be deter-mined in spectral domain. This information is useful in the design of the local and global structure, and to avoid oscillations and harmful vibrations. The relationship between the duration time of an impact (which is linked the spectral contents) and the period of a mode of deformation of the structure is shown by Kapsenberg et al. (2002). This type of curve should systematically be an output supplied when the experimental set-up allows it, but also at full-scale.
e) Results are often expressed in term of bending moment; i.e., the integration, from one of extremities, of the moments of efforts expressed in a specific location. This result depends on longitudinal and vertical distances from the cells to the origin. Experimentally it is impossible to distinguish moments due to the vertical

forces from those due to the horizontal forces. Thus position of the origin is an important factor which must be specified in the report. It is usually taken as the vertical position of origin, the neutral fibre, or the centre of gravity to minimize the effects of inertial force.

f) Frequency of resonance is proportional to:

$$\omega = \sqrt{\frac{EI}{\Delta l^3}} \tag{2.1}$$

where,
E is the Young Modulus of the material, I is the moment of inertia of the girder, Δ is the displacement and l is the length of the girder. Usually segmented models on a flexible beam use a beam of the same material as full-scale. Theoretically the scaling law is then λ^5. For many reasons (length of the beam, uncertainty of the Young's modulus, "sprung" effect, Achtarides, 1983), it is difficult to obtain natural frequencies of the model and the real ship. That means that the model's natural frequency should be adjusted to a value estimated numerically from full-scale data.

g) For segmented models on a rigid beam, it is possible to estimate the accuracy of measurements with the difference of results by integration from the twos extremities References.

Kapsenberg et al. (2002) described experiments on a flexible segmented model. A theoretical dynamic representation of the experimental set-up is described in order to simulate the effect of different impacts. Importance of the ratio of impulse period over resonance period is shown for a flexible model and a rigid model. The experiment used a large number of pressure gauges. Measured pressures are integrated in order to estimate the whipping responses. The measure of the pressures at many locations can allow with some hypothesis, to obtain the efforts of an impact a part of the ship. These results are attractive in particular to use them as input for a numerical analysis of the structure. The main drawbacks are the number of sensors which must be large and the interpolating method which is not unique. It seems that it could be necessary to adjust the interpolating method to each case (slamming of bow or bottom, geometry of the ship). Thus one should be able to check the integration by a global measure made with strain gages based sensors.

Malenica et al. (2003) presented numerical calculations to solve simultaneously the motion and the flexural modes of a beam. Validation of the methodology is made with experiments for a barge composed of 12 segments. Comparisons are made on the RAO of vertical displacement of each segment. Comparison between numerical calculation and experiments is good.

Katoh et al. (2004) described numerical methodology to estimate structural damping. Validation is given on a girder. Linear relation between logarithmic decrement and nodal number is found.

Couty et al. (2004) used a mechanical structural model in order to explain the influence of some parameters of the excitation impact as rise time, duration time and impulse magnitude. Comparison between simple girder approximation and full 3D approach is performed.

Parametric Rolling. In longitudinal seas, large amplitude vertical motions, coupled with the waves, leads to a time varying restoring term in the roll equation of the ship. This can mean that small perturbations in roll motion can grow, leading to excessive roll motion and possible capsize. This phenomenon of parametrically induced rolling is well known. It was initially thought to be a problem for smaller high-speed craft in following seas. However, more recent experiences have been reported in larger ships operating in head seas. France et al. (2001) describes the problems experienced by a post-Panamax C11 class container ship when she encountered extreme weather in the North Pacific: roll angles of 35-40 degrees in bow seas were reported to have occurred during the storm. From this incident, it was conjectured that parametric rolling lead to accelerations that caused substantial loss and damage to containers stowed on the deck. It appears therefore that longitudinal seas, rather than following or head seas alone, should be considered to represent the realm of parametric rolling.

The basic physics of the phenomenon is a result of the cyclic variation of the restoring force of the ship between wave crests and troughs: a phenomenon exhibited by many ships in steep longitudinal waves. These variations set up a mechanism of internal (parametric) excitation in the roll equation. There is a clear analogy with a simple oscillator governed by the so-called Mathieu equation with damping. Despite the progress made through research, a few issues remain still open, like the development of methods to assess the effects of coupling with other motions; of effective criteria for the prevention of parametric rolling through design; and the derivation of optimal experimental/numerical procedures for safety verification in a realistic sea.

Numerical Methods: There are essentially two numerical approaches to understanding the magnitude of parametric rolling once the stability boundaries have been exceeded. These take the form of a 1 degree-of-freedom roll equation or a fully coupled 6 degrees-of-freedom non- linear ship motion code. The development of the 1 DOF model is ongoing to avoid the use of complex fully coupled ship motion programs.

For the uncoupled 1 DOF approach the roll equation usually takes the form of:

$$\ddot{\phi} + d(\dot{\phi},\phi) + r(\phi,t) = 0 \tag{2.2}$$

where,
d is the damping terms which is a function of roll and roll velocity and *r* is the restoring term which is a function of roll and varies with time. In the simplest form (so called Mathieu equation) this equation can be reduced to a linear differential roll equation with periodic coefficients as shown:

$$\ddot{\phi} + 4\frac{\omega_0^2}{\omega_e^2}\left[1+\frac{\delta GM}{GM}\cos(2t)\right]\phi = 0 \tag{2.3}$$

A solution to this equation can be in the form $e^{\pm\sigma t}\psi(t)$ where $\psi(t)$ is a periodic function and σ is the characteristic exponent. The solutions to this Mathieu equation are diverging if $\sigma \neq 0$ and stable if $\sigma = 0$. Francescutto (2001) demonstrated that the addition of damping meant that the solution of the damped Mathieu equation would be: diverging if both $-\frac{2\mu}{\omega_e} \pm \sigma > 0$ stable if $\frac{2\mu}{\omega_e} = \sigma = 0$, or decaying if $-\frac{2\mu}{\omega_e} \pm \sigma < 0$.

The key is to determine the value of the characteristic exponent from the relevant parameters $\frac{\omega_e^2}{\omega_o^2}\,\text{and}\,\frac{\delta GM}{GM}$ in the above roll equation. Indeed the roll equation has several zones of instability originating from (2/n,0), where n is an integer, in the $(\frac{\omega_e}{\omega_o},\frac{\delta GM}{GM})$ plane, the first zone of instability at a point where $\frac{\omega_e}{\omega_o} \approx 2$.

Bulian et al. (2003) used a 1.5 DOF non-linear mathematical model and compared the stability boundaries derived from an analytic, numerical and experimental treatment of the rolling of a ship in regular and irregular head waves. The extended degrees of freedom come from treating explicitly in the roll equation, the variation in the restoring lever as a function of roll and pitch angle, heave displacement and wave position. Two techniques were considered for the derivation of the stability boundaries in irregular waves, the Fokker-

Planck method (used by Rong et al, 1998) and the Multi-scale method (used by Roberts, 1982). Both these techniques make assumptions regarding the form of the one degree-of-freedom uncoupled roll equation. The results have shown that the principal factor determining the extent of the instability region are the non-linearities of the restoring moment. However, the paper states that the linear approach is probably satisfactory if only the stability boundaries are of concern. However, the simple solution is not sufficient to capture the magnitude of rolling once exceeded the stability zone. Indeed, the asymptotic behaviour of the Mathieu equation inside the instability zone if infinity.

In order to be able to assess the magnitude of roll once the threshold of stability has been exceeded, the non-linearities of *d* and *r* need to be well defined. In the case of the single DOF roll equation, the non-linearities of the damping and restoring terms are explicitly defined by the form that the *d* and *r* functions take. Their form is critical in the determination of the extent of rolling beyond the stability threshold. Generally, the damping consists of contributions from linear and cubic terms of roll velocity, see Francescutto and Bulian (2002) and Umeda et al. (2003).

The restoring term can be described by cubic or higher order functions of roll angle. Bulian et al. (2003) considered a cubic restoring function to account for the calm water righting arm, the variation of metacentric height and to account some higher order righting arm fluctuations. Umeda et al. (2003) for example, chose 5th order restoring function derived from captive model tests.

Matusiak (2003) compared numerical prediction of parametric rolling with model tests conducted on a free running fast RoPax vessel. Tests were conducted in head and following seas. The numerical approach is described as a two-stage approach whereby the linear approximations and non-linear portions in the ship dynamics model are decomposed. The linear approximation derived from strip theory with information regarding the instantaneous ship position on the wave and the non-linear portions are evaluated in the time domain.

The alternative approach to using a 1 DOF roll equation to determine the magnitude of parametric rolling once the thresholds have been exceeded is to use a fully coupled non-linear time domain such as LAMPS (Lin and Yue, 1990) or FREDYN (DeKat and Paulling, 1989). Unlike a 1 DOF roll equation where the form of the restoring and damping terms need to be known a priori, in a fully coupled non-linear ship motion program, the restoring function is implicit in the determination of the position of the metacentre for the instantaneous underwater hull form. For the damping term, the potential effects, as with the restoring term, are implicit in the calculation process. However, most time domain ship motion programs are potential methods and hence cannot account for viscous effects without recourse to empirical data derived from model tests or more recently from CFD calculations. In FREDYN, for example, the roll damping is determined implicitly from empirical measurements of the viscous effects from roll. France et al. (2001), tuned the predicted roll decay response of the C11 class containership to match experimental results by specifying a cubic damping function in terms of roll angle and roll velocity. Multiple calculations are undertaken in different spectral realizations to investigate the stochastic properties.

Levadou and Van Walree (2004) compared numerical model tests with numerical predictions of the C11 class containership, paying attention to the validity of the numerical results and the consequence of the validity. Again the FREDYN simulations were improved by tuning the roll model. The paper presents statistics from predictions and experiments (although the paper does not provide the length of the simulation time) and the results are in remarkable agreement.

Riderio e Silva et al. (2003) used a 5 DOF (neglected surge) time domain non-linear numerical model and compare the results with experimental results. A quasi-static approach is adopted to determining the non-linear restoring coefficients in heave, roll and pitch. The conclusions in the paper included the remark that very good correlation between the model tests and numerical analysis were achieved when the roll damping in the model was tuned to the tests.

Taguchi et al. (2004) reported on a series experiments to clarify the overall property of parametric rolling. In the experiment, the wavelength, wave height, model speed and heading were varied.

Criteria for Parametric Rolling: In regular waves, parametric oscillations may occur in various combinations of ship speed and wave frequency, provided that the resulting frequency of encounter is near to (2/*n*) times the natural frequency, where *n* is any integer. The practical relevance of the *n*=1 scenario ("principal resonance", $\omega_e = 2\omega_\phi$) is well established for ships. The *n*=2 scenario ("fundamental resonance") is also believed to be of interest although with a lower probability of occurrence in a seaway. Additionally, the build-up of parametric rolling requires a threshold wave height. This minimal height is determined in principle by two factors: the degree of fluctuation of roll restoring due to wave passage; and the ship's roll damping which is speed dependent. The damping is a key design parameter for the avoidance of parametric rolling. Whilst the restoring variation is easily predicted at the design stage, none of the current state-of-the-art computational programs can claim to calculate the roll damping accurately for any given vessel including all roll damping devices.

For the prediction of parametric rolling due to principal resonance the following simple rule may be applied, which is based on consideration of the asymptotic stability of the upright state of the ship:

If the amplitude of fluctuation of metacentric height (scaled with respect to the mean meta-centric height of the ship for the considered wave) exceeds 4 times roll damping ratio, then the occurrence of parametric rolling is possible.

Furthermore, in the vicinity of exact principal resonance the following expression may be used for the threshold level of the scaled GM fluctuation. Francescutto (2001) was able to demonstrate a deterministic method for defining the thresholds of the parametric rolling phenomena which as far as the first instability zone is concerned is given by the following inequalities:

$$2 - \frac{\omega_e^2}{2\omega_o^2} < \frac{\delta GM}{GM} < \frac{\omega_e^2}{2\omega_o^2} - 2 \qquad (2.4)$$

and, when including damping effects, gives a boundary value of

$$\frac{\delta GM}{GM} = \sqrt{\left(2 - \frac{\omega_e^2}{2\omega_o^2}\right)^2 + \frac{\omega_e^4}{2\omega_o^4}\left(\frac{4\omega_0^2}{2\omega_e^2} + 1\right)\left(\frac{2\mu}{\omega_e}\right)^2} \qquad (2.5)$$

Spyrou (2004) showed that if the ship experienced parametric rolling, the amplitude of roll was small to moderate, and with certain limits on the detailed shape of the restoring lever (a third-order polynomial could represent reasonably the exact shape of the initial part of the lever). Then, the following expression could be used for predicting the steady roll amplitude *A* in the vicinity of principal resonance:

$$A^2 = \frac{4}{3c_3}\sqrt{\left(1 - \frac{1}{a}\right) \mp \sqrt{\frac{h^2}{4} - \frac{4\zeta^2}{a}}} \qquad (2.6)$$

If the amplitude of parametric roll is moderate to large, a fifth order polynomial is likely to be required. In such a case the following expression of the amplitude could be useful:

$$A^2 = -\frac{3c_3}{5c_5} \pm \sqrt{\left(\frac{3c_3}{5c_5}\right)^2 - \frac{8}{5c_5}\left(-1+\frac{1}{a} \pm \sqrt{\frac{h^2}{4} - \frac{4\zeta^2}{a}}\right)} \tag{2.7}$$

In the above two expressions, $a = 4\omega_\phi^2 / \omega_e^2$, $h = \frac{\delta GM}{GM}$, c_3, c_5 are nonlinear stiffness factors, corresponding respectively to the third and fifth order restoring terms, according to the following roll equation:

$$\ddot{\varphi} + 2k\dot{\varphi} + \omega_\phi^2\left[1 - h\cos(\omega_e t)\right]\varphi - c_3\omega_\phi^2\,\varphi^3 - c_5\omega_\phi^2\,\varphi^5 = 0 \tag{2.8}$$

where,
φ is the roll angle and k is the ratio of the ship's dimensional damping, divided by the roll moment of inertia (including the added roll moment of inertia). The damping ratio ζ can then be determined from the expression: $\zeta = k / \omega_\phi$.

Parametric rolling could be characterised as "severe" if the steady amplitude is higher than 15 deg. The above simple expressions can be used in order to check whether this limit is exceeded.

Analysis of Results: Once the zones of instability have been identified then the magnitude of parametric rolling can be determined through numerical simulation or experimental testing.

Figure 2.1 shows an example of a ship in severe irregular head waves exhibiting parametric rolling.

Irrespective of whether a numerical or experimental method is adopted to predict the onset and magnitude one key issue is the whether parametric rolling can be regarded as a stationary stochastic process. Belenky et al. (2003) described a background for assessing the risk of parametric roll in head seas. If the waves can be described as quasi-stationary (which is practicable for short periods of time) then, with the assumption of linearity, the motions themselves would be quasi-stationary also. Belenky et al. (2003) described an ergodic process as applicable to a stationary stochastic process in which the statistical moments can be estimated from one sufficiently long realization. Hence, for near linear motions, the ITTC recommendation is 100 wave encounters to ensure statistical significance.

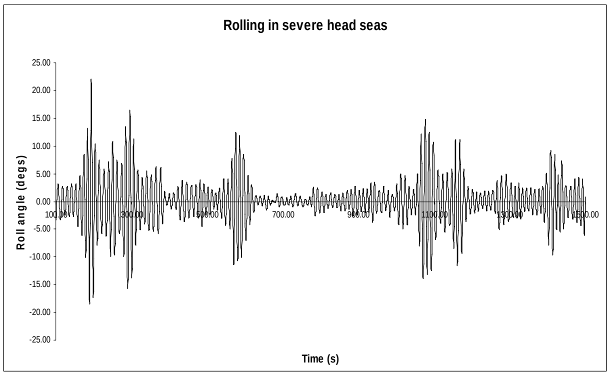


Figure 2.1- Parametric rolling in head waves (Speed = 5 knots, $H_{1/3}$=6 metres, T_Z=5.38 seconds).

Figure 2.2 shows the results of evaluating the RMS cumulatively over time. Each response represents a different realization of the same wave spectrum. It is clear from Fig. 2.2a that the waves do converge to around 1.5 m ($H_{1/3}$=6.0 metres) and as such the wave realizations are regarded as ergodic.

Figure 2.2b shows the cumulative evaluation for RMS pitch from the different wave realization shown in Fig. 2.2a; so, each line represents the resulting pitch motion from the different realization of the same wave spectrum. Again, each curve does converge to an RMS pitch value of 3 degrees and so exhibits ergodic behaviour.

Both the ergodic nature of the waves and pitch motion was demonstrated by Belenky et al. (2003). In this paper it was also stated that the same behaviour was seen for encountered waves, heave displacement, heave and pitch velocity.

Figure 2.2c shows the cumulative evaluation for RMS roll from the different wave realization shown in Fig. 2.2a. Estimates of roll angle do not converge to a single value and should be regarded a non-ergodic.

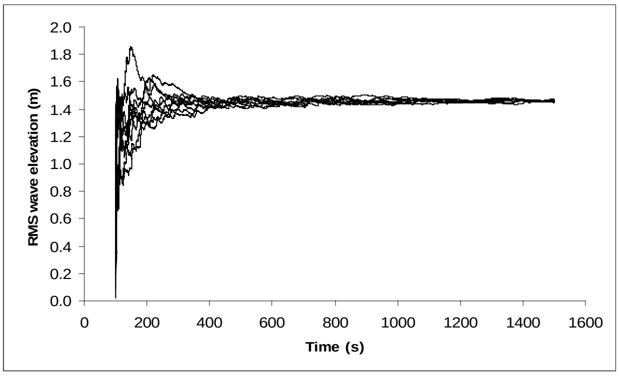
Belenky et al. (2003) demonstrated a method for quantifying ergodicity by comparing the confidence intervals associated with each realization and assessing the extent to which the confidence intervals overlap. A relative measure of the dispersion due to non-ergodicity was expressed as:

$$k = \frac{\sqrt{V[V_r]}}{V_e}.100\% \qquad (2.9)$$

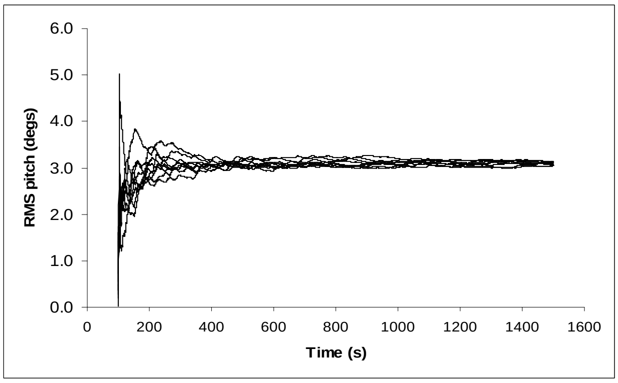
where,
V_e is the mean value of the variance estimates across realizations and $V[V_r]$ is the variance of the “variance estimates” about V_e. The paper demonstrated that the k-value for waves from a fixed location is about 1.4%; for the encounter waves, heave motion and pitch motion the k-value is about 3.5; and for roll motion the k-value is about 30. These k-values were computed from 50 numerical simulations (i.e., in different wave realizations).

The fact that parametric rolling is non-ergodic has some implication on the number of simulations or experimental tests required to establish some confidence in the result. As mentioned earlier one hour full scale equivalent is generally acceptable for deriving statistics from model tests of rarely occurring events: numerical simulations have shown that 30 minutes is probably sufficient to understand motions that can be regarded as ergodic.

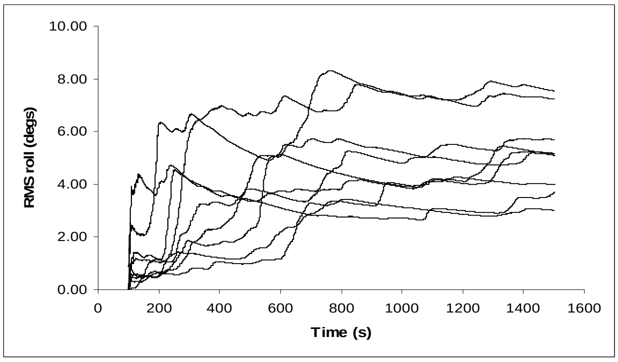
However, for non-ergodic responses a single calculation (or experimental run length) of 30 minutes or indeed one hour could give erroneous results. Now, Belenky et al. (2003) analysed 50 realizations of parametric rolling predicted through numerical simulations and found a relative difference of 30% difference between the variance of roll for each realization.



(a) RMS wave elevation



(b) RMS pitch



(c) RMS roll

Figure 2.2- RMS responses at each time step.

Bulian et al. (2004) presented some preliminary results regarding the problem of no-ergodicity of parametric rolling. This is addressing the issue of obatining reliable information from ensemble averages. The main conclusion of the paper wa that temporal averages for parametric rolling responses can lead to very large coefficients of variation. It showed that, in some cases, the anlysis of a single 30-minute time history can be almost useless in if carried out in a single realization.

2.3 CFD Applications in Seakeeping

Introduction. Numerical calculation methods with the potential-flow assumption have been used for seakeeping computations such as wave loads and wave-induced ship motions. For example, as previously re-viewed, strip theories and 3-D panel methods may be used as a reliable numerical tool particularly in the regime of linear problems. Even for the study on nonlinear effects, such as the effects of bow and stern flares and nonlinear terms in the free-surface condition, the potential-flow computations have traditionally been conducted. However, there exist strongly nonlinear phenomena that the potential-flow theory cannot deal with, such as wave breaking, green water, slamming with fragmentation of fluid and entrainment of air. Furthermore, for the prediction of viscous resistance and damping force on a ship advancing and oscillating in waves, free-surface viscous-flow computations are prerequisite. Needless to say, for these viscosity-related problems, the potential-flow theories are of no use.

In this section, recent developments in the so-called CFD (Computational Fluid Dynamics) for studying strongly nonlinear and free-surface viscous-flow problems are reviewed. Here the term of CFD is used to mean numerical calculation methods which can deal with viscous flows and/or highly nonlinear phenomena, in contrast to the potential-flow calculation methods. Specifically, the finite difference method, the finite volume method, the finite element method, and the particle method may be typical numerical calculation methods to be categorized with the term of CFD.

RANS Codes for Global Ship Motions. Recent development of the computer technology enabled us to implement viscous-flow simulations without explicit approximations. Research activities for viscous-flow simulations using the so-called CFD became active since the 21st ONR Symposium in 1996 and the 7th Int. Conf. on Numerical Ship Hydrodynamics in 1999. Most of the viscous codes for computing ship motions in waves solve the RANS (Reynolds-Averaged Navier-Stokes) equations and the continuity equation. A recent contribution along this line is the work by Weymouth (2003), which computed heave and pitch motions of ships in head waves using an extension of the RANS code developed at the University of Iowa. After numerical verification, computed results for a modified Wigley model were compared with experimental ones by Journée (1992), confirming good agreement over a wide range of Froude numbers, wavelengths, and wave amplitudes.

Orihara and Miyata (2003) also developed a RANS code named WISDAM-X, using the finite-volume method and a MAC (Marker and Cell)-type solution algorithm. An overlapping grid system, a curvilinear body-fitted grid for the near field and a rectangular grid for the far field, was employed to simulate the wave generation, the interactions of ships with incident waves, and the resultant ship motions. The free surface was captured by the density-function method. Unlike other recent works on unsteady CFD, main interest was placed on the added resistance in waves, and validation was performed through a comparison with measured results of the S-175 container ship. A fairly good agreement was shown not only for heave and pitch motions but also for the added resistance.

The current work on CFD simulations at Hamburg Ship Model Basin was reported by Hochbaum and Vogt (2002), which aims at accurate simulations for not only seakeeping but also manoeuvring problems. The interface capturing was based on the level-set method and computational grids were generated with commercial software to reduce time for grid generation. Although some results are shown, extensive work on the validation of the code is still being performed.

Hino (1997, 1999) developed a CFD code named SURF for steady flow problems, which was modified by Hinatsu and Hino (2002) to treat ship motions in waves. This code solves the Navier-Stokes equations using an unstructured grid system with pseudo-compressibility assumption, and the grid moving effect associated with ship motions is taken into account. The free-surface capturing was based on the level-set method. Computed results were shown for various quantities of a Wigley model, but main interest was placed on the influence of ship motions on the mean velocity at the propeller plane.

Recently, Luquet et al. (2004) presented a new method for studying wave-body interactions, in which all unknowns of the problem were split into the sum of an incident term and a diffracted term, and incident quantities are supposed to be provided by a nonlinear calculation method based on the potential flow. Then a set of the RANS equations is modified to compute only for the nonlinear diffracted flow. The boundary conditions are also modified to define the diffracted problem only, which are satisfied by introducing boundary-fitted curvilinear coordinates. The resultant formulation is named SWENSE (Spectral Wave Explicit Navier-Stokes Equations) approach. Numerical computations were performed for the DTMB Model 5512, and computed results were compared with benchmark experiments conducted by Gui et al. (2001). The results for unsteady components of the force and wave pattern look promising, but the steady components need to be improved.

CIP-Based Methods for Violent Flows. In the context of nonlinearities in seakeeping problems, of vital importance are not only global ship motions but also localized, strongly nonlinear phenomena, such as slamming, water on deck, green-water impact, and sloshing. In these strongly nonlinear phenomena, the free surface will be highly distorted, and wave breaking and air trapping may occur. For these extreme cases, conventional numerical approaches based on the potential-flow theory will break down, and sharp pursuit of the interface between water and air will be a key issue. As a new method to serve this purpose, a CFD technique by means of the CIP (Constrained Interpolation Profile) method is being studied by Hu and Kashiwagi (2003, 2004). The CIP method was initially proposed by Yabe (1991) and has been developed by his group. 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. With the latter feature, this algorithm is named C-CUP (CIP Combined and Unified Procedure) method. The CIP-based method is relatively easy to extend to 3-D simulations with acceptable resolution and computation time, because rectangular Eulerian grids are used.

Momoki et al. (2003) and Hu et al. (2003) conducted a validation study using a 2-D Numerical Wave Tank (NWT) and the capability of the CIP-based method was checked for wave generation, hydrodynamic forces on a plunger-type wave-maker, and nonlinear wave-induced motions of a floating body with wave impact and water on deck. Some of them were compared with corresponding experiments, showing acceptable agreement (Hu and Kashiwagi, 2004). The position of the interface is captured by solving the advection equation for a density function by means of the CIP scheme. However, sharp pursuit of the boundary surface of a freely moving ship with complicated geometry is not easy but very important, because the pressure integration over the wetted surface of a body must be performed at each time instant to simulate ship motions.

In principle, the translational and rotational velocities of the centre of gravity of a ship can be determined by solving the motion equations, and then the density function of solid phase can be mapped into a computational cell defined in the Cartesian coordinate system moving with the mean forward speed of a ship. To realize this procedure for a 3-D problem with the resolution and simplicity retained at reasonable level, Hu (2004) considered two overlapping grids; the main grid defined in the inertial reference coordinate system and the moving grid defined in the body-fixed moving coordinate system. In the moving grid, the value of the solid-phase density function is unchanged at each grid point. Mapping this information into the main grid was implemented by using a relation between temporal derivatives of the Euler angles and the angular velocities of a moving ship. Hydrodynamic computations with the CIP-based method were performed only with the main grid. A demonstrative example is shown in Fig. 2.3 for a container ship moving in large-amplitude waves at Fn=0.23 ($\lambda/L=1.0$, $H/\lambda=1/10$ and T_0 is the incident-wave period). This example includes the occurrence of water on deck and wave breaking, which may be enough to indicate that the CIP-based method is very robust even for strongly nonlinear wave-body interactions. Further validation should be conducted through a quantitative comparison with experiments.

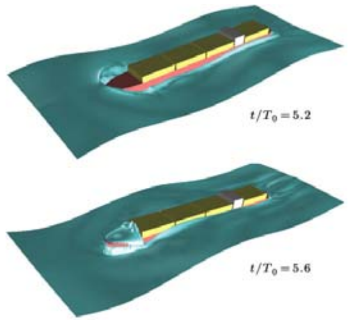


Figure 2.3- 3-D ship motions in a large-amplitude wave, computed by the CIP-based method (Hu, 2004).

Even the CIP method has some disadvantages. First, since the original CIP scheme is based on the non-conservative form of the advection equation, the mass conservation, for instance, may deteriorate in long-time simulations. Furthermore, although the CIP scheme is featured with sub-cell resolution, the numerical diffusion becomes prominent at the air-water interface when the wave breaking and splash occur. These disadvantages were elucidated in computations of a violent sloshing problem by Hu et al. (2004). To surmount these problems, Hu et al. (2003) investigated a conservative form of the CIP scheme and found it to be effective in reducing the numerical diffusion. This new scheme is named CIP-CSL3 (Conservative Semi-Lagrangian scheme with 3rd polynomial function), following the original paper by Xiao and Yabe (2001).

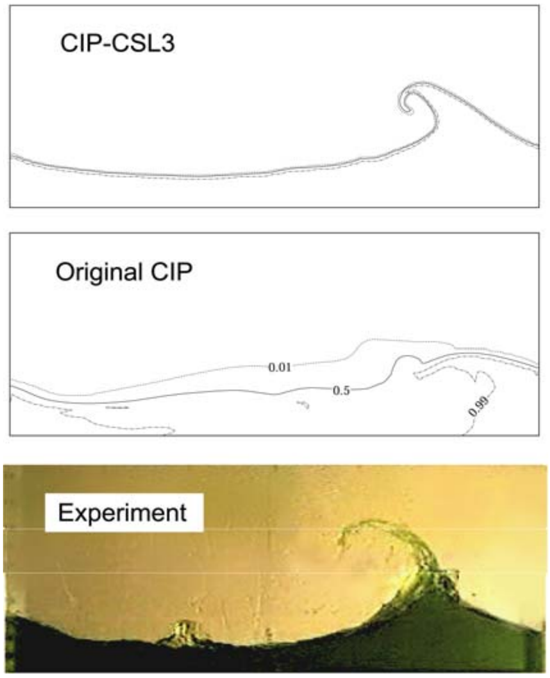


Figure 2.4- Comparison of the free-surface profiles at t/T=5.8 for T=0.8 sec.

For validation of the CIP-based method, Hu et al. (2004) carried out a series of experiments with a horizontally oscillating rectangular tank. In comparison with the experiments, both of the original CIP scheme and the CIP-CSL3 scheme were tested. Figure 2.4 shows a comparison of the free-surface profile at $t/T=5.8$ for the case of $T=0.8$ sec. The location of the air-water interface is usually taken as the line of $\phi_1=0.5$ in the density function, but the lines of $\phi_1=0.01$ and $\phi_1=0.99$ are also shown to illustrate the numerical diffusion. The thickness of the inter-face becomes large for the original CIP scheme as time proceeds, whereas the CIP-CSL3 scheme performs well as the interface capturing method and suppresses the numerical diffusion successfully.

Figure 2.5 shows time histories of the pressure for the case of $T = 1.3$ sec (which is approximately the first resonant period), measured at the point on the vertical side wall 1.0 cm below the still water surface. In this resonance case, the phenomenon is featured such that an impulsive pressure is exerted when the water impinges upon the vertical wall and the second peak in the pressure appears when the overturned free surface plunges into the free surface again. Superiority of the CIP-CSL3 scheme is obvious in resolution of these peaks, too, although the peak value tends to be small as compared to the measurement.

Particle Methods for Violent Flows. As demonstrated above, the CIP-based method is robust and can deal with strongly nonlinear free-surface flows, and with the CIP-CSL3 scheme as the interface capturing method, sharpness of the interface may be kept and adequate even for long-term simulations. However, as long as a fixed Eulerian mesh is used, the numerical diffusion is unavoidable, and the resolution will be worse in 3-D problems.

The MPS (Moving Particle Semi-implicit) method, one of the particle methods and developed for an incompressible fluid by Koshizuka and Oka (1996), is also considered to be a promising method for treating violent free-surface flows, because it has the following features:

- Grid-less Lagrangian method, and thus
- No numerical diffusion and perfect conservation of mass,
- Robust and simple because of no necessity of geometric connectivity among particles.

Sueyoshi and Naito (2001, 2003) has been applying this MPS method to seakeeping problems such as the motion of a damaged ship in waves, the sloshing, and the wave impact by green water. For simulation results by the MPS method, the reader is referred to recent papers published by Sueyoshi and Naito (2004, 2005). One example of the result is shown in Fig. 2.6, which is a comparison with the experiment of violent sloshing used for validation of the CIP-based method. Very good agreement can be seen between measured and computed profiles of the free surface, in spite of occurrence of large deformation of the free surface and fragmentation of the fluid.

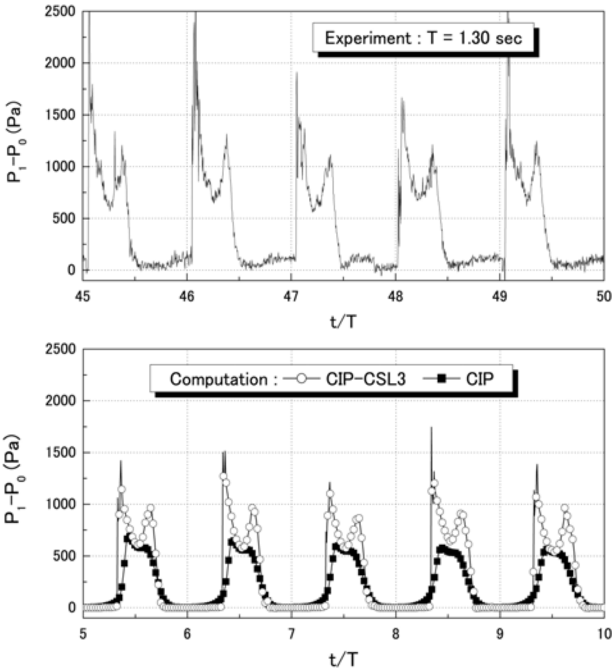


Figure 2.5- Comparison of the pressure in sloshing for T=1.3 sec.

Figure 2.7 shows the time history of the pressure, in which measured results were obtained in the same experiment as that for validating the CIP-based method. Good agreement exists between the experiment and computed results by the MPS method. With the original MPS method, the computed pressure oscillates violently in time, although the mean value in the time history looks reasonable. This violent oscillation is exerted by a numerical reason and suppressed by an auxiliary calculation method proposed by Sueyoshi and Naito (2003).

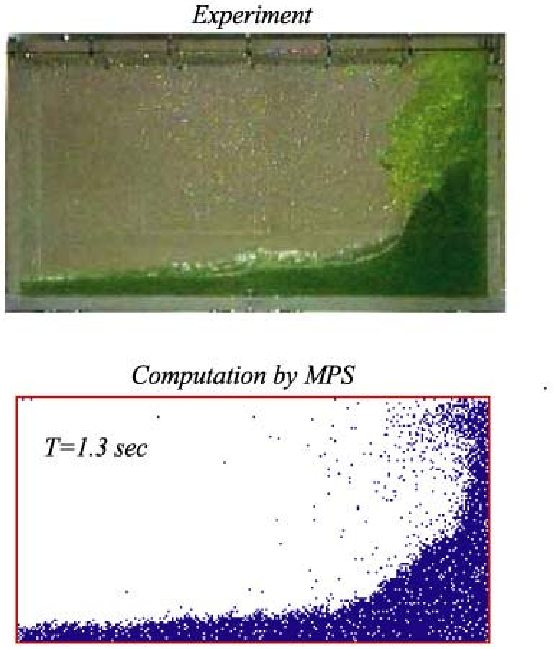


Figure 2.6- Comparison of the free-surface profile for T=1.3 sec, computed by MPS method.

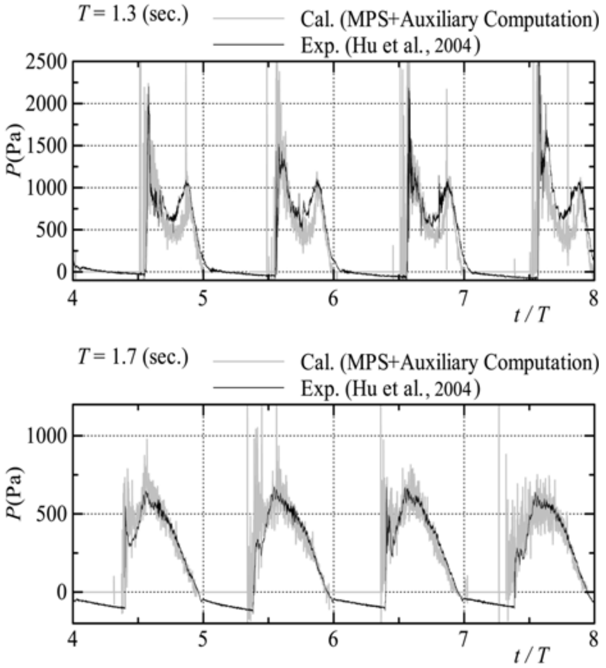


Figure 2.7- Comparison of the pressure for T=1.3 sec and 1.7 sec, computed by MPS method.

3-D problems were also simulated by Sueyoshi and Naito (2003), examples of which are a simple model of green-water impact onto the foredeck of a moving ship and the sloshing in a sphere and a rectangular container. In the MPS method, 3-D computations can be performed without major modification of the computer code, but the computation time may become prohibitive if the number of particles is very large for the sake of high resolution. To make it possible to compute for particles more than 10^6 with practical computational time, Sueyoshi and Naito (2004) devised some numerical techniques, such as a cell portioning method and the parallel computing with optimum memory distribution. Kashiwagi (2004) reviewed recent development in both the CIP-based and MPS methods done at Research Institute for Applied Mechanics, Kyushu University.

In contrast to the MPS method which is popular in Japan, the SPH (Smoothed Particle Hydrodynamics) method seems to be more popular and tested for seakeeping problems mainly in Europe. The SPH method was designed initially for a compressible fluid by Monaghan (1994) and developed by Tulin and Landrini (2000). This method is based on a grid-less Lagarangian method, which is the same as the MPS method. However, unlike the MPS method, the kernel function is used to discretize the Navier-Stokes equations and the continuity equation through a convolution with the variables under consideration, and the equation of state for the pressure is adopted without solving Poisson’s equation for the pressure.

Landrini et al. (2003) and Colagrossi et al. (2004) applied the SPH method to a 2-D sloshing problem with violent free-surface deformation. Experiments using a rigid square tank were also conducted, whose results were used for validation of computed results by the SPH method. The time history of the slamming pressure on the vertical side wall is surprisingly in good agreement between computed and measured results.

Doring et al. (2004) also applied the SPH method to simulations of the wave-body interactions. As a preliminary validation, the water entry of a wedge was simulated, and a comparison with experimental data was made for the dynamic acceleration. The capability of treating violent free-surface flows and the robustness in numerical computations is well demonstrated.

The SPH method was also used by Iglesias et al. (2004) to study and design passive roll damper tanks for fishing vessels. A quantitative comparison with experimental data was made for moment phase lags against the tank movement, and the free-surface shape was compared as a more qualitative comparison. The degree of agreement for those quantities was very satisfactory. However, further work has yet to be done, such as inclusion of hydro-elasticity, extension to 3-D problems, reduction of computation time, and so on.

Other Studies with CFD Methods. Greco et al. (2002) investigated the water shipping on the fore deck of a ship in head waves experimentally and numerically. Experimental observations confirm the formation of a cavity entrapping air during the initial stages of the water shipping and then the free-surface breaking and dispersion of bubbles in the main water field. To deal with this violent flow, a DD (Domain Decomposition) approach was presented, combining a boundary element method for the outer field and a VOF (Volume of Fluid) method for the wave-breaking region. Overall results appeared rather promising, although numerical inaccuracy was observed in computed results by the VOF solver.

Kim et al. (2003) studied wave-induced ship motions coupled with sloshing flow in a rectangular tank. For direct simulations of sloshing flow in the time domain, the finite difference method based on the SOLA scheme was applied, and the computed force and moment were treated as external excitations for ship motions. Computed results for a modified S-175 hull equipped with partially filled tanks show an importance of nonlinearity in sloshing flows.

2.4 Benchmark Data and Uncertainty Analysis

Benchmark Data. *Review of Existing ITTC Benchmark Data:* The ITTC Recommended Procedure 7.5-02-07-02.1 on Seakeeping Experiments contains a tentative list of sources for benchmark data that could be used for seakeeping code validation. An overview of the characteristics of these data is given in Table 2.1 for sources containing model test data and in Table 2.2 for those which only contain numerical model results. These last ones can be suitable for comparison between codes but not for validation purposes. All the sources are taken from previous ITTC Proceedings.

From Table 2.1 several drawbacks of this data are observed. Most of the data correspond to two kinds of ships (Series 60 and S-175) in similar conditions and therefore they are somewhat redundant. Most of the data correspond to head seas. The few including data for other headings do not describe the characteristics of the autopilot control system. As the autopilot is known to have an appreciable influence in lateral motions and transversal loads, it can be difficult to reproduce the actual conditions in the numerical codes or new experiments. In most cases the tests have been done in relatively small wave slopes where a linear response is to be expected. Data in irregular waves only cover head seas but some include large amplitude waves, as in No. 13 in Table 2.1, which includes data on deck wetness. It is typical not to include a body plan or offsets, although the Series 60 and S-175 can be found in other sources (see, for example, Ballard, 2003). Worse is the lack of any information regarding weight distribution of the model. This happens, for example, in all the S-175 cases. None of these references gives any indication about the level of uncertainty in the data. Finally, only a few cases are the data presented in tabulated form. Therefore some kind of scanning and digitizing will be needed to use the data for validation.

Potential Sources of Benchmark Data: In more recent years, a tendency is observed in the publications to take more care in providing all the data necessary for exact reproduction of the test conditions. Some examples are given in Table 2.3. This table presents some references where additional benchmark data can be found. It is not intended to be exhaustive. Some of the references do not comply with the requirement to provide full information allowing exact reproduction of test conditions, but are included to provide data on other kind of ships like catamarans, fast vessels or SWATHs.

Table 2.1- Benchmark data from model tests in ITTC Recommended Procedure 7.5-02-07-02.1.

				Inputs					Regular waves				Irregular waves				Data				
No.	Ship	Comments	ITTC	DOF	AutoPilot	Scale	BP	Weight	Heading	Fn	h/L	L/Lpp	Heading	Fn	Hs	Tp	Mot	Acc	RM	Load	AR
1	Series 60 Cb=0.6	7 tanks	7	X,Z,M	-	25-80	N	Y	180	0.2-0.28	1/36-1/72	0.75-1.5					x				x
6-1	Series 60, Cb=0.6		11	6	NA	60	Y	Y	180-135-90	0.0-0.25	1/30 (*)	0.2-2.5					x				
6-2	Series 60, Cb=0.6		11	X,Z,M		44	N	Y	180	0.15-0.30	1/50 (*)	0.6-2.0					x				
4	Series 60 Cb=0.7		11	Z,M	-	?	N	Y	180	0.0-0.2	1/50	0.5-2.0					x		x	x	
7-4	Series 60, Cb=0.7		11	X,Z,M	-	60	N	Y	180	0.15-0.30	/50,1/40 (*	0.6-1.8					x				
6-3	Series 60, Cb=0.6&0.7		11	X,Z,M	NA	30	N	Y	180	0.0-0.275	1/50 (*)	0.5-2.5					x				x
6-4	Series 60, Cb=0.6&0.7		11	6	NA	30	N	N	180	0.0-0.25		0.5-2.5					x				x
7-2	Series 60, Cb=0.6&0.7		11	X,Z,K,M	NA	30	N	Y	180	0.0-0.2	1/50	0.5-2.5					x				x
2	Cairndhu steamer	3 tanks	11	X,Z,M	-	35	N	Y	180	0.14-0.18		0.6-3.0	180	0.17	?	?	x				
3	Destroyer	Full scale	11	6	-	1	Y	Y					180	0.18-0.44	2-4	10-14	x	x			
6-5	?		11	?	NA	40	N	N					180	0.18	5-10	?	x				
9	S-175		15	6	NA		N	N	0-180	0.275		0.4-1.5					x				
10	S-175		16	6	NA		N	N	0-180	0.275		0.4-1.5							x	x	
11	S-175		17	6	NA		N	N	0-180	0.275		0.4-1.5								x	
12	S-175	20 tanks	18	Various	NA	35-87	N	N					180	0.2-0.275	1.5-11	6-12	x	x			
13	S-175	12 tanks	19	Various	NA	35-87	N	N					180	0.275	7.9	14.8			x		
14-1	2D sections	2D models	20	Y,Z,K	-	1	Y	-	-	0										x	
14-2	Wigley		20	Z,M	-	?	Y	Y	180	0.2-0.4		0.4-3					x		x	x	x

NOTES
(1) The No. Is the number given in the Seakeeping Recommended procedure.
(2) Column ITTC refers to the ITTC Conference Proceedings in which the data is given
(3) The Degrees Of Freedom (DOF) are X,Y,Z for linear motions and M,N, K for angular motions. 6 means totally free model.
(4) The "Autopilot" column indicates if the autopilot characteristics are given or are irrelevant. NA means that although an autopilot is used, no infoermation is given on its characteristics.
(5) Column "BP" indicates if the Body Plan or offsets are reported.
(6) Column "Weight" indicates if the information in weight distribution is complete.
(7) In the slope column (h7L) an asterisc indicates that the reference length is the Ship Length. Otherwise, the reference length is the wave length.
(8) The data provided can be absolute motions (Mot), accelerations (Acc), relative motions (RM), global loads (Load), added esistance or power increase (AR) or wetness statistics (Wet).
(9) Column "Tab" indicates if the data is given in tabular form.

Table 2.2- Benchmark data from numerical codes in ITTC Recommended Procedure 7.5-02-07-02.1.

			Input		Regular Waves			Data				
No.	Ship	ITTC	BP	Weight	Heading	Fn	L/Lpp	Mot	Acc	RM	Load	Tab
5	Series 60, Cb=0.6&0.7	11		Y	0-180	0.1-0.2	0.0-2.0	x		x	x	N
7-3	Series 60, Cb=0.6&0.7	11	N	Y	180	0.0-0.25	0.16-4.0	x		x	x	N
7-6	Series 60 Cb=0.7	11	N	Y	180	0.0-0.2	0.5-2.0	x		x		Y
7-5	?	11	N	N	180	0.0-0.2	0.5-2.0	x		x		Y
8	Ore carrier	14	Y	Y	0-180	0.0-0.1	0.1-3.2	x	x	x	x	N
13	S-175	19	N	N	180		0.7-6	x				N

Table 2.3- Examples of recently published test data.

			Input					Regular waves				Irregular waves				Data						
No.	Ship	Comments	DOF	AutoPilot	Scale	BP	Weigh	Heading	Fn	h/L	L/Lpp	Heading	Fn	Hs	Tp	Mot.	Acc	RM	Load	AR	Tab	Ref.
A	High speed	6 models	Z,K,M	-	5 m	Y	Y	180	0.29-1.14	1/50 (*)	0.6-2.8					x	x	x		x	N	Block (1984)
B	High Speed	2 models	Z,M	-	?	Y	Y	180	0.2-0.864	1/30-1/65	0.8-5.0	180	0.4-0.9	0.1-0.2	1.4-1.8	x	x	x			N	Lahtiharju (1990)
C	Frigate	Flexible model	6	Manual	1/20	Y	Y	180-135	0.06-0.25	1/30-1/15	0.5-2.0	180-135	0.06-0.25	4-6	9-13	x			x		N	Taggard (1997)
D	Warship	Segmented	6	OK	L=6.157	Y	Y	0-180	0.21	1/50	0.5-2.0					x			x		N	Lloyd (1980)
E	Catamaran	4 shapes	6	NA	L=1.6-2.1	Y	Y	180-120	0.2-0.8							x	x			x	N	Molland (2001)
F	Warship DTMB 5415	Wave Exc.	0	-	46.6	N	Y	180	0.19-0.41	1/125-1/3	0.5-1.5								x	x	N	Longo (2001)
H	High Speed Cat.		6	NA	8	Y	Y	180-120	0.65							x	x				N	Hudson (2001)
I	Series 60 Cb=0.6 & 0.8	Forced oscill.	Z,M	-	L=1.2	N	-	-	0.04-0.29										x		N	Maury (2003)
J	Semi-SWATH	2 models	Z,M	-	L=2.5	Y	Y	180	0.2-0.7		1.0-2.6					x					N	Holloway (2003)
K	High Speed Ferry	Forced oscill.	Z,M	-	25	Y	-	180	0.0-0.63										x		N	Schelling (2003)
	Fast Monohull		Z,M		27	Y	-	180	0.0-0.4										x		N	
	High Speed Ferry		Z,M	-	25	Y	N	180	0.0-0.63	1/8-1/20	0.25-2.5					x			x		N	
	Fast Monohull		Z,M		27	Y	N	180	0.0-0.4	1/8-1/21	0.25-2.6					x			x		N	
L	S-175		Z,M	-	40	Y	Y	180	0.15-0.25	1/120-1/3	0.5-2.0					x			x		N	Fonseca (2004)
M	S-175		Z,M	-	40	Y	Y					180	0.25	4.2-9.9	1.5-16.	x			x		N	Fonseca (2004)

NOTE: For description of column headings, see notes on previous tables.

Still, most of the references deal with head seas. Only a few give results in bow quartering seas and only one (D) in beam or following seas.

Lloyd (1980, 1989) (D in Table 2.3) is a good example of how to provide complete information for exact reproduction of test conditions. Mainly:

- Main particulars, hull form and appendages.
- Weight distribution for the full model and for each separate segment.
- Complete description of appendages.
- Propeller characteristics.
- Response of the autopilot control system.

Regrettably, no indication on uncertainty is included.

The references in the table cover a wider scope than those included already in the Recommended Procedure for Seakeeping Experiments and give data, not only on conventional seakeeping tests, but also in forced oscillations, wave excitation and unsteady wave field. For these reasons, it is recommended that they are included in next revision of the Procedure.

One final note: Detailed data of a sloshing model test using a rectangular tank has been made open to the public through web site by DSME (Daewoo Shipbuilding & Marine Engineering Co., LTD) of Korea. The details can be found on the web site http://www.dsme.co.kr/Hydro.jsp. Additional information about this experiment can be found in the following papers:

- Kim, Y., Y.B. Lee, Y.S. Kim, 2005, “Sensitivity study on computational parameters for the prediction of slosh-induced impact pressure”, 5th ISOPE, Seoul, Korea.
- Lee, Y.B., Y. Kim, Y.S. Kim, 2004, “Parametric Studies on slosh-induced Impact Pressures”, Int. Workshop on Water Waves and Floating Bodies, Cortona, Italy, 2004.
- Kim, Y., 2002, “A numerical study on sloshing flows coupled with ship motion: Anti-rolling tank problem,” Jour. of Ship Research, Vol. 46, No.1, 2002.
- Kim, Y., 2001, “Numerical simulation of sloshing flows with impact load,” Applied Ocean Research, Vol.23, No.1.
- Kim, Y., 2000, “Sloshing flows in ship liquid tanks,” Journal of Ship and Ocean Technology, Vol. 5.

Uncertainty Analysis. It is still difficult to find references where model test data are accompanied by any estimation of uncertainty or error bounds.

Gui (2001) (F) is the most complete reference in this respect. They dedicate a complete chapter to the analysis of uncertainty for their results on loads and unsteady waves around restrained model advancing in waves. They address the question on how to estimate the uncertainty in Fourier components from the uncertainties in the raw data. They conclude that the uncertainty increases quickly as the order of the harmonic increases. They recommend following the AIAA standard for uncertainty analysis. The measured data can be obtained freely from www.iihr.uiowa.edu.

The model test data in Fonseca et al. (2004) had not been subjected to a complete uncertainty analysis due to the difficulty in tracking all the error sources but some estimation on uncertainty is given based on two alternatives. One is the analysis of variation between pairs of repeated tests. The results coincide with the previous statement in that uncertainty increases with the order of the harmonic. For the first order harmonic the variations are less than 2% while for the third can go up to 20%. But this happens when the forces to be measured are very small. The other method consists in dividing a long record into several shorter sub-records and comparing the results from the individual analysis of each one. The results are similar to the previous ones. Part of the variation is though to be due to some modulation in the incoming regular waves.

A similar analysis with similar conclusions is made in Schelling (2003). This reference gives comprehensive data on forced oscillation and seakeeping tests with a segmented model. Regretfully the weight distribution for the seakeeping tests is not reported but it could be obtained from the test facility.

Another publication which considers the question of uncertainty is Maury (2003) (I).

They estimate that the errors in added masses and damping are of the order of 10% while the error in the measurement of the wave field is considered negligible in comparison.

It can be seen that uncertainty analysis is far from being a standard in seakeeping model tests. Probably the main reason is the large amount of sources of uncertainty: model construction, instrumentation, wave field, data reduction as well as the inherent statistical variability in irregular sea tests. Therefore, more effort is needed in identifying the main sources of error and their relative importance to concentrate in a few of them.

2.5 Seakeeping Operability Criteria

Introduction. In order to evaluate if a hull design is successful, criteria are established against which an analysis can be made. Basic seakeeping criteria will typically include ship motions and ship-motion related phenomena (e.g., deck wetness, slamming, etc.) as well as addressing seaway-induced loads and dynamic stability (capsize). In general, mission effectiveness will degrade with increasing motions in a seaway. From a seakeeping perspective, the probability of success of military operations, such as aircraft launch & recovery, or underway replenishment, can be assessed by evaluating the effects of ship motions on the subsystems involved. “Subsystem” as defined here is any element that plays a role in the ability of the ship to function and operate successfully. Thus, the hull, machinery, personnel, aircraft, sensors, weapons, etc. qualify as ship subsystems. How effective a ship is in performing its mission, from ferries, to containerships, to warships, can often be determined by the degradation of the subsystems that support the mission. Table 2.4 presents typical motion response and response-derived criteria as they apply to naval military missions.

A discussion of these types of seakeeping operability criteria, their derivation and use follows.

Table 2.4- Military Operability Criteria (Smith and Thomas, 1989).

MISSION	Motion	ROLL	PITCH	VERTICAL ACC.	LATERAL ACC.	SLAMS	SUBMERGENCE	EMERGENCE
	Measure	SSA (deg)	SSA (deg)	SSA (g)	SSA (g)	#/hour	#/hour	#/hour
	Location	CG	CG			Keel	Foredeck	Sonar Dome
MOBILITY		8	3	0.4 @ Pilothouse	0.2 @ Pilothouse	20	30	N/A
COMMAND & CONTROL		15	6	N/A	N/A	N/A	N/A	24
ANTI-AIR WARFARE		6	4	1.3 @ Missile Launcher	0.8 @ Missile Launcher	N/A	N/A	N/A
ANTI-SUBMARINE WARFARE		18	6	N/A	N/A	N/A	N/A	24
SURFACE WARFARE		6	4	1.3 @ Missile Launcher	0.8 @ Missile Launcher	N/A	N/A	N/A
UNDERWAY REPLENISHMENT		5	2	N/A	N/A	N/A	N/A	N/A

*SSA = Significant Single Amplitude

Motion Response Criteria. Motion response criteria are those formulated on the basis of ship motions predicted by seakeeping computer programs or measured by experiments and/or full-scale trials. These include, e.g., RMS roll, pitch and yaw angles, RMS vertical and lateral displacements, RMS vertical velocity as well as RMS longitudinal, lateral and vertical accelerations. All these criteria refer to whole ship responses which are not, in general, very sensitive to the prediction method applied, i.e. whether predicted by means of one of the strip method programs, other programs, or measured by tests.

Designers and operators frequently seek ship motion guidance in terms of probability of exceedance (PE). When giving guidance to other authorities on the likely performance of a new design in probability of exceedance terms, it is important to bear in mind the limitations of the current methods for predicting motions. Thus, it is to be stressed that the information is for guidance only and cannot be regarded as an assurance that higher values will not arise in service.

PE can be easily derived from root mean square (RMS) values because of the underlying assumptions of the motions from which they are derived.

- Proportion of time- the motion exceeds a given value (derived from Gaussian or Normal probability theory)
- Proportion of peaks- exceeding a given level (derived from Rayleigh probability theory)

In general probability of exceeding peaks is used.

Derived Response Criteria. Derived response criteria are those that are formulated from a basis of direct responses of the linear frequency domain computations. These are, e.g., propeller emergence index, slamming index, sonar emergence index and wetness index.

Some criteria of this group are based on relative motion between ship hull and wave surface. These must be expected to be sensitive to the prediction method applied. The formulations of the criteria are briefly covered in the following.

Propeller Emergence Index: Back-ground of this criterion is the risk of propeller racing which could lead to engine damage. The usual formulation of this index describes the probability of a certain proportion of the propeller disk emerging from the water. In the case of strip theory predictions, the relative wave motion does not include the deformation of the incoming waves by radiation and diffraction. The deformation of the incoming waves by radiation and diffraction becomes more pronounced as the waves travel along the ship.

Slamming Index: Slamming occurs when a hull section emerges and re-enters with a vertical velocity sufficient to cause very high pressures of short duration, and two types can be identified:

a) Bottom impact slamming- Both emergence of the section and high re-entry velocities are required for this to occur, causing very high pressures on hull plating;
b) Bow or flare slamming- In general this does not lead to such high local pressures. It can, nevertheless, impose a high overall loading on the hull girder.

Thus the slamming risk can be summarized as either local shell damage or hull girder overload or fatigue. The slamming loads are intrinsically non-linear and cannot be predicted by linear methods. Most strip method slamming predictions use the definition of a slamming event developed by Ochi (1964**.** This formulation assumes a slam if the forefoot has emerged from the water and the re-entry velocity of the keel exceeds a certain threshold. The threshold was derived from model tests with a 'Mariner' hull form. Usually Froude scaling of the threshold velocity V_{TH} is assumed: $V_{TH} / \sqrt{gL} = 0.093$. This formulation describes impact loads upon the bottom, but without consideration of the geometry and the load carrying capability of the bottom structure. Another formulation avoids some of the limitations and is based on the pressure at re-entry, see, e.g., Lloyd (1992). The pressure is assumed proportional to the square of the re-entry velocity and a pressure coefficient which depends on the bottom cross section. Such formulation also focuses on bottom impact loads. The two alternative formulations should not be expected to result in equivalent slamming indices. During full scale trials, above formulations would be extremely difficult to apply. Aertssen (1968) defines a slam by the midship whipping stresses exceeding certain ship dependent thresholds.

This formulation is not limited to bottom slamming. So far, no formulations exist which allow the computational assessment of the risk of bottom slamming as well as flare slamming. As no really satisfactory formulation of slamming risk is available, the Ochi criterion should be seen as an interim.

The probability of excessive bottom slam loading occurring at a section is the product of the probability of emergence of the section and the probability that a specified limiting pressure will be exceeded. The relative re-entry velocity associated with a slamming pressure can be calculated from the Ochi formula and this velocity will have the same probability of exceedance as the specified slam pressure.

$$\begin{aligned} &P_r(\text{bottom slam}) \\ &= P_r(\text{emergence}) \times P_r(\text{pressure exceedance}) \quad (2.10) \\ &= P_r(\text{emergence}) \times P_r(\text{velocity exceedance}) \end{aligned}$$

$P_r(\text{emergence})$ can be derived by comparing the draft of the section with the *RMS* output for relative vertical displacement at that section.

For bow or flare slamming, since emergence is not involved:

$$P_r(\text{flare slam}) = P_r(\text{velocity exceedance}) \quad (2.11)$$

Sonar Emergence Index: This criterion describes the risk of loss of sonar contact as the sonar approaches the water surface or even emerges. It is usually formulated as the probability of a specified point of the sonar emerging from the water surface. Basically the same comments apply as for the propeller emergence index, except that the deformation of the incoming wave by diffraction and radiation is less pronounced in head seas.

Wetness Index: The term "wetness" is used to cover:

- propensity to immerse the fore end of the ship and take on green seas;
- the extent to which spray and broken water is thrown on to the upper deck, upper deck equipment, and superstructure.

The extent to which the upper deck becomes immersed is governed primarily by the freeboard and section shape. Immersion occurs chiefly at the bow and stern. The shape of the fore end in particular determines the extent to which spray and broken water arises. Computer techniques to assess this are not available. Model testing provides a useful indication of performance.

Loads arising from green seas, broken water, and spray are of concern to the designer of upper deck equipment (e.g., missile launchers) but research in this area is still at an early stage.

The wetness criterion describes the risk of equipment damage by green seas or impairment of work on deck by wetness. The index is usually formulated as the number of events in which the wave surface is higher than the deck-side at a specified position. In the case of strip theory predictions, the relative wave motion does not include the deformation of the incoming waves by radiation and diffraction. The effect of the above water hull sections, as bow flare, spray deflectors, knuckles etc. is also not covered. Further, the predictions do not include the effect of the bow wave. In model tests all these influences are included.

So, in general, the prediction of the relative motion is the key in the context of deck wetness and sonar or propeller emergence. Linear frequency domain techniques have no means to include the effect of above water hull form in the prediction as, e.g., due to flare, spray strips or knuckles. For relative bow motion, Blok and Huisman (1984) recommended that an overall correction for 'dynamic swell up' should be applied.

Ideally, predicting the relative motion between the deck and the water surface in the time domain will give a much better prediction of deck wetness since is can account for the above water hull form. Furthermore, it removes the need to make assumptions about the motion amplitude distribution model being employed. However, the various indices previously discuss are still derived from some assumption that an event follows an exceedance. Typical criteria, presented in the Table 2.5, are based on this premise.

Table 5- Typical Derived Response Criteria Limits.

Hull type	Performance Limitations		
	Motion	Limit	Location
Monohull	Wetness Index	30/hr	Bow (Worst location)
	Slamming Index	20/hr	Keel (Worst location near bow)
	Propeller Emergence	90/hr	1/4 Propeller Diameter
Aircraft Carrier	Slamming Index	20/hr	Sponson
SWATH	Wetness Index	5/hr	Lower Leading Edge of Cross Structure if it has a corner
	Wetness Index	30/hr	Forward Edge of Weather Deck
	Slamming Index	20/hr	Worst Location Under Cross Structure
	Propeller Emergence	90/hr	1/4 Propeller Diameter

2.6 Requirements for Future Research

Loads and Responses in Waves. With rapid progress in computer technologies, our research concern is directed to 3-D effects and nonlinearities in large amplitude waves. To study these, time-domain nonlinear (or at least weakly nonlinear) calculation methods are developed. However, since time-domain calculation methods are generally very time-consuming, the calculation region tends to be small and the size of each panel on the body and free surfaces tends to be large. To resolve these problems, numerical techniques to accelerate time-domain computations must be studied further, although some promising techniques have already been proposed, such as a pre-corrected FFT technique, a multi-pole expansion technique, and the use of higher order boundary element method. With these fast calculation schemes, a convergence test of numerical solutions should be conducted with increasing the number of panels and the size of calculation region.

In time-domain computations, the stability of numerical solutions is also crucial, especially in computing the wave-induced ship motions by time marching both ship-motion equations and hydrodynamic boundary-value problems. Stable time-marching schemes are needed in conjunction with a reasonable panel arrangement that is numerically efficient and robust for any kind of ship hulls.

Development of new model test techniques for nonlinear and extreme responses of a ship in waves is encouraged and similar test results are demanded for validation of time-domain computer codes.

Added Resistance and Added Power in Waves. Recently it has been found numerically as well as experimentally that the bow form of a ship above the calm-water surface affects the added resistance in waves quite significantly. Therefore, it is necessary to develop reliable numerical tools that can account for the interaction of waves with the bow form of ship above the calm-water surface. With those numerical tools, it may be possible to develop a new bow form that can reduce the added resistance in waves by a significant amount.

High-speed Vessels and Multihull Ships. There are little data for 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 not 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.

Slamming, Deck Loads and Whipping. *Slamming and Deck Loads:* The real concern for slamming should be the maximum slamming induced structural stresses, thus the slamming should be considered in the framework of structural dynamics response. Different physical effects like air cushions, sound waves in air and water should be accounted for in certain circumstances in the hydro-elasic analysis. In addition to local hydro-elastic analysis, efforts should also be made in integrating the slamming analysis in the global flow description around the ship, and this will lead to the consideration of the mutual interaction between slamming loads and global ship behaviour.

It is found that the flow interactions and the efflux occurring between the deck area and the outer region play an important role in deck flow and loads prediction, in addition to the influence of the above-water hull form. Numerical methods to describe green water on deck should be further developed, and it is better to combine numerical methods with model tests to better describe different scenarios of water shipping. The effect of hull parameters like bow flare and stem angle on green water should be further investigated.

Whipping: Hydro-elastic analyses coupled with seakeeping computations are now available. There is a need for experimental data to validate those computations. Experiments must be performed in accordance with recommended ITTC procedures in order to give all information required for the validation task. More study is needed on the influence of structural damping and on the number of eigen modes needed to represent the full-scale case.

There is also a lack of experimental methodology to derive the impact force on a section from a set of pressure gauges. Theoretical materials could be helpful.

Parametric Rolling. It is recommended that the non-ergodic process of parametric rolling be investigated further and that the impact on the experimental testing process for parametric rolling should be considered.

CFD Applications in Seakeeping. In recent years, some studies using CFD techniques have been made on highly nonlinear phenomena, such as water on deck, green water, and sloshing. However, most of them are concerning 2-D problems and generally time-consuming. Numerical accuracy and stability in time marching must be confirmed through comparisons with reliable experimental data for both 2-D and 3-D 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 in less numerical diffusion, but validation study and extension to 3-D problems must be made.

Particle methods (the 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 3-D problems. Although some ideas have already been proposed, more advanced techniques must be developed for reducing the computation time significantly.

Recently unsteady RANS calculations have been conducted for studying global nonlinear ship motions in waves and the added resistance. Unfortunately, unsteady RANS calculations are extremely time consuming and generally can not deal with violent flows including fragmentation of the fluid. Reduction of the computation time and enhancement of the resolution may be achieved by coupling the RANS solution near the ship to a potential-flow solution away from the ship. Development of this kind of calculation codes and validation of numerical results are to be done in the future.

Benchmark Data and Uncertainty Analysis. Little published seakeeping experimental data exists that can be used as benchmark data for the validation of seakeeping codes, because they lack some of the following information that is necessary for the exact reproduction of test/calculation conditions:

- Main particulars, hull form and appendages
- Weight distribution for the full model and for each separate segment
- Complete description of appendages
- Propeller characteristics
- Response of the autopilot control system

Ideally, it would be quite useful if reliable experimental/numerical benchmark data were available on a website that anyone could access and download the information. Since many in the ITTC seakeeping community have valuable unpublished experimental/numerical data, it may be necessary for the ITTC to actively seek such data and to encourage their publication in an appropriate manner.

As for the uncertainty analysis, it can be seen that uncertainty analysis is far from being a standard in seakeeping model tests. The main reason, no doubt, is that there exist many sources of uncertainty: model construction, instrumentation, wave field, data reduction as well as the inherent statistical variability in irregular sea tests. Therefore, more effort is needed in identifying the main sources of error, assessing their relative importance, and to concentrate on characterizing a few of them.

Seakeeping Operability Criteria. The success of a hull form design can often be measured by its success in achieving its mission. This is not a foreign concept to military naval designs which are often judged by their operational effectiveness in a seaway. The establishment of operability criteria and the evaluation of hull designs via computer simulation and/or model experiments against these criteria is generally part of the military design spiral. Some criteria are specific to weapon or sensor effectiveness. Many common criteria, such as the acceptable level of deck wetness or the number of slams per hour, have been established in the literature, and have a more general usage. There has also been much work performed in the area of human factors, including motion sickness incidence (O'Hanlan and McCauley, 1973) and motion-induced interruptions, as reported by Baitis et al. (1984) and Graham (1990), that can have a practical use in providing operator guidance, as demonstrated by Crossland et al. (2003). Extending the establishment and validation of operability criteria, including for commercial craft, is seen as useful for design assessment and at-sea operations.

3. ITTC RECOMMENDED PROCEDURES

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

Apart from several minor changes mostly related to the style, the following modifications have been made:

- Additional graphs for tank wall interference have been added.
- Adaptation, as much as possible, to the ITTC standard style.
- Drafts for Chapters 2.5 to 2.8 have been written. Titles for these sections were provided in the previous versions but no text was included. These sections are: "Free running tests", "Measurement of wave loads", "Measurement of Added Resistance" and "Measurement of impact loads".
- Section 3.1 on "Parameters to be Taken into Account" was actually more an extension of the section on "Parameters to be measured". It was

modified to describe those parameters which define the test as an input to the tests (waves, headings, and so on) rather than those that should be measured as output from the tests.

- A new reference for benchmark tests has been added and some additional information has been included in some of the previous references. Some new benchmark data references are proposed in Section 2.3.1 of this report as good candidates to be included in future versions of this Recommended Procedure. Also in this section, additional information on the previously included benchmark references is given.

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

In the report of the last 23rd ITTC, other than “direct power method,” “torque and rate of rotation method,” “thrust method”, “thrust identity” method was added in the Recommended Procedures 7.5-02-07-02.2 as a possible alternative method for the prediction of power increase in irregular waves from model experiments in regular waves.

In the current report, a brief explanation on how the power increase is estimated by the thrust identity method was added in the Recommended Procedures. Figures that show the example comparisons of the power increase estimated by the four different methods were also added in the Recommended Procedures.

3.3 ITTC Procedures 7.5-02-07-02.4, Validation of Seakeeping Computer Codes in the Frequency Domain

The Recommended Procedures provided by the 23rd ITTC Loads and Responses Committee were stringently reviewed, and a number of modifications were made, although the general structure in the Recommended Procedures remained the same.

Since there were no descriptions for Section 3.6 on Transfer Functions of Added Resistance and for Section 3.8 on Computations for Irregular Waves, the procedures for verification of computer code elements and validation were newly developed for these sections. The list of related papers was added at the end of the Recommended Procedures.

It seemed that the original Procedures were written with strip-theory type solutions mainly kept in mind. However, 3-D panel methods are common and routinely used these days, thus some modifications for the 3-D Green-function method and the Rankine panel method were incorporated in the Procedures.

3.4 ITTC Procedures 7.5-02-07-02.*x*, Validation of Seakeeping Computer Codes in the Time Domain

This new Recommended Procedure is provided to enable the reader to understand the verification and validation process necessary for a time domain seakeeping code. In this first instance the procedure is aimed very much a linear seakeeping responses, the aim being that this can be used as a foundation for providing procedures for fully non-linear time domain calculations. Because of the linear nature of the time domain code the general structure is very similar to the Recommended Procedure on the Validation of Seakeeping Computer Codes in the Frequency Domain.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The Seakeeping Committee has updated five Procedures as mentioned in Section 3, while the Procedures for the Risk and Magnitude of Parametric Rolling has been transferred to the task of the Speciality Committee on the Stability in Waves.

The state-of-the-art of research activities in the field of seakeeping have been reviewed. Review of research works on multi-hull ships and on the application of CFD to seakeeping computations of ships has been added to the committee work, although not included in the tasks imposed on the Seakeeping Committee by the ITTC, because the committee thought the two subjects would have a very important impact on the ITTC. The specific requirements for future research have been identified from these review works.

The attempt of a detailed review of the existing ITTC benchmark data in the field of seakeeping listed in the previous ITTC Proceedings has been made. The drawbacks of the existing would-be benchmark data and the future requirements for the benchmark data have been identified. Recently published data on sloshing in tanks have been added as potential benchmark data.

The review of available seakeeping operability criteria, which had not been dealt with in any of the previous ITTCs, has been conducted and the required works for this subject have also been identified.

The conclusions obtained from these work are summarized below.

Loads and Responses in Waves. There is a trend that seakeeping computations transfer from frequency to time domains, from linear to nonlinear problems, and from potential-flow to viscous-flow computations. Much work has been done on geometrical nonlinear effects on the wave loads and wave-induced ship motions by means of time-domain nonlinear strip theories and the body-nonlinear time-domain Green function method. Developments were also found in 3-D Rankine panel methods and comprehensive experiments providing reliable benchmark data for validation of numerical methods.

Added Resistance and Added Power in Waves. Instead of the ship performance in calm water, the ship performance in actual seas is being given more weight, because that is the real performance of the corresponding ship directly connected to the operability and thus the economic value of the ship. As the consequence of this trend, various theoretical and experimental attempts are being conducted toward the reduction of added resistance or added power in waves. Through these activities, it has been found and verified that the bow form of a ship above the calm-water surface affects the added resistance in waves quite significantly. Although some bow forms have already been proposed that actually reduce the added resistance in waves by a certain amount, there could be some other novel bow forms that can further reduce the added resistance.

High-Speed Vessels and Multihull Ships. A significant amount of effort has been devoted to developing capabilities to predict the response of multihull vessels and high-speed craft in waves. 3D Green function and Rankine source methods haven been applied to the problem. Many of the theoretical formulations have been validated using vertical plane responses derived from experiments. There are fewer examples of validation using experimental measurements of both lateral and vertical plane responses. Efforts should be devoted to obtaining suitable benchmark data for multihull vessels in oblique waves.

For high speed planing craft most of the effort involves the use of 2D potential flow theory, with non-linearities accounted for by the treatment of the instantaneous underwater hull form. The theories are derived for vertical plane responses only – no examples of responses in oblique waves could be identified. This is reflected in the lack of availability of validation data relating to planing craft responses in oblique seas. 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.

Slamming, Deck Loads and Whipping. *Slamming and Deck Loads:* For slamming, common analysis assumes a rigid body, symmetric impact, incompressible fluid, irrotational flow, neglecting of gravity, no air cushion and no flow separation. Methods are well established for two dimensional flow conditions and have been used to calculate slamming loads on ship hulls. Necessary relative vertical motions and velocities are obtained by neglecting the influence of water-entry loads on ship motions. Three dimensional effects, on the contrary, are still in the premature condition.

Extensive experimental studies have been done on green water on deck, but it is only recently that its physics becomes better understood by use of experimental and numerical investigations interactively. Variable numerical methods, such as BEM, NS-VOF, SPH, dam-break model, etc. have been tested to simulate the fluid flow on deck, with only partial success. Some semi-analytical design tool has been suggested that incorporates probabilistic approach and linear hydrodynamic analysis with empirical relations and modern numerical methods, but it needs further refinement and verification.

Whipping: There are more and more experiments and numerical computations on hydro-elasticity coupled with seakeeping. With those tools it will be possible to increase study on this topic and to evaluate influence of new parameters on the global and local responses.

Parametric Rolling. Traditionally a problem for smaller vessels in following waves, recent events have highlighted the problems of parametric rolling in larger vessels in head seas. Single degree of freedom roll models, some with implicitly extended degrees of freedom through the non-linear restoring terms, have been developed to assess the parametric rolling problem. In parallel six degrees of freedom non-linear time domain ship motion codes have been used to demonstrate the issues of parametric rolling. The main problem with evaluating the response is the determination of the run length required to produce stable statistics. The roll response of a ship experience parametric rolling is not an ergodic process, in as much of demonstrating statistically stable responses after a suitably long run length.

This has an impact on any proposed testing process for parametric rolling and should be considered in future ITTC efforts.

CFD Applications in Seakeeping. Several CFD techniques have been developed for studying global nonlinear ship motions and localized strongly nonlinear phenomena such as violent sloshing and green water. Remarkable advance has been achieved by the studies based on the CIP method and particle methods, capable of dealing with fragmentation of fluid and entrainment of air with less numerical diffusion. However, improvement is still needed for higher resolution of the pressure distribution on the boundary surface and reduction of the computation time.

Benchmark Data and Uncertainty Analysis. Most of the published seakeeping data that could be candidates for benchmarking lack the necessary information to make them reproducible in other tests or computer codes. For this reason it seems appropriate to develop a new Procedure on “Data Reporting from Seakeeping Tests”. This Procedure should cover all the aspects of the model description, test arrangements, sensor descriptions, wave characteristics and, of course, the uncertainty analysis related to all these aspects.

Even lower is the number of publications on seakeeping test results addressing the problem of uncertainty. This is primarily due to the complexity of this kind of analysis when applied to seakeeping tests that involve a large number of variables. For this reason, it seems necessary to identify a reduced set of variables which are the major sources of uncertainty, and concentrate on them. No guidance on this issue can be found in the literature.

Seakeeping Operability Criteria. Operability criteria provide an evaluation capability that utilizes limitations on undesirable events that affect mission effectiveness. Proper consideration of their use can lead to several advantages:

- eliminates pass/fail options and allows for gradual degradation assessment;
- permits the combination of motions and forces that together affect operability;
- focuses on the underlying physical phenomena that degrade performance not anecdotal motion values;
- is ship-independent allowing objective comparison of vastly different platform designs; and,
- provides helpful operator guidance.

4.2 Recommendations to the Conference

Adopt the amended Procedure “Seakeeping Experiments”, 7.5-02-07-02.1.

Revise the following procedures, which were not accepted as the ITTC Procedures after being reviewed by the Advisory Committee of 24th ITTC:

- Procedure “Predicting the Power Increase in Irregular Waves from Model Experiments in Regular Waves,” 7.5-02-07-02.2.
- Procedure “Validation of Seakeeping Computer Codes in the Frequency Domain,” 7.5-02-07-02.4.
- Procedure “Validation of Seakeeping Computer Codes in the Time Domain”.
- Procedure “Experiments on Rarely Occurring Events”, 7.5-02-07-02.3.

Initiate a new Procedure on “Data Reporting from Seakeeping Tests” in order to uncover and collect would-be benchmark experimental/ numerical data in such a way that the experiments or the numerical calculations could be reproduced.

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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